Wear 350-351 (2016) 10–20

Contents lists available at ScienceDirect

Wear

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

Dry sliding wear behavior of superelastic Ti–10V–2Fe–3Al β-titanium alloy

M. Mehdi, K. Farokhzadeh, A. Edrisy*

Department of Mechanical, Automotive & Materials Engineering, University of Windsor, 401 Sunset Ave, Windsor, ON, Canada N9B 3P4

A R T I C L E I N F O

Article history:
Received 11 August 2015
Received in revised form
12 December 2015
Accepted 15 December 2015
Available online 30 December 2015

Keywords:
Superelasticity in titanium alloys
Wear mechanisms
Recovery ratio
Transition load
Adhesion

A B S T R A C T

The dry sliding wear behavior and wear mechanisms of near-β Ti–10V–2Fe–3Al alloy were investigated with respect to its superelastic characteristics. The β-annealed Ti–10V–2Fe–3Al alloy exhibited high recoverable elastic deformation, e.g., maximum recovery ratio of 90% at 200 mN load during indentation tests using a diamond Rockwell stylus (200 μm radius). Wear tests were carried out under unlubricated conditions using a ball-on-disk tribometer under unidirectional sliding (single pass) and rotational conditions within a load range of 1–5 N against AISI 52100 steel counterface. The dominant wear mechanism, at low loads (≤ 2 N), was oxidative wear and superelasticity enhanced the wear resistance mainly due to the high strain recovery of the alloy. A transition to severe wear occurred at higher loads (> 2 N) characterized by higher wear rates, adhesion, and transfer of titanium alloy to the counterface. After the transition, superelasticity did not contribute to wear enhancement.

1. Introduction

Shape memory alloys (SMAs) exhibit superior wear resistance compared to conventional metals and alloys [1–4]. The majority of studies on the tribological behavior of SMAs is focused on nickel-titanium alloys (i.e., nitinol) due to their extensive application in biomedical industry, microelectromechanical systems, aerospace, and oil exploration [5–7]. Superior wear resistance of NiTi alloys has been confirmed in many tribological conditions such as reciprocating sliding [8–10], impact [11,12], and erosion [11,13–15] and is mainly attributed to their high strain recovery. The reversible martensitic transformation and detwinning of the martensite phase retard plastic deformation and hinder deformation-dominated wear mechanisms [16,17]. Yan et al. [16] reported that a transition to severe wear occurs when the contact stress is higher than the yield stress of detwinned martensite. Qian et al. [17] reported the existence of a critical load, above which the wear mechanism altered, due to the inability of superelasticity to accommodate the applied high contact stresses.

The superelastic effect is the result of a reversible transformation from β (BCC structure) to α″ martensite (orthorhombic structure) phase [18,19]. Multiple cycle scratch test experiments by Feng et al. [17] revealed that the stress-induced martensite phase recovered to the austenite phase upon increasing the temperature ($M_d > T > A_f$) and the scratch grooves were self-healed. Farhat and Zhang [20] and Li [21] proposed that a portion of the friction-induced heat under sliding conditions is consumed for reverse transformation of stress-induced martensite to the parent austenite phase. This reverse transformation results in the reduction of surface temperature and enhances superelasticity. In addition to the high recoverable strain limit and thermoelastic behavior, the wear resistance of shape memory NiTi alloys is linked to their low E/H ratio (e.g., low elastic modulus and high plastic yield strength). Several researchers have reported that superelastic NiTi alloys exhibit larger contact areas during sliding, compared to conventional alloys, leading to lower contact stresses and less local wear damage [10,11,21–23].

In addition to NiTi alloys, superelasticity and shape memory effect have been observed in several β-titanium alloys including, but not limited to, Ti–Nb [24–26], Ti–Nb–Al [27,28], Ti–Mo–Sn [29], Ti–V–Al [30], and Ti–10V–2Fe–3Al [18]. Ti–10V–2Fe–3Al is a near-β titanium alloy that offers excellent properties such as formability, hardenability, strength, ductility, fracture toughness and fatigue strength as well as resistance to corrosion and hydrogen embrittlement. Ti–10V–2Fe–3Al is one of the main aerospace β titanium alloys in production for forged aircraft components such as landing gear structures, flap tracks, airframe systems, fittings, fasteners, actuators, cargo handling structures as well as helicopter rotor assemblies and has recently found applications in automotive an oil and gas industries [5,31–39]. However, poor wear resistance and susceptibility to galling is a major drawback especially when sliding contact is inevitable. Previous investigations by the authors revealed that the near-β Ti–10V–

---

* Corresponding author. Tel.: +1 519 253 3000x2622.
E-mail address: edrisy@uwindsor.ca (A. Edrisy).

http://dx.doi.org/10.1016/j.wear.2015.12.006
0043-1648/

2Fe–3Al alloy (as-received condition with α+β microstructure) exhibited lower wear rates compared with Ti–6Al–4V alloy. Ti–10V–2Fe–3Al alloy also showed higher resistance to subsurface crack initiation and unstable plastic deformation; thus its mild to severe wear transition was extended to higher loads [40].

In the present investigation, the effect of superelasticity on the sliding wear behavior of near-β Ti–10V–2Fe–3Al titanium alloy was studied. The tribological properties of β-annealed Ti–10V–2Fe–3Al (single-phase β microstructure) were studied using a ball-on-disk tribometer under unidirectional sliding (single pass) and rotational conditions. The wear tests were also carried out on the as-received Ti–10V–2Fe–3Al (bimodal α+β microstructure) under the same conditions for the purpose of comparison. The controlling wear mechanisms were identified through microscopic examination of worn surfaces and wear debris and the results were discussed with respect to the superelastic characteristics of the alloy.

2. Materials and experimental procedure

Disks of 20 mm diameter and 3 mm thickness were cut from the as-received hot-rolled bars of Ti–10V–2Fe–3Al alloy (hereafter referred to as Ti-1023). The alloy had the following composition in mass percent: 10.65% V, 1.73% Fe, 2.99% Al, and the balance Ti, measured using inductively coupled plasma optical emission spectrometry (ICP-OES) analysis [41]. The average content of the α phase was 36.5 vol%, determined using an image analyzing software [42]. The hardness and elastic modulus were determined by microindentations using a diamond Vickers tip (CSM Instruments Micro-Combi Tester) and averaged over at least ten measurements.

In order to obtain a completely retained β microstructure at room temperature, test coupons were heated to 900 °C (above the β-transus temperature of the alloy, 800 °C [32]) inside a tube furnace under controlled atmosphere for 90 min. In order to evaluate the superelastic behavior, a series of instrumented indentation tests were carried out using a diamond Rockwell tip (200 μm radius) at maximum applied loads ranging from 200 mN to 1000 mN [43]. The samples were loaded at a constant loading rate of 200 mN/s and unloaded at the same rate after a 10 s dwell time at peak load. Each test was repeated twice and the recovery ratios were calculated based on the residual depth measurements [44].

The unlubricated (dry) sliding performance was evaluated using a ball-on-disk tribometer (UMT tribometer, Bruker) under unidirectional sliding (single pass) and rotational conditions within a load range of 1–5 N. The wear tests were carried out at

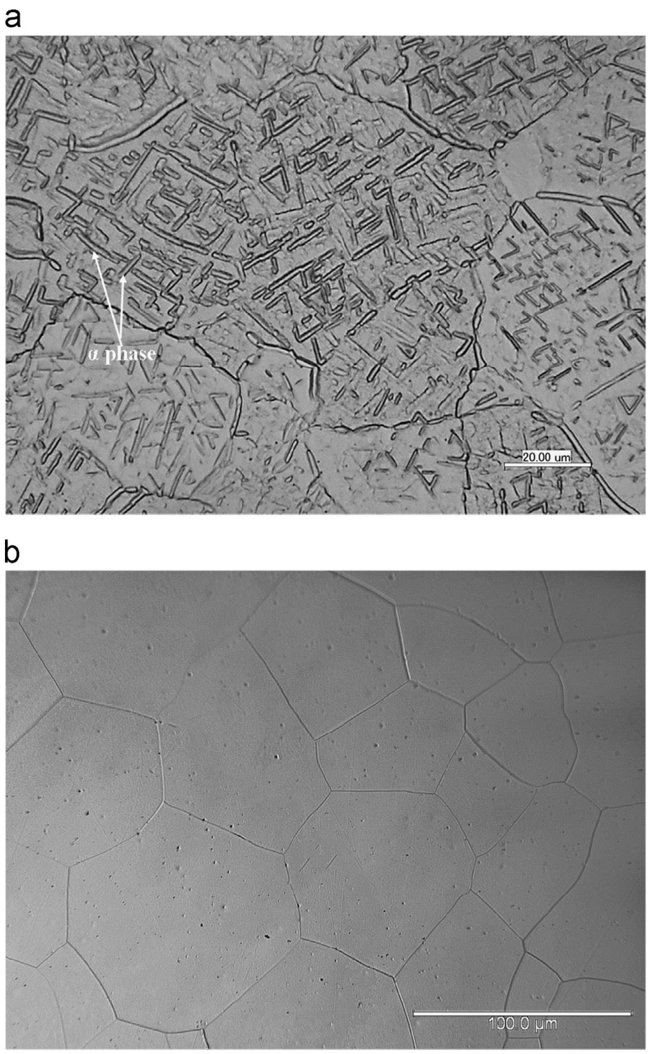

Fig. 1. Optical micrographs of the microstructure of Ti–10V–2Fe–3Al alloy used in this investigation, (a) as-received microstructure and (b) β-annealed microstructure.