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Wear mechanisms of nitinol under reciprocating sliding contact

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ABSTRACT

It has been recently found that nitinol (TiNi) alloy has superior wear resistance compared to other conventional materials. The stress-induced martensite transformation exhibited by this alloy contributes to its high wear resistance. Nitinol is characterized by shape memory and superelastic effect which occur due to reversible martensite transformation. The superelastic effect of TiNi alloy is characterized by large recoverable deformation associated with the reversible stress-induced martensite transformation. Understanding the tribological properties of superelastic TiNi under reciprocating wear helps to increase its utilization in application where high wear is expected. In the present study the tribological behavior of superelastic TiNi is studied using reciprocating wear tests. Wear tests were performed under various normal loads and frequencies. The effect of normal load, frequency and sliding distance on wear behavior of superelastic TiNi is investigated. Several effects were found to control the wear response under a range of normal load and reciprocating frequency. Abrasion, adhesion and delamination mechanisms were identified during wear.

1. Introduction

TiNi shape memory alloy is widely known for shape memory and superelastic effect which occurs due to reversible martensitic transformation. The superelastic effect of TiNi is characterized by large recoverable deformation associated with reversible stress-induced martensitic transformation. The reversible martensitic transformation takes place as a result of applied heat or mechanical load [1–3]. TiNi alloy exhibits shape memory effect at low temperature and superelastic behavior at higher temperature [3,4]. During loading, the austenite phase transforms to detwinned martensite. The reverse transformation from martensite to austenite parent phase occurs upon unloading, accompanied by large deformation. The superelastic TiNi alloy has large capacity to accommodate high loading without permanent deformation. In the case of conventional materials, during loading, materials undergo elastic deformation i.e. recoverable, followed by plastic deformation i.e. non-recoverable [5]. While, in the case of TiNi alloy, upon unloading both elastic and plastic deformations are recoverable due to reversible martensitic transformation.

TiNi alloy has been widely used in a variety of applications, such as automotive, aerospace, biomedical and micro-electro-mechanical systems (MEMS). Recent studies have shown that superelastic TiNi alloy has superior wear resistance compared to other conventional materials such as steels, Ni-based, and Co-based tribo-alloys [6,7]. Wear resistance of materials depends on their mechanical properties, such as strength, hardness, toughness, work hardening, and many more [5,8,9]. Wear resistance of sliding pairs also depends on contact angle and sliding speed. But in the case of superelastic TiNi alloy, stress-induced martensitic transformation also significantly affects wear resistance. Sliding wear tests on Ti-50.3 at% Ni alloy and 2Cr13 steel were performed by Li and Liu [10]. They found that TiNi alloy has much higher wear resistance than steel. Furthermore, sliding wear behavior of superelastic TiNi alloy is studied by Farhat and Zhang [6] on superelastic TiNi, pure Ti and Ni using pin-on-disc configuration. In their work, superelastic TiNi alloy showed about 30 and 10 times higher wear resistance than pure Ti and Ni. Also, superelastic TiNi exhibited superior wear resistance when compared to AISI 304 stainless steel, although both have similar hardness [4]. The superior wear resistance of superelastic TiNi alloy was attributed to low E/H ratio, high elastic recovery ratio and large contact area [1,4,6,9].

Previous studies showed that superelasticity of TiNi alloy is considerably affected by testing condition during wear, i.e. tribo-system. Lin et al. [11] investigated the effect of various load on the wear characteristics of TiNi shape memory alloy. Their results showed that during sliding wear, weight loss increases with increasing load according to Archard's law [12]. They suggested that under low loads, the interface between the martensite and parent austenite phase is fairly mobile and the strain is within the superelastic strain range. However, under high loads superelasticity is not completely functional and deformation occurs by slip. Much work is needed to quantify wear and identify wear mechanisms in nitinol. In the present work, a comprehensive study is carried out

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to investigate the superelastic behavior of TiNi under reciprocating wear under ambient conditions. Morphological examination is also performed to identify dominant wear mechanisms and relate to wear rate and coefficient of friction.

2. Experimental methodology

In order to investigate the tribological properties of superelastic TiNi, reciprocating wear tests were conducted using a multi-function tribo-meter system developed by CETR, USA. A flat oxide free and semi-polished plate, 458 × 97 × 1 mm^3 of superelastic TiNi alloy was obtained from Johnson Matthey Inc. and cut into squares of 15 × 15 × 1 mm^3 and mounted in Bakelite. Mounted specimens were ground using 240, 320, 400 and 600 grit SiC abrasive paper followed by polishing with 1, 0.3 and 0.05 μm aluminum oxide abrasive. The chemical composition (wt%) of the as-received superelastic TiNi alloy is shown in Table 1. X-ray diffraction (XRD) tests were carried out using a high speed Bruker D8 Advance XRD system with CuKα radiation, tube current of 40 mN, tube voltage of 40 kV and radiation wavelength of 1.54 Å. Diffraction pattern was analyzed using Bruker's EVA software and compared to known diffraction patterns present in the International Centre for Diffraction Data (ICDD) powder diffraction files (PDF) database. The diffraction pattern reveals cubic TiNi (austenite) structure at room temperature, hence, presence of superelasticity.

The reciprocating wear test method involves a ball upper specimen of a tungsten carbide (WC) that slides against a flat lower specimen of polished superelastic TiNi in a liner back and forth sliding motion, having stroke length of 5.03 mm. A 6.3 mm diameter tungsten carbide ball having a hardness of HRA 92 was used as a counterface material. A WC ball was selected because it has much higher hardness than superelastic TiNi alloy. This minimizes wear of the counterface and prevents shape change, which can lead to change in the contact geometry of the tribo-system, hence, change in mean pressure during testing. Specimens were securely fastened inside a wear chamber. The load on the flat specimen is applied vertically downward with a motor driven carriage that uses a load sensor for feedback to maintain a constant load. The instantaneous values of calibrated normal load (F_z) and tangential load (F_x) were measured and continuously recorded using a data acquisition system. The system automatically computes the variation of the coefficient of friction ($COF = F_x/F_z$) with time.

Wear tests for superelastic TiNi were performed under normal loads of 20, 40, 60, 80, and 100 N with varying reciprocating frequencies from 5 to 20 Hz and time intervals between 30 and 180 min. The weight of specimens was measured before and after each test to determine individual weight-loss at 30 min intervals. All the tests were conducted at room temperature with relative humidity of 40–55%. The test method is based on ASTM standard G133-05 (2010) [13], i.e. a standard test method for reciprocating sliding wear. The test method simulates motion and vibration that are encountered by bearings in service [14]. Experiments were designed to cover a range of parameters based on expected load, frequency and stroke length that bearings may be subjected to. After reciprocating wear tests, worn surfaces, tungsten carbide ball surface, and wear debris were examined using Hitachi S-4700 cold field Scanning electron microscopy. An Oxford® X-Sight 7200 Energy Dispersive X-ray Spectroscopy (EDS) was used for chemical analysis of wear tracks and wear debris.

Table 1
Chemical composition of superelastic TiNi (wt%).

Elements	Ni	Ti	Fe	C	O	H	Others
wt%	55.99	43.68	0.05	< 0.05	0.0216	< 0.005	< 0.20

3. Results and discussion

Reciprocating wear tests were performed under varying normal load, frequency and time to understand the wear behavior of superelastic TiNi alloy. 5 samples were used with 4 wear tracks in each sample. Each testing condition showed excellent repeatability of not more than 10% variation. Bodies in contact are controlled by many factors, including, load, sliding speed, surface film, temperature, humidity, hardness and work-hardening. A major factor that can be added to the above list, for superelastic TiNi alloy, is the stress-induced martensitic phase transformation. During wear, load and thermal cycling in superelastic TiNi gives rise to microstructural changes as a result of martensite twinning, detwinning, austenite-to-martensite and martensite-to-austenite phase transformation. These microstructural changes significantly affect wear and deformation behavior of superelastic TiNi.

The cumulative weight loss versus sliding distance data was plotted and representative curves are shown in Fig. 1. Weight loss as a function of sliding distance curves is characterized by two wear regimes. Initially the wear rate, i.e., slope of the curve, is high but after a short sliding distance, the slope decreases to a lower steady state value, hence, lower wear rate. The initial high wear rate region is believed to be due to a "break-in" period. This break-in region corresponds to a similar rise in the coefficient of friction, as will be seen below. The figure also shows that the weight loss increases with the increase in applied normal load for a constant reciprocating frequency of 10 Hz. This is also evident from incremental weight loss versus sliding distance curves in Fig. 2. Here, weight loss was

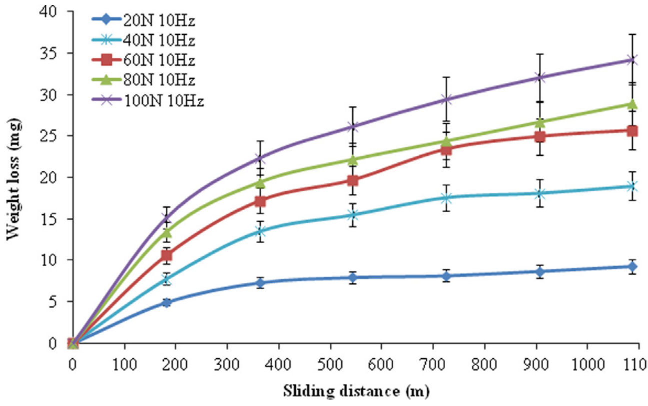

Fig. 1. Cumulative weight loss versus sliding distance for different loads.

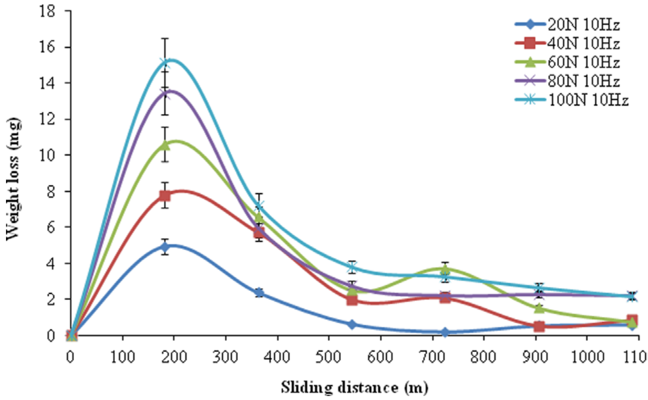

Fig. 2. Incremental weight loss versus sliding distance for different loads.