Wear 408–409 (2018) 120–130

Contents lists available at ScienceDirect

Wear

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

Comparison of the reciprocating sliding wear of 58Ni39Ti-3Hf alloy and baseline 60NiTi

Khashayar Khanlari[a,*], Maziar Ramezani[a], Piaras Kelly[b], Peng Cao[c], Thomas Neitzert[a]

[a] Department of Mechanical Engineering, Auckland University of Technology, New Zealand
[b] Department of Engineering Science, University of Auckland, New Zealand
[c] Department of Chemical and Materials Engineering, University of Auckland, New Zealand

ARTICLE INFO

Keywords:
NiTi alloys
Sliding wear
Scratch test
Indentation

ABSTRACT

Hardened 60NiTi, due to combination of high compressive strength, high Rockwell hardness, low stiffness and large elastic compressive strain, is a desirable alloy to be employed in different load bearing applications. However, a more complex ternary NiTi-Hf alloy (~58 wt% Ni-~39 wt% Ti-~3 wt% Hf) designated as 58Ni39Ti-3Hf, shows improved properties over baseline 60NiTi and is recently receiving recognition as an alternative for this intermetallic. Nevertheless, it is not yet understood how the sliding wear properties of 58Ni39Ti-3Hf differ from those of baseline 60NiTi. In this research, a series of ball (WC)-on-plate reciprocating sliding wear tests are conducted under moderate and extreme sliding induced stress conditions to illustrate how 58Ni39Ti-3Hf responds as compared to 60NiTi. In addition, to fully understand the reasons causing divergence in the wear response of both materials, mechanical and micro-tribological properties of these two alloys were investigated and compared through indentation, hardness and scratch tests. Obtained results, other than confirming the possibility of employing 58Ni39Ti-3Hf as an alternative for 60NiTi, emphasize the role of good lubrication and stress design in sliding applications where 58Ni39Ti-3Hf and 60NiTi are exploited as wear resistant alloys. Fatigue wear, adhesion and abrasion are different wear mechanisms causing damage in these NiTi alloys. 58Ni39Ti-3Hf, due to its improved fatigue properties, shows a slightly improved unlubricated sliding wear behavior than 60NiTi. However, 58Ni39Ti-3Hf appears to be slightly more prone to cracking and brittle fracture than 60NiTi in the single pass scratch tests showing its inferiority to resist wear under abrasive modes.

1. Introduction

60NiTi, a binary Ni-Ti alloy containing 60 wt% Ni and 40 wt% Ti (~55 at% Ni and ~45 at% Ti), is a hard (~60 HRC) and highly corrosion resistant intermetallic with a high compressive strength (~2.5 GPa). In addition, this superelastic material shows a relatively low elastic modulus (~100 GPa) and large elastic recoverable deformations (over 5%) under compression [1–7]. Furthermore, as opposed to Ti metallic alloys which generally show poor response to hydrocarbon and fluorocarbon oils, 60NiTi shows a good lubrication behavior causing low (< 0.2) and steady coefficients of friction [1,8–14]. These have resulted in recognition of 60NiTi as a desirable alloy to be used in different load bearing applications such as bearings and gears [4,6,9].

60NiTi, in order to attain the mentioned properties, needs to be employed in a hardened condition. The recently elucidated hardening mechanism in Ni-rich NiTi alloys is the formation of nanoscale Ni_4Ti_3 precipitates in NiTi matrix. To harden 60NiTi, this intermetallic is heated to high temperatures of approximately ~1050 °C so that all precipitates are dissolved and a single phase B2 austenitic NiTi is formed. Subsequent quenching under a very fast cooling rate prevents the formation of soft Ni_3Ti and Ni_3Ti_2 phases. However, even under a very fast cooling rate, precipitation of a high fraction of hard nanoscale Ni_4Ti_3 is nearly inevitable as this metastable phase is formed extremely rapidly in just tens to hundreds of milliseconds [15–17]. These consequently result in a high hardness in this intermetallic through the activation of an Orowan strengthening mechanism [17]. However, rapid quenching from such high temperatures of ~1050 °C results in the generation of significant residual stresses leading to quench cracking in treated parts [7,15,16,18]. Recent studies show that addition of Hf, even in low concentrations, decreases the temperature (more than 100 °C) needed to solutionize 60NiTi to obtain a single phase B2 austenitic NiTi [19]. This consequently will decrease the amount of generated residual stresses in solutionized parts [18,20]. In addition, it was found that Hf-addition slows the formation of Ni_3Ti and Ni_3Ti_2 Ni-rich phases and reduces the kinetics of Ni_4Ti_3 coarsening. This also helps in

* Corresponding author.
E-mail address: kkhanlar@aut.ac.nz (K. Khanlari).

https://doi.org/10.1016/j.wear.2018.05.011
Received 4 April 2018; Received in revised form 18 May 2018; Accepted 18 May 2018
Available online 19 May 2018
0043-1648/

reducing residual stresses since a lower cooling rate is needed to prevent the formation and coarsening of the mentioned phases in the quenching process [21,22].

Further, Hf additions appear to have a positive effect on the microstructural homogeneity of 60NiTi. This is because Hf acts as an oxygen "getter" reducing the amount of contaminant phases in 60NiTi parts resulting in more homogenized structures [18].

These findings have caused an interest in considering a NiTi-Hf alloy (~58 wt% Ni-~39 wt% Ti-~3 wt% Hf) as a substitute or alternative for 60NiTi alloy. This ternary compound is now under development at NASA for applications such as bearings and gears [18,19]. The exact composition by weight percent is 57.6% Ni-39.2% Ti-3.2% Hf (54 at% Ni- 45 at%Ti-1 at% Hf) and is designated as 58Ni39Ti-3Hf [18].

Despite the positive interest in this alloy, direct comparisons of the sliding behavior of 58Ni-39Ti-3Hf and the forerunner 60NiTi alloy have not been made. Considering this, there exists a critical requirement to evaluate and compare the sliding performance of 58Ni39Ti-3Hf with baseline 60NiTi for applications such as gears where contacting materials slide over each other. Further, localized sliding arises in rolling contact bearings, especially those used at low speeds and high loads where NiTi alloys are expected to be used. In this respect, the sliding tests can be viewed as an accelerated and more aggressive simulation of a ball bearing.

In this research, reciprocating (ball-on-plate) sliding wear tests were conducted under lubricated and unlubricated conditions and a range of low to high loads to evaluate how the sliding properties of 58Ni39Ti-3Hf diverges from those of 60NiTi under both moderate and large sliding-induced tensile stresses. In addition, scratch tests using a Rockwell C indenter and indentation tests using conical and pyramidal indenter geometries were carried out in order to understand factors leading to different wear responses and the mechanisms that at a microscopic level cause damage in these NiTi alloys.

This research, apart from defining the conditions under which the response of these alloys differ, and answering questions which arise from testing, will help in understanding the conditions under which 60NiTi and 58Ni39Ti-3Hf are suitable for use as wear resistant alloys in sliding conditions.

2. Materials and experimental methods

Hardened 60NiTi and NiTi-Hf (~58 wt% Ni-~39 wt% Ti-~3 wt% Hf) samples were received from the National Aeronautics and Space Administration (NASA), Glenn Research Center in Cleveland, Ohio. These samples were processed through Hot Isostatic Pressing (HIP) method. The details regarding the fabrication of the 60NiTi parts are given in [23]. Residual thermal stresses that are created by the quenching step might lead to fracture during subsequent cutting of the samples. To avoid this, these samples were cut into plates (of a suitable size to fit in a tribology machine) prior to conduction of the final hardening treatment [11]. The 60NiTi and the 58Ni39Ti-3Hf plates were both similarly hardened through a solutionizing treatment carried out at ~1050 °C under an open atmosphere condition followed by water quenching. In this study, a scanning electron microscopy (SEM) machine equipped with an energy dispersive X-ray spectrometer (EDS) and an X-ray diffraction machine using Cu Kα radiation were employed to study the microstructure and phase composition of these solutionized alloys.

Indentation tests were conducted at varying loads of 25, 50, 100 and 150 N under the loading and unloading rate of 40 N/min using a Rockwell C indenter (200-μm diamond tip conical indenter) by a tribometer capable of applying loads up to 200 N. Additionally, a Rockwell C hardness tester was employed to apply other higher loads of 60, 100 and 150 kgf; corresponding to, respectively, approximately 588, 980 and 1471 N loads. An optical profilometer was used to measure the indent depths that resulted from these tests. Further, a micro-indentation hardness machine was used to measure the Vickers hardness of the samples at varying loads of 0.5, 1, 2.5, 5 and 10 kgf.

The sliding wear tests were implemented on a ball-on-plate configuration, using a linear reciprocating tribometer. The tribometer was capable of recording the friction forces and Coefficients of Friction (CoF) values during the wear tests. These tests were conducted at varying loads of 2, 5, 10, 30 and 40 N under unlubricated and lubricated conditions at room temperature. These tests were performed under a constant frequency of 2 Hz for 1 h and 42 min and a constant wear track length of 20 mm. These parameters were selected to cover the sliding distance of ~500 m. Lubrication tests were conducted under a boundary regime using castor oil and a synthetic gear oil (Mobil Shc 320 gear oil). To ensure boundary lubrication, only a small quantity of oil (2–3 droplets) was dropped on the plate before starting each test. The specific wear rates ($mm^3/N.m$) of samples under different loads were computed and assessed by measuring the wear volumes using the following procedure: The cross-sectional images of the wear tracks were obtained by using a stylus profiler. In the next step, an imaging analysis software was used to compute the wear areas from these cross-sectional images. Finally, to deduce the wear volume of the wear tracks, the averaged wear areas were multiplied by the wear track length (20 mm).

Carrying out the experiments under lubricated and unlubricated conditions under a wide range of loads allows the evaluation of the response of these materials to a range of low-to-high sliding-induced tensile stresses. Since such tensile stresses are thought to be a main contributor to damage for brittle materials under sliding motions, the use of a hard counterface (6 mm diameter WC ball) may help elucidate the wear processes and damage behavior, as it results in the generation of high stresses [24]. In addition, the high stresses mimic the localized high-stress micro-sliding that occurs in rolling contact bearings.

To further reveal the differences in the wear response, other than studying the wear tracks, the subsurface regions of wear tracking was additionally studied using the SEM machine.

Single pass scratch tests were carried out in order to investigate the micro-mechanical properties of these alloys and to reveal the mechanisms responsible for damage in these materials. The tests were performed using the same Rockwell C indenter and tribometer (capable of recording CoF and applying loads up to 200 N) employed in indentation tests at different constant loads of 2, 5, 7, 10, 15 and 20 N.

The sliding velocity of the indenter in these tests was low and constant (0.1 mm/s). Low speeds were used so the frictional bulk heating, that would normally cause surface oxides to grow (as in a high-speed ball-on-plate test), does not come into play. This allows the observation of microstructural features and mechanisms responsible for damaging the alloys during sliding wear tests. In these tests, the scratch grooves were inspected by scanning electron microscopy (SEM) and an optical profilometer. Inspection by optical profilometry enabled the computation of pile-up/groove area ratio (A_p/A_g) through the measurement of the cross-sectional area of the lateral pile-up (A_p) and the cross-sectional area of the groove (A_g). The pile-up to groove area ratio (Ap/Ag) is directly related to the plastic deformability of the materials [25]. In addition, further inspections were conducted on the grooves by SEM analysis. These studies revealed the mechanisms that cause damage at the microscale and the approximate critical loads for the onset of specific damages in these alloys.

Prior to the tests, samples were ground and polished with SiC abrasive papers of P80, P180, P360, P800, P1200 and P2400. An average surface roughness (R_a) of about 0.03 μm was obtained after conducting these grinding and polishing procedures. All the mechanical tests mentioned above were repeated three times and the average obtained results are reported. Samples used for the microstructural studies were additionally etched (to reveal the microstructure) with a room temperature aqueous solution of 1 vol% HF and 10 vol% HNO_3 for 90 s [23].