Tribology International 44 (2011) 1488–1494

Contents lists available at ScienceDirect

Tribology International

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

Improvement of the fretting damage resistance of Ti-811 alloy by Cu/Ni multilayer films

Xiaohua Zhang [a], Daoxin Liu [a,*], Guohua Liu [a], Zhenya Wang [a], Bin Tang [b]

[a] Corrosion and Protection Research Laboratory, Northwestern Polytechnical University, Xi'an 710072, China
[b] Research Institute of Surface Engineering, Taiyuan University of Technology, Taiyuan 030024, China

ARTICLE INFO

Article history:
Received 12 May 2010
Received in revised form
26 October 2010
Accepted 16 November 2010
Available online 23 November 2010

Keywords:
Fretting fatigue
Fretting wear
Multilayer films
Titanium alloy

ABSTRACT

The Cu/Ni multilayer films were prepared on the titanium alloy surface by ion-assisted magnetron sputtering deposition (IAD) technique. The Cu/Ni multilayer films could significantly improve the resistance of fretting wear and fretting fatigue (FF) of Ti-811 alloy at room temperature. The FF resistance of the titanium alloy substrate did not increase monotonically with increase in the modulation period thickness of the Cu/Ni multilayer films. The Cu/Ni multilayer films with modulation period thickness of 200 nm had the highest FF resistance among the prepared Cu/Ni multilayer films for its comprehensive properties with high toughness, high strength and good lubricating action.

1. Introduction

Titanium alloys are important structural materials for aerospace components because of their excellent performance [1,2]. Titanium alloys are very sensitive to fretting fatigue (FF) damage because of their low thermal conductivity and high coefficient of friction. This can result in FF failure of compressor blades and disk dovetail joints in aircraft engines [3,4]. FF damage is thus a major concern when considering the use of titanium alloys in aircraft engines. Many studies have investigated the use of surface coating and modification treatments to improve the FF resistance (FFR) of titanium alloys [5–8]. However, it is difficult to improve the FF resistance by surface treatment methods because the anti-friction and anti-fatigue properties should be improved at the same time and methods to achieve these aims are usually incompatible. Anti-friction behavior can be remarkably improved by hard coatings or surface hardening treatments. However, the fatigue resistance is often reduced due to the poor fracture toughness of the hard treated surface. Thus, it is difficult to improve the FF resistance by this method [9]. Matching of the intensity and toughness could be achieved by a special multilayer film structure to improve the anti-friction and anti-fatigue properties at the same time. It would be valuable to investigate whether the FF resistance of titanium alloys can be improved by the deposition of multilayerfilms.

The hardness, fracture toughness, wear resistance and oxidation resistance of multilayer films are better than those of monofilms. In particular, super modulus and superhardness properties can be achieved when the modulation period is of nanometer magnitude [10,11]. Cu and Ni have a face-centered cubic crystal structure and the metals have low hardness and good ductility. Thus, contact stress and friction force on the surface of a material could be reduced by the deposition of a Cu or Ni film. The wear and fretting wear (FW) of materials can be remarkably improved by the deposition of Cu/Ni multilayer films, which can be prepared by electroplating [12,13]. But this method has the hydrogen brittleness incipient fault for the titanium alloy. Ion-assisted deposition (IAD) is a surface treatment method that effectively combines ion implantation with physical vapor deposition. This method can yield films with high density and bonding strength between the film and the substrate at low temperature. The wear and corrosion resistance of the material surface can be improved and the integral properties of the substrate are not affected by IAD [14,15]. Magnetron sputtering (MS) is advantageous for multilayer preparation and yields films with high density, small grain size and a low void ratio. There are no reports on improving the FF resistance of Ti alloys by Cu/Ni multilayer films using ion-assisted magnetron sputtering, which combines IAD with MS. In the present study, the effect of IAD–MS Cu/Ni multilayer films on the FF and FW resistance of the titanium alloy was investigated.

Ti-811 titanium alloy is characterized by low density, high Young's modulus, excellent damping capacity, good thermal stability, and fine welding and molding performance. In particular, its Young's modulus/density ratio is excellent for applications in the aviation industry [16]. Thus, Ti-811 alloy is an important material for the manufacture of rotary parts used in high-temperature sections of advanced aircraft compressors. Therefore Ti-811 alloy was selected to be researched in the present study.

* Corresponding author. Tel.: +86 29 88491479; fax: +86 29 88492344.
E-mail address: liudaox@nwpu.edu.cn (D. Liu).

0301-679X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.triboint.2010.11.005

2. Experimental procedures

FF specimens and fretting pads were obtained from Ti-811 titanium alloy bars (∅ 16 mm). Ti-811 alloy is almost all α-phase and contains 7.9% Al, 1.0% Mo, 0.99% V, 0.05% Fe, 0.1% C, 0.01% N, 0.001% H, 0.06% O and balance, Ti. The material was treated by double annealing (910 °C for 1 h and 580 °C for 8 h, cooled in air). The resulting microstructure is an equiaxial α-phase and intergranular β-phase. The mechanical properties of the alloy are: σ_b=931 MPa, $\sigma_{0.2}$=890 MPa, δ=23% and Ψ=46%.

A PIEMAD-03 multifunction apparatus was used to prepare the Cu/Ni multilayer films. The multilayer films were prepared using the ion-assisted magnetron sputtering method. The specimen was finely ground using 1200 grit SiC paper and ultrasonically cleaned with acetone. The surface of the specimen was cleaned with a 1 keV Ar ion beam in a flux of 20 μA/cm^2 for 20 min before film deposition. After etching, a layer of pure Cu of about 1 μm was deposited in order to improve adhesion providing a smooth transition between the ion-cleaned substrate and the films. The two MS targets used in this study consisted of 99.99% Cu and Ni, each of which was sequentially turned on to prepare Cu/Ni multilayer films. The modulation period of the films was controlled by varying the opening time of the MS power supply. To prevent sputtering pollution between the targets, a baffle was used to protect the target that was not sputtering. To improve the bonding strength between the film and the substrate, a high-energy assisting ion beam was used to bombard the surface of the film during deposition. The thickness of all Cu/Ni multilayer films was 10 μm and a Ni monolayer was deposited on the surface of all films. Pure Cu and Ni films of 10 μm in thickness were prepared for comparison. During the deposition, the argon flow (60 sccm), the current (1 A), and the bias voltage (−200 V) were kept constant.

A HITACHI S-570 scanning electron microscope (SEM) was used to investigate the morphology of the Cu/Ni multilayer films. An XRD-700 X-ray diffraction analyzer was used to analyze the phases of the Cu/Ni multilayer films. A HV-1000 microhardness instrument was used to measure the Knoop microhardness of the Cu/Ni multilayer films with a load of 0.245 N and loading time of 20 s. The bonding strength of the Cu/Ni multilayer films to the substrate was evaluated by the method of scratch. The critical bonding strength (L_c) that resulted in spalling of Cu/Ni multilayer films was defined as the bonding strength. The ductility of Cu/Ni multilayer films was estimated by using a self-made repeating press tester with low energy. The total number and load of the repeating press was 1×10^4 and 60 N, respectively. The maximal impact load that resulted in cracking of the Cu/Ni multilayer films was defined as the critical ductility load. A rectangular pyramid indenter made of diamond was used.

The fretting wear resistance of Cu/Ni multilayer films was evaluated by using a ball-on-flat geometry where a Ti-811 titanium alloy ball of diameter 10 mm acted as the fixed counter body and Cu/Ni multilayer films deposited on the titanium alloy substrate acted as flat. The fault in Cu/Ni multilayer films was fixed and the ball was reciprocated in the perpendicularity plane at a frequency of 120 Hz and slip amplitude of 36 μm. The friction force was measured by the piezoelectric transducer attached to the ball. The slip amplitude was measured by the eddy current transducer. The friction force signal after necessary amplification was fed to the computer.

A PLG-100C high-frequency fatigue machine was used to conduct FF tests. A schematic drawing of the FF test setup is shown in Fig. 1. The load was set in pull–pull mode. The contact state between the pad and the specimen was flat to flat, with a rectangular contact area of 2 mm × 6 mm. Relative slip between the specimen and the pad was introduced by the difference in elastic deformation between them. The contact stress of the pads with the specimen was 85 MPa, which was loaded by using a proving ring. The span length between the fretting bridge foots was 15 mm. The cycle load was conducted with a frequency of 110 Hz, over a wide range of applied stress amplitude (σ_{max}=400–800 MPa) and a stress ratio, R=0.1. The FF life was taken as the average value of three specimens. The test temperature was room temperature.

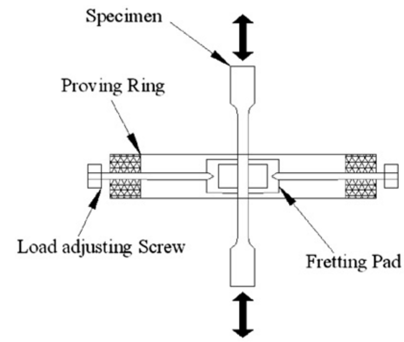

Fig. 1. Fretting fatigue test schematic.

3. Results and discussion

3.1. Properties of the Cu/Ni multilayer films

Fig. 2(a) shows the surface SEM morphology of the Cu/Ni multilayer films. The Cu/Ni multilayer films had high density, small grain size and low void radio. Fig. 2(b) shows the cross-section micrograph of Cu/Ni multilayer films. The alternating dark and bright lining of the Cu/Ni multilayer films can be seen. The light-colored layer is Ni layers, while the deep-colored layer is etched Cu layers. A close-knit combination of Cu and Ni layers is evident. No interspace can be seen in the film and the bonding strength between the film and the substrate is good.

Fig. 3 shows X-ray diffraction patterns of Cu/Ni multilayer films with different modulation periods. It should be noted that the growth of all the films had a predominance of crystals oriented with (1 1 1) planes parallel to the substrate. It is known that the (1 1 1) planes are the high atomic density and low surface energy planes in the Cu and Ni face-centered cubic crystal system. Thus, these structures of the Cu/Ni multilayer films, with predominance of crystals oriented in (1 1 1) planes parallel to the substrate, would be beneficial for the films in obtaining good tribological properties. The peak width observed for pure Cu or pure Ni film was greater than that for the corresponding bulk Cu or Ni materials because of the decrease in grain size. Analysis revealed that the grain size was $<$30 nm. The patterns for the Cu/Ni multilayer films with a modulation period of 1200 and 600 nm exhibit doublet-like peaks due to the existence of distinctive Cu and Ni layers, each with its own lattice parameter. With decrease in modulation period (200, 120 and 20 nm), the diffraction peaks of the Cu/Ni multilayer films move towards single peaks. Because the crystallographic lattice constant of Cu is greater than that of Ni (3.608 vs. 3.517 Å, lattice mismatch of 2.6%), it is reasonable that the interplanar Ni distance increased to match the crystallographic lattice of Cu for epitaxial growth. Fig. 3 also shows the X-ray diffraction pattern for a CuNi alloy film. The diffraction peak location is the same for the CuNi alloy film and Cu/Ni multilayer films with a small modulation period. However, the reason for the peak location differs for the CuNi alloy film and Cu/Ni multilayer films. The single diffraction peak for the CuNi alloy film is due to the formation of a single-phase substitution solid solution between Cu and Ni. By contrast, the single diffraction peak for Cu/Ni multilayer films with a small