Wear Characteristics of NiTi/Al6061 Short Fiber Metal Matrix Composite Reinforced With SiC Particulates

Wear characteristics of Al6061 composites, reinforced with short NiTi fibers, were investigated. The NiTi/Al6061 composite samples were fabricated using pressure-assisted sintering process in ambient air where the NiTi fibers are aligned unidirectional in the Al matrix. In addition, NiTi/Al6061 composite with 5 wt % SiC particulates and monolithic Al6061 and Al6061 with 5 wt % SiC particulates were processed in similar conditions. The wear tests were performed using a reciprocating tribometer in ball-on-flat configuration where the counterbody material was martensitic steel. The effects of fiber isotropy and SiC reinforcements on wear resistance were experimentally investigated in dry sliding. Wear properties of the samples were studied using an optical profiler and a scanning electron microscope analysis. The results showed that transverse NiTi fibers improve the wear resistance significantly. Samples with transverse fiber orientation show mostly abrasive wear, whereas, monolithic and parallel samples show adhesive wear mechanism. In addition, SiC reinforcements improve the wear resistance of the composite and the monolithic samples. Since the Al6061 matrix material is smeared onto NiTi fibers in a short period, all composite samples show similar frictional characteristics after certain period of running in dry sliding. [DOI: 10.1115/1.4002332]

Keywords: wear mechanism, NiTi wires, fiber orientation, short fiber composites

1 Introduction

Shape-memory-alloy NiTi materials show improved wear resistance due to their unique mechanical characteristics such as pseudo-elasticity, microstructural effects, and reversible martensitic transformation. In addition, the fact that NiTi alloys have high resistance to cavitation and corrosion makes them ideal candidate materials in advanced tribological applications. As a hard asperity passes over a bump on the NiTi surface, the contact area between the bump and the asperity increases due to its low hardness resulting from the stress induced martensitic transformation. This prevents the probability and the propagation of cracking. However, advanced wear properties of NiTi alloys do not only benefit from the martensitic transformation but also from its high degree of cyclic hardening and good fatigue resistance in the austenitic phase [1-4].

On the other hand, continuous, short fiber, or particulate NiTi alloy reinforced metal matrix composites are attracting considerable interest due to their advanced mechanical properties. Usually, the shape recovery effect of NiTi reinforcements has been used to improve the mechanical properties of the composite materials. A significant contribution to NiTi fiber reinforced metal matrix composites have been made by Furuya et al. [5]. They reported improved tensile properties by creating compressive stress in the matrix caused by shape memory shrinkage of TiNi fibers. Later, Armstrong and Lorentzen [6] and Armstrong et al. [7] reported that NiTi continuous fiber reinforced Al matrix composite combined high strength and high tensile toughness with unusual thermal mechanical behavior. Dixit et al. [8] used friction-stir-process to prepare NiTi particle reinforced aluminum composite. They showed that improved mechanical properties could be achieved by using the shape memory effect of the NiTi particles to induce compressive and tensile stresses in the parent matrix. Porter et al. [9] investigated the fatigue and fracture behavior of NiTi reinforced aluminum composite. They fabricated NiTi particle reinforced Al matrix composite using powder metallurgy and hot pressing and activated the shape memory effect by cold rolling. They reported significant improvement in the yield strength and ultimate strength compared with the monolithic Al samples, while the elongation was sharply reduced. A remarkable improvement on the fatigue life of the composite was observed particularly above the yield strength of the material. Xie et al. [10] and Xie et al. [11] developed short NiTi fiber reinforced Al6061 matrix composites prestraining the fibers at a temperature between martensitic start temperature and austenite start temperature and investigated the relationship between the amount of prestrain and yield stress. They showed that the yield stress of the composite increase with increasing prestrain rates.

Although a number of investigators studied the mechanical characteristics of NiTi reinforced metal matrix composites such as tensile stress, fracture, fatigue, and damping, no detailed work was found in the literature investigating the tribological aspects of these structures. The focus of this study is to investigate the wear characteristics of short NiTi fiber reinforced Al6061 composites including the effects of fiber orientation and SiC particulate reinforcements.

2 Experimental Details

2.1 MMC Fabrication and Sample Preparation. The short-fiber-reinforced NiTi/Al6061 composite was fabricated using pressure-assisted sintering process in ambient air. Short fiber reinforcements enable the use of these unidirectional composites in complex forms unlike continuous fibers. The as-received NiTi fiber (SM495) was in cold-drawn condition and could shrink 4% in length upon heating. The NiTi fiber has 54.5 wt % Ni,
0.005 wt % O, 0.02 wt % C, and Ti in balance [12]. In order to bring out the desired shape memory performance and stabilization, the chopped fibers were heated at 550°C for 30 min, followed by immediately quenching to room temperature in water. Thus, no prestraining exists in the composite. In order to create the intermetallic compound, the oxide layer of NiTi fibers was mechanically removed before they were mixed with aluminum powder. Interfacial reactions are enhanced to ensure that there is a good bond between the aluminum matrix and the NiTi fibers. A good bond is essential to improve the mechanical properties of the composite such as Young’s modulus and strength. However, all these species are extremely brittle in nature and their presence can often be the sites of fracture initiation and failure.

The volume fraction of NiTi fibers in the composite was 5%. The premix was placed in a mold and compressed at 70 MPa at room temperature to form a green compact. The pressure-assisted sintering process was used to fabricate NiTi/Al6061 composite in air. Good mechanical properties of both elongation and strength of NiTi/Al6061 composite have been obtained under the conditions of heating rate at 20–25°C/min, sintering temperature at 570–580°C, and hot-pressing pressure at a pressure of 50–70 MPa for 20–30 min.

The composite samples are composed of Al 6061 (Al-balance, Cr 0.08 wt %, Cu 0.27 wt %, Fe 0.26 wt %, Mg 0.97 wt %, Mn 0.02 wt %, Si 0.56 wt %, Ti 0.02 wt %, and Zn 0.05 wt %) and short 0.45×0.01×0.03 in. NiTi short fibers (ribbons). The fiber is in martensitic phase in room temperature and phase transformation temperatures of the NiTi fiber are shown in Table 1. The fibers are unidirectional aligned on the surface of the sample as indicated by the arrow as shown in Fig. 1. The fibers are stacked layer by layer to form the composite.

To understand the contribution of the matrix strength, NiTi/Al6061 composites are manufactured with 5 wt % SiC as well. For comparison, the monolithic Al6061 and Al6061 with 5 wt % SiC specimens were also processed from powder consolidation by pressure-assisted sintering under identical conditions.

The surface material has been removed using a lathe to clean the oxidized surface and find the actual fiber layer before conducting the wear tests. The surface material of the monolithic Al6061 and SiC/Al6061 samples were also removed to obtain consistent testing conditions. The samples have been mechanically polished with fine grid SiC paper and cleaned with acetone and isopropyl alcohol.

### 2.2 Tribological Tests

The wear tests were performed using a reciprocating tribometer. The test rig was operating in ball-on-flat specimen configuration in dry sliding conditions. Normal load of 1 N was applied by means of martensitic steel (100 Cr6) semi-spherical pins with a radius of 10 mm against the reciprocating specimen under investigation. The calculated Hertzian contact pressure was 124 MPa. The stroke length and the reciprocating frequency of the test were 6 mm and 5 Hz, respectively. The total sliding distance was 100 m. The composite samples were tested both in parallel and transverse directions to the unidirectional NiTi fibers.

### 2.3 Optical Profiler Measurements and Microstructural Evaluation

The wear scar of each composite specimen was examined using a three-dimensional optical profiler. Removed material volume under the reference plane was calculated, integrating the surface profile. Microstructural analysis and the extent of wear damage were examined using a JEOL-JSM-5410 model scanning electron microscope (SEM). In order to remove the smeared aluminum from the steel counterface balls, surfaces were cleaned using 10% NaOH solution prior to the SEM evaluation.

### 3 Results and Discussion

NiTi/Al6061 and NiTi/SiC/Al6061 samples were tested in transverse and parallel to the moving direction according to the aforementioned test procedure. Monolithic Al6061 and SiC/Al6061 samples were also tested in similar conditions for comparison. Calculated wear volume of the samples obtained by optical profiler measurements are shown in Fig. 2. Since the pin samples show different wear characteristics in each fiber orienta-
tion, optical profiler or spherical cap method based volume calculations can be misleading for the counterface materials. Therefore, wear characteristics of the pin samples were evaluated using the SEM images only as shown in Fig. 3. Optical profiler measurements used to calculate the wear volume of the flat samples are also shown in Fig. 4.

The presence of SiC particle reinforcements improved the wear resistance of the Al6061 matrix considerably as expected. The effect of SiC particles on the pin wear was minor since the SiC particles are covered with the transferred matrix material and the smeared aluminum dominates the adhesive wear.

NiTi/Al6061 composite sample exhibited significantly higher wear resistance when the fibers are aligned transverse to the direction of reciprocating motion. Wear resistance of the composite samples can be further improved by using SiC particulate reinforcements in the matrix. NiTi/SiC/Al6061 transverse test showed the lowest sample wear volume. In addition, SiC reinforcements do not affect the pin wear pattern in this orientation.

Whereas the wear mechanism was adhesive in monolithic samples, composite samples in transverse configuration exhibited mostly abrasive wear. This is mainly due to abrasive effect of the hard NiTi wires. Unlike the monolithic samples, composite samples in transverse orientation show worn cavities between the NiTi wires. It is observed that significant amount of Al6061 matrix material was transferred onto the NiTi fibers. The NiTi fibers reinforce the matrix material and the smeared Al6061 alloy prevents the direct contact between the ball and the fibers forming a thin layer. The NiTi fibers support the matrix, distributing most of the applied load and prevent the propagation of the wear scar. SEM images of the flat specimens are shown in Fig. 5. Wear scar images of the monolithic Al6061 and Al6061/SiC samples show that matrix material was removed in the form of large flakes due to adhesive effect. However, in the transverse fiber orientation, matrix wear was mainly due to material transfer and the abrasive wear dominates the counterface pin surface. Flaky material removal in the wear scar was not observed in this configuration.

SEM images show that the NiTi fibers were not pulled out of the composite and the good interfacial bonding between the fiber and the matrix was maintained after the tests. The composite specimens do not have shape memory properties in this study since the fibers have not been prestrained during the manufacturing process. However, the NiTi fibers can elongate significantly without fracture, debonding or pulling out of the matrix due to their pseudo-elastic properties.

In the parallel configuration, the steel pin travels between the NiTi wires and does not directly contact the fibers. Parallel fibers may strengthen the matrix material and restrict adhesive material transfer. Slightly higher wear resistance obtained in parallel configuration compared with the monolithic samples can be attributed to these properties. Higher wear resistance was obtained using SiC particulate reinforcements, and the wear mechanism was adhesive similar to the case of monolithic Al6061 and Al6061/SiC samples.

Fig. 3 SEM images of pin wear: (a) NiTi/Al6061 (parallel), (b) NiTi/SiC/Al6061 (parallel), (c) NiTi/Al6061 (transverse), and (d) NiTi/SiC/Al6061 (transverse)
The elemental composition of the materials on the NiTi fibers after the wear tests was examined using energy dispersive spectroscopy (EDS), as shown in Fig. 6. Significant aluminum content on the NiTi fibers confirms the adhesive material transfer and indicates that the fibers are covered with the smeared aluminum alloy. The friction coefficient of composite and monolithic samples showed very similar characteristics after a certain period of running. The average coefficient of friction for Al plate and steel ball pairs was 0.57, and the effect of fiber orientation and SiC reinforcements on coefficient of friction was insignificant. The soft aluminum alloy is transferred easily onto the NiTi fibers, and this prevents the direct contact between the NiTi fibers and the counterface material, and thus friction occurs between the aluminum alloy and the steel ball only.

4 Conclusions

Al6061 matrix NiTi short fiber composites were fabricated, and the effects of fiber isotropy and SiC reinforcements on wear resistance were investigated. The following conclusions have been formed based on the experimental results:

1. Transverse NiTi short fibers improve the wear resistance of
Al samples significantly. Soft Al matrix material is transferred on the short fibers, and they act as load carrying elements distributing the applied load. However, transversely aligned fibers induce abrasive wear on the counterface material.

(2) Samples with parallel-aligned NiTi short fibers show slightly lower sample wear compared with the monolithic samples. NiTi wires strengthen the matrix, eliminate fracture, and improve the wear resistance of the matrix material even if there was no direct contact between the NiTi wires.

Fig. 5 SEM images of the worn specimens: (a) Al6061, (b) SiC/Al6061, (c) NiTi/Al6061 (transverse), (d) NiTi/Al6061 (parallel), (e) NiTi/SiC/Al6061 (transverse), and (f) NiTi/SiC/Al6061 (parallel)
and the steel counterface material. However, the wear mechanism was adhesive, similar to the monolithic samples.

(3) SiC particle reinforcements also improve the Al6061 matrix strength and increase the wear resistance of the monolithic and unidirectional short fiber composite samples. While the addition of SiC particles in monolithic Al6061 and parallel samples does not increase the counterface wear, these reinforcements result in increased counterface wear in the transverse short fiber configuration where a mainly abrasive wear regime was observed.

References