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ScienceDirect
Wear 263 (2007) 1386–1389
WEAR
www.elsevier.com/locate/wear

A study on scuffing and transition of friction and wear of TiN films using ultrasonic backward radiation

Sung-Hoon Jeong, Yoon-Ha Shin, Hak-Joon Kim, Sung-Jin Song, Young-Ze Lee *

School of Mechanical Engineering, Sungkyunkwan University, 300 Chunchun-dong, Jangan-gu, Suwon, Gyeonggi-do 440-746, Republic of Korea

Received 10 August 2006; received in revised form 25 January 2007; accepted 26 January 2007
Available online 26 March 2007

Abstract

To examine the tribological characteristics of the very thin titanium nitride (TiN) ceramic layers coated on AISI 1045 steel substrate, the ultrasonic backward radiation technique was applied on worn surfaces. The ultrasonic backward radiation profiles have been measured under the variation in the applied sliding loading up to scuffing failure. The sliding tests were performed with pin-on-disk type. Mildly worn surfaces of coating were compared with severely worn surfaces, and also the scuffed surfaces are compared with usually worn surfaces. In the experiments performed in the current study, the peak angle and the peak amplitude of ultrasonic backward radiation profile varied sensitively depending on worn surfaces. In fact, these results demonstrate a high possibility of the ultrasonic backward radiation as an effective tool for the nondestructive characterization on the wear of the TiN coated layers.

Keywords: Ultrasonic backward radiation; TiN coating; Scuffing; Mild wear; Severe wear

1. Introduction

Thin coating layers of various ceramics such as titanium nitride (TiN), diamond-like-carbon (DLC) and chromium nitride (CrN) are increasingly applied to surfaces of machinery parts since they can provide excellent wear resistance and low friction characteristics to the surfaces of substrates [1]. Of the many coatings, TiN is the most commonly used. Recent research on TiN coating emphasized its promising oxidation and corrosion resistance, and indicated that TiN film possessed good wear resistance [2–5]. Additional characteristics of TiN are its low friction and its high toughness [2–5]. This remarkable step forward is a result of improvements in the coating process and in the control of the coated substances. Whatever its function, the expected performance of the coated products can only be achieved if the adhesion and the intrinsic cohesion of the coating are sufficient during repeated sliding with applied load.

The catastrophic mode of surface failure due to wear is referred to as scuffing [6]. On scuffing, there is a sudden increase of friction so that it is very important to recognize the onset of scuffing for the reliable use of machinery components rotating at high speed [7]. Therefore, it is necessary to have an effective nondestructive tool for monitoring of scuffing.

The ultrasonic backward radiation is leaky ultrasonic wave returning back to a transmitting transducer from the backward propagating leaky surface wave, which is converted from the forward surface wave generated in the incident surface region [8,9]. Let us consider the ultrasound that is incident on a specimen immersed in water. When ultrasound is incident at/or near the Rayleigh angle, surface wave is generated by mode conversion and propagates along the surface of the specimen. A portion of its energy leaks into water to be detected by the transmitting transducer. In pulse-echo measurements of ultrasonic backward radiation, there can be captured three responses including: (1) direct scattering at the incident position, (2) leak of the surface wave propagating backward due to scatterers and (3) leak of the surface wave reflected at the specimen edge. In the present study, the ultrasonic backward radiation technique is applied for the nondestructive characterization of thin TiN ceramic layers

* Corresponding author. Tel.: +82 31 290 7444; fax: +82 31 290 5276.
E-mail address: yzlee@skku.edu (Y.-Z. Lee).

0043-1648/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2007.01.060

coated on AISI 1045 steel substrate. To characterize the wear transition from mild wear to severe wear and scuffing failure, the ultrasonic backward radiation profiles are measured to be analyzed.

2. Ultrasonic backward radiation profiles

In an immersion setup, some portion of ultrasonic Rayleigh waves are returning back to a transmitting transducer (along the opposite direction to the incident beam) from the backwardly propagating leaky wave which is converted from the forward surface wave generated in the incident surface region [8,9]. Amplitudes of the backwardly radiated leaky waves can be expressed by beam directivity and frequency characteristics of the transmitting transducer, incidence angle of beam center, dispersion and scattering of Rayleigh surface waves [10]. Thus, characteristics of coating layer and/or subsurface can be determined by measuring peak angle and amplitude of backward radiated Rayleigh waves since peak angle is related to the Rayleigh surface wave velocity and the profile width is related to the wave dispersion.

In this study, peak angles and profile widths of backward radiated Rayleigh wave of specimens were measured from the ultrasonic backward radiation profiles [10,11]. To construct ultrasonic backward radiation profiles, backwardly radiated leaky waves were acquired in an immersion, pulse-echo setup by changing angle of incident beam continuously. From the acquired signals, it can be easily obtained the peak amplitude variation according to the angle of incidence, $A_{\mathrm{BR}}(\theta_{\mathrm{inc}})$, using Eq. (1), which is known as the ultrasonic backward radiation profile [10,11]:

$$A_{\mathrm{BR}}(\theta_{\mathrm{inc}}) = [|\max(V_{\mathrm{m}}(\theta_{\mathrm{inc}}))| + |\min(V_{\mathrm{m}}(\theta_{\mathrm{inc}}))|]^2 \quad (1)$$

where $V_{\mathrm{m}}(\theta_{\mathrm{inc}})$ is acquired signal of backwardly radiated leaky wave at incident angle θ_{inc}.

3. Experimental details

For the present study, TiN ceramic coated specimens were prepared. These specimens were made of AISI 1045 steel as the substrate materials that have been shaped in a form of disc with the diameter of 60 mm and the thickness of 10 mm. The surfaces of substrate were treated to have the average value of surface roughness with 0.022 μm in R_{a}. Then TiN ceramic coating layers were built on the substrates by an arc ion plating method up to thickness level of 1.0 μm. AISI 52100 steel balls with a diameter of 10 mm were used for the counter part in the sliding test.

Two kinds of loading were used in this experiment, namely, immediate loading and step loading. The first one was applied by constant loads of 0.4 N without break-in procedure. This test was performed without lubricant to reveal the difference between mild wear and severe wear. The second loading was done from 5 N with a step size of 5 N for 3 min per each step up to scuffing failure. To investigate the scuffing phenomenon, the tests were done in lubricated condition. The mineral oil was used as

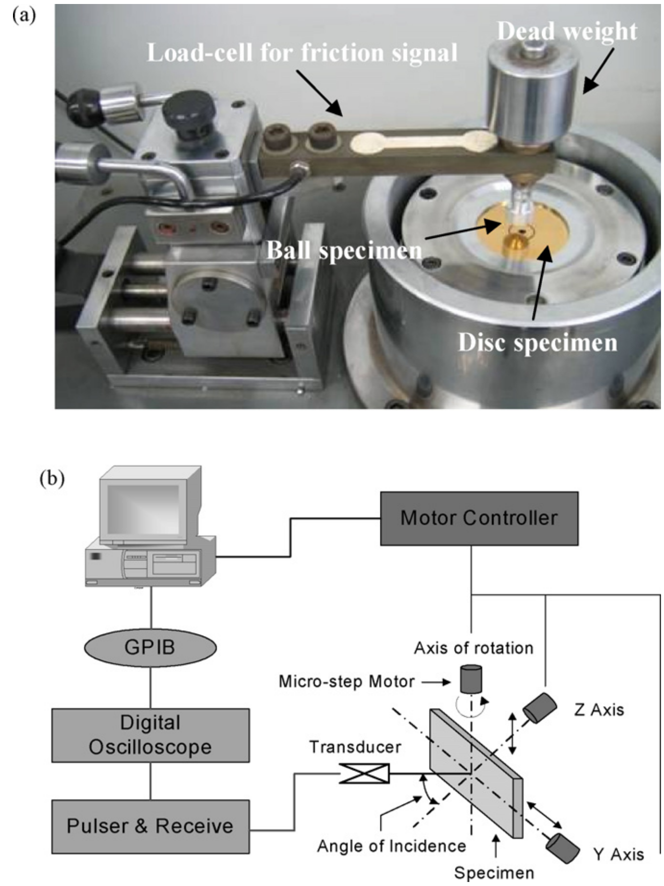

Fig. 1. Experimental equipment: (a) sliding wear tester and (b) schematic diagram of the automated measurement system used for obtaining the ultrasonic backward profiles [11].

a lubricant. After the ultrasonic measurement of the "virgin" specimen, a contact load was applied to the coated specimens using a ball-on-disc sliding tester with a slow sliding speed of 0.063 m/s (60 rpm) as shown in Fig. 1(a). During sliding loading the friction force was measured by a load cell and the signal from the load cell was stored in a computer at a sampling rate of 5 Hz. Then the stored signal was converted to the coefficient of friction (COF) signal.

The ultrasonic backward radiation profiles were measured from the specimens in the "virgin" condition, which means the "as-fabricated" condition before applying any contact sliding load. For the measurement of backward radiation profiles, a broadband ultrasonic transducer (with the center frequency of 20 MHz) was used to interrogate the specimen immersed in water at different angles of incidence. Fig. 1(b) shows a schematic representation of the automated measurement system that has been used for obtaining the ultrasonic backward radiation profiles. This system has the capability of changing the angle of incidence automatically by a control computer, and can store the ultrasonic backward radiation signal at every incident angle. In the present study, the ultrasonic backward radiation signals were captured by the "direct backward radiation" method. The backward radiation profiles were then constructed from the stored ultrasonic backward radiation signals for each set of measurement.