Experimental Studies on Tribological Properties of Pseudoelastic TiNi Alloy with Comparison to Stainless Steel 304

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Tribological and mechanical properties of pseudoelastic Ti-51 at. pct Ni alloy were investigated. Particular attention was paid to effects of the pseudoelasticity on wear and friction of the alloy, with comparison to a conventional material—304 stainless steel. Wear and friction tests were performed on a pin-on-disc tribometer under lubricated-sliding and dry-sliding conditions, respectively. Localized wear behavior of the materials and their mechanical properties were also investigated using a triboscope—a combination of a nanomechanical probe and an atomic force microscope. It was demonstrated that the pseudoelasticity of the TiNi alloy was significantly beneficial to its tribological properties. It was observed that the wear resistance of TiNi alloy was two orders of magnitude higher than that of the stainless steel when the alloy behaved pseudoelastically, while this difference in wear resistance decreased to one order of magnitude when the pseudoelasticity deteriorated. It was also demonstrated that the pseudoelasticity strongly influenced the frictional behavior of the alloy.

I. INTRODUCTION

Near equiatomic TiNi alloy is a well-known shape memory alloy.\cite{1,2,3,4,5} The shape memory effect of this alloy results from a thermoelastic martensitic transformation occurring around room temperature. On cooling, the parent phase (\(\beta\)) having an ordered B2 (CsCl) structure transforms to a martensite phase that has a monoclinic structure of B19 type.\cite{6,7} This martensitic transformation is thermoelastic or reversible and can be induced either by changing temperature or by applying a stress. When temperature decreases to the starting temperature of martensitic transformation, \(M_s\), the martensite begins to form and the transformation completes when the temperature is below the martensite finishing point, \(M_f\). The martensitic transformation, \(\beta \rightarrow M\), may occur above \(M_s\) when the alloy is under an external stress. This process is reversible and the initial \(\beta\) phase can be recovered as the stress is removed. As a result of the reversibility of the martensitic transformation, TiNi alloy exhibits a special mechanical behavior termed pseudoelasticity.\cite{8} With the pseudoelasticity, the TiNi alloy behaves like an elastic spring and the recoverable strain is usually in the range of 5 to 8 pct or even higher.\cite{9,11} Theoretically, all shape memory alloys may exhibit pseudoelasticity, but whether a shape memory alloy has good pseudoelasticity depends on many factors, such as crystal structures of the martensite and the parent phase, microstructure, and thermal history.\cite{2,5} For example, dislocations and inclusions would hinder the martensitic transformation, thus deteriorating the pseudoelasticity.

Recently, the TiNi alloy was found to exhibit excellent wear resistance to erosion and abrasive wear.\cite{12,13,14,15} This high wear resistance makes the TiNi alloy more attractive, in addition to its shape memory effect that has been extensively studied and used for many medical, electrical, and mechanical applications.\cite{9,11} Different from conventional wear-resistant materials, hardness is not the main parameter that dominates the wear resistance of this alloy.\cite{14,15} It was observed that the resistance of TiNi alloy to erosion or abrasion was strongly dependent on its chemical composition as well as microstructure. When the composition of a TiNi alloy falls into the range in which the reversible martensitic transformation takes place, this TiNi alloy exhibits superior wear resistance. It was suggested that the pseudoelasticity played an important role in producing high wear resistance of TiNi alloy.\cite{12–15} Liang et al.\cite{12} investigated the performance of TiNi alloy during sliding wear, impact abrasion, and sand-blasting erosion. They demonstrated that TiNi specimens with good pseudoelasticity exhibited higher wear resistance than those having no pseudoelasticity. Shida and Sugimoto\cite{14} studied the erosion behavior of a TiNi alloy and observed that the erosion resistance of the TiNi alloy was strongly dependent on its chemical composition and microstructure but not significantly on its hardness. They suggested that the excellent erosion resistance of TiNi alloy might be related to the thermoelasticity of its martensite transformation or the pseudoelasticity. Richman et al.\cite{15} tested the cavitation erosion resistance of two TiNi alloys, respectively, in B2 phase and martensitic phase and reported that the alloy in B2 phase was superior to that in martensitic phase. It should, however, be mentioned that the pseudoelasticity is affected by the wear condition. As discussed in this article, the pseudoelasticity of a TiNi alloy may vary with the applied stress. Under different wearing loads (low or high), a TiNi alloy may exhibit complete or incomplete pseudoelasticity, thus leading to variations in wear behavior. Temperature is another factor influencing the wear performance of TiNi alloy.

In order to better understand the mechanism responsible for high wear resistance of TiNi alloy, wear and friction of Ti-51 at. pct Ni alloy in an as-received state (cold-drawn) and a heat-heated state, respectively, with different degrees of pseudoelasticity were investigated. Wear and friction tests...
were performed on a pin-on-disc tribometer. The pseudoelasticity of the TiNi alloy under simple tension condition and under a more complicated stressed state, indentation, was determined using a hydraulic-servo machine and a nanomechanical probe, respectively. Local wear behavior of the materials was also investigated using the nanomechanical probe for more direct evidence, since possible temperature effect (i.e., frictional heat) could be ignored when wear test was carried out on microscopic level. The main objective of this research is to fundamentally understand the tribological behavior of TiNi alloy toward the optimization of this novel tribomaterial. The observed tribological phenomena and possible mechanisms involved are discussed in this article.

II. EXPERIMENTAL DETAILS

The TiNi specimens used for the present study were cut from a commercial TiNi rod provided by Shape Memory Applications, Inc. (Santa Clara, CA). The as-received TiNi alloy was cold drawn, and it did not exhibit a high degree of pseudoelasticity. However, superior pseudoelasticity of this alloy could be obtained by aging treatment. Half of the TiNi specimens were aged at 500 °C for 5 minutes, followed by water quench. In order to better understand the beneficial effect of pseudoelasticity on wear, 304 stainless steel, a conventional material, was also tested for comparison. Stainless steel specimens were cut from a commercial 304 steel rod provided by Atlas Alloys, Inc. (Hamilton, ON, Canada). Compositions and heat treatment conditions of the TiNi specimens and the steel specimens are given in Table I.

| Ti Ni C O H Others kN, corresponding to the contact pressure from 1.8 to 5.9 MPa. The sliding speed of the pin specimen on the disc was 60 m/min. Wear resistance of the materials was evaluated by measuring its volume loss after being worn for 5 minutes, corresponding to a sliding distance of 300 m.

Friction coefficients of the materials under study were determined by measuring the ratio of the friction force to the applied normal load on the pin-on-disc tribometer. A strain sensor was used to measure the lateral displacement of the pin specimen, and the friction force was then calculated using a cantilever approach. The entire friction measurement was automated and variations in friction coefficient during the entire sliding process were recorded by a data-logging system.

Pseudoelastic behavior of TiNi alloy under a more complicated stress condition (indentation) was evaluated using a triboscope. Local wear behavior of the materials on microscopic level was also investigated using the triboscope. The triboscope is a system combining an atomic force microscope and a nanomechanical probe, which allows nanoinindentation, nanoscratching, and microwear tests. The sample surface prepared for the triboscope test was lapped and polished to an average roughness (Ra) of 0.02 μm. During indentation, the indenter tip penetrated into the surface layer under a normal load that was increased continuously up to a designated level and the load was then gradually decreased back to zero. The indentation depth vs the load was recorded automatically during the entire loading and unloading process. Regarding the microwear test, wear loss was resulted by reciprocally scratching a target surface area of 0.4 × 0.4 μm at a speed of 4 μm/s under a contact load. The volume that was removed from the worn region reflects the local wear resistance of the material. The indentation and wear tests were performed under different loads.

III. RESULTS

A. Wear Loss

1. Macrowear behavior

Wear losses of the as-received and the heat-treated TiNi alloy specimens determined using the pin-on-disc tribometer are presented in Figure 1. It was observed that the volume loss increased with the applied normal load for all the tested materials under the two sliding conditions. The volume losses of the TiNi alloy, no matter in the as-received state or the heat-treated state, were considerably lower than that of the 304 steel under both the oil-lubricated sliding and dry sliding conditions. The difference in volume loss between the TiNi alloys and the 304 steel was one order of magnitude larger under high loads, and this difference increased as the normal load was decreased. No large difference was observed between the heat-treated TiNi alloy and the as-received TiNi alloy under high loads, but the former showed significantly higher wear resistance than the latter under lower loads. In the lubrication condition (Figure 1(a)), the volume loss of the 304 steel was two orders of magnitude larger than that of the heat-treated TiNi alloy under the