Wear Characteristics of TiNi Shape Memory Alloys

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The wear characteristics of TiNi shape memory alloys against Cr-steel have been studied. Experimental results indicate that the Ti$_{50}$Ni$_{50}$ alloy can exhibit a better wear resistance than Ti$_{49}$Ni$_{51}$ alloy due to their higher hardness and pseudoelastic behaviors. Four main mechanisms, adhesion, abrasion, surface fatigue, and brinelling, are found to have important contributions to the wear characteristics of TiNi alloys. The weight loss increases with increasing wear load and sliding distance but decreases with increasing sliding speed. The contact area during sliding wear will be increased due to the variant accommodation and/or pseudoelasticity and, hence, will reduce the average compressive stress and wear damage. Variant accommodation and/or pseudoelasticity can also stabilize the crack tips and hinder crack propagation, hence improving the wear characteristics of TiNi alloys.

I. INTRODUCTION

The TiNi alloys are known as the most important shape memory alloys because of their many applications based on the shape memory effect\(^1\) and pseudoelasticity.\(^2,3\) This comes from the fact that TiNi alloys have superior properties in fatigue,\(^4\) corrosion resistance,\(^5\) biocompatibility,\(^6\) ductility, and recoverable strain.\(^7,8\) It is also well known that TiNi alloys can exhibit a high mechanical damping due to the easy movement of twin boundaries.\(^7,8\) In addition to these functional properties, TiNi alloys have recently been observed to exhibit excellent wear resistance,\(^9\) which is ascribed to their pseudoelastic behavior and hardening phenomena. Suzuki and Kuroyanagi\(^13\) and Shida and Suginoto\(^14\) also reported that the TiNi alloys exhibit good slurry and water jet erosion resistance in corrosive environment. Hence, TiNi alloys may become a new type of tribomaterial in some new applications. However, our understanding in this area is incomplete. No systematic investigation has been reported on the tribology of TiNi alloys. In the present study, we aim to investigate the wear characteristics of TiNi alloys under dry sliding, including wear mechanisms, morphologies of worn surfaces, and factors influencing the sliding wear. Meanwhile, deformation phenomena and phase transformations during sliding wear process are also discussed.

II. EXPERIMENTAL PROCEDURE

The conventional tungsten arc-melting technique was employed to prepare the Ti$_{50}$Ni$_{50}$ and Ti$_{49}$Ni$_{51}$ alloys. The as-melted buttons were homogenized at 1050 °C for 24 hours, hot rolled into plates with a 5-mm thickness, annealed at 800 °C for 30 minutes, and then quenched in water. The differential scanning calorimetry (DSC) measurement of transformation temperatures was conducted using a DU PONT* 2000 thermal analyzer equipped with a quantitative scanning system, 910 DSC cell, and a cooling accessory, LNCA II. Measurements were carried out at temperatures ranging from −150 °C to +150 °C under a controlled cooling/heating rate of 10 °C/min. A ball-on-disk type of apparatus with ASTM standard was used to test the specimen’s wear resistance. The testing parameters include wear load, sliding distance, and sliding speed. The SUJ-2 Cr-steel ball, with hardness Hv = 720, was used as the against-wear material. The average friction coefficient was automatically calculated by a digit computer after the sliding wear process. The X-ray diffraction (XRD) analysis was carried out at room temperature with a MAC-MXP-3 X-ray diffractometer under the conditions of Cu $K_a$ radiation, 40 kV tube voltage, and 30 mA current. The surface morphologies were observed by a Topcon ABT-55 scanning electron microscope with an energy-dispersive X-ray analysis facility. The surface hardness was measured with a microvickers tester with a load of 500 g for 15 seconds. For each specimen, the average hardness value was calculated from at least five test readings.

III. RESULTS AND DISCUSSION

A. Metallurgical Properties Influencing the Wear Characteristics in TiNi Alloys

To investigate the wear characteristics of TiNi alloys, it is helpful to first understand some important metallurgical properties of these alloys. Table I presents the transformation temperatures, hardness, and crystal structures at room temperature for both Ti$_{50}$Ni$_{50}$ and Ti$_{49}$Ni$_{51}$ alloys. Based on tribological theory,\(^15\) materials with high hardness exhibit high wear resistance. However, it is quite interesting to find that the hardness of TiNi alloys, as presented in Table I, is so much lower compared to commercial wear-resistant materials,\(^9\) but the alloys can exhibit excellent wear resistance. Hence, not only the hardness, but also the other metallurgical properties, such as phase transformations, work hardening, and resistance to crack nucleation and propagation, will have important influence on the wear characteristics of TiNi alloys. It is well known that the TiNi
Table I. The Transformation Temperatures, Hardness, and Crystal Structure at Room Temperature for Both Ti$_{50}$Ni$_{50}$ and Ti$_{49}$Ni$_{51}$ Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>M* (°C)</th>
<th>A* (°C)</th>
<th>Hardness (Hv)</th>
<th>Crystal Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti$<em>{50}$Ni$</em>{50}$</td>
<td>46</td>
<td>82</td>
<td>200</td>
<td>B19° martensite</td>
</tr>
<tr>
<td>Ti$<em>{49}$Ni$</em>{51}$</td>
<td>-104</td>
<td>-60</td>
<td>320</td>
<td>B2 parent phase</td>
</tr>
</tbody>
</table>

Martensite can be preferentially reoriented to accommodate the deformation strain. This phenomenon will release the stress concentration around the crack tips and, hence, hinder crack propagation. Meanwhile, the pseudoelastic behavior originating from the stress-induced martensitic transformation of the parent B2 phase will increase the elastic contact area and reduce the normal stress during sliding. All these unique properties of TiNi alloys are considered to be responsible for the alloys’ high wear resistance. Hence, the transformation temperatures and the pre-existing structures will considerably influence the wear characteristics of TiNi alloys.

B. Morphologies of Worn Surfaces in TiNi Alloys

Four main wear mechanisms, adhesion, abrasion, surface fatigue, and brinelling, are observed during sliding wear tests of TiNi alloys against Cr-steel. Some morphologies of these worn surfaces are shown in Figures 1(a) through (d). As can be seen in Table I, the TiNi alloys are so much softer than Cr-steel (Hv = 720); hence, adhesive wear will produce fragments of TiNi alloys (Figure 1(a)), which adhere to the surface of Cr-steel. Figures 2(a) and (b) show the scanning electron microscopy (SEM) observation and energy-dispersive X-ray analysis of the adhesive protrusion on the surface of Cr-steel, respectively. As shown in Figure 2(b), there are intense Ti and Ni peaks appearing together with Fe peak. These features provide direct evidence that TiNi fragments transfer to the Cr-steel surface because of adhesion during sliding wear. The ploughing grooves in Figure 1(b) illustrate abrasive wear, which originates from the interaction of microcutting and plastic deformation. Surface fatigue wear is also observed in Figure 1(c). Due to the repeated loading and unloading cycles, many surface or subsurface cracks form and eventually result in the breakup of the surface into large fragments, leaving large pits on the surface, as shown in Figure 3. At the same time, Figure 1(d) shows the wavy tracks in the outer surface. This feature, so-called brinelling wear, occurs from the plastic deformation of softer materials. It should be mentioned that the phenomenon of brinelling wear will increase the friction coefficient, but it has little contribution to the weight loss. Meanwhile, the brinelling wear in Ti$_{49}$Ni$_{51}$ alloy, being ascribed to its higher hardness, is slighter than that of Ti$_{50}$Ni$_{50}$ alloy.

C. Factors Influencing the Wear Characteristics of TiNi Alloys

As well as the metallurgical properties, many testing parameters, e.g., the wear load, sliding distance, and sliding speed in this study, can influence the wear characteristics of TiNi alloys.