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Shock- and Corrosion-Resistant Bearings for Space Mechanisms

Samuel Howard
Glenn Research Center, Cleveland, Ohio

Christopher DellaCorte
University of Akron, Akron, Ohio

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Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Samuel Howard
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Christopher DellaCorte*
University of Akron
Akron, Ohio 44325

Summary

Nickel-titanium (NiTi) alloys are an emerging class of materials for rolling element bearing applications that require superior corrosion resistance and/or high load capability. Certain space mechanisms fall into one or both of those categories. Often, due to size and mass considerations, space mechanism systems are limited in torque margin and necessarily require small, precision-instrument bearings with very little frictional drag (i.e., low torque). In addition, space mechanism bearings must survive launch conditions without suffering raceway dents known as brinnelling, which would increase operating torque and reduce overall smoothness. Consequently, a bearing material or design that reduces or eliminates brinnelling under high contact stress conditions would represent a beneficial technology advancement. One specific alloy, nickel-titanium-hafnium (NiTi-Hf), under development for several years at the NASA Glenn Research Center as a bearing material, has the potential to mitigate concerns about brinnelling under extreme load conditions due to its unusually high elastic strain capability. In the present work, a sample of small precision bearings produced with three different ball materials (steel, ceramic, and NiTi-Hf) is subjected to a range of load conditions sufficient to dent the races. The dent depth as a function of load is compared and demonstrates that NiTi-Hf has the potential to increase bearing load capacity from the perspective of brinnelling under severe load conditions; additional testing of full NiTi-Hf bearings demonstrates corrosion resistance superior to that of 440C bearings.

Introduction and Background

Although the first material development of nickel-titanium (NiTi) alloys (commonly known as Nitinol) occurred in the 1960s (Ref. 1), their utilization in rolling element bearings is relatively new because of recent material processing capabilities, namely, powder metallurgy. An unusual combination of material properties makes certain NiTi alloys extremely attractive for niche bearings applications. Specifically, 60NiTi, with 60 wt% nickel and 40 wt% titanium, is hardenable (up to 62 Rockwell C), highly corrosion resistant, nonmagnetic, electrically conductive, and superelastic; it also has low density compared to steel (Refs. 2 and 3). This unique combination of properties leads to some interesting capabilities as a bearing material. The hardness is similar to that of conventional bearing steel grades like 52100 and 440C, which results in good wear performance. However, NiTi alloys' corrosion resistance is on par with or better than highly corrosion-resistant stainless steels like 304SS, which is soft and has poor wear performance relative to hard bearing steels. In addition, the superelasticity of NiTi alloys leads to

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*Retired Senior Technologist, Tribology and Rotating Machinery, NASA Glenn Research Center. Currently Director of Akron Engineering Tribology Laboratory, University of Akron.

high load capacity due to the material's resistance to permanent denting at the ball/race interface under high applied loads or shock loading, called brinnelling (Ref. 4). In combination, these properties yield bearings that are capable of long life under high applied loads with no corrosion.

Previous work has demonstrated, through ball-on-flat plate and single ball-on-race load tests, that NiTi as a bearing material is more resistant to brinnelling than most conventional bearing materials, like 52100 steel and 440C stainless steel (Refs. 5 and 6). The increased load capacity is a result of the combination of the reduced modulus of NiTi distributing the load over a slightly larger area and its high elastic strain capability. The current tests expand on the previous load tests by examining the dent resistance of complete bearings. Consistent with the previous results obtained using a single ball-on-flat or ball-on-race, these full bearing tests show that NiTi alloys can enhance the load-carrying capability of bearings.

Motivation and Objectives

The manufacturability and performance of 60NiTi bearings has been demonstrated in earlier work in which 50-mm- (~2.0-in.-) bore 60NiTi bearings were manufactured and successfully life tested at the component level; they are currently undergoing evaluation and assessment for flight readiness in the International Space Station (ISS) Environmental Control and Life Support System (ECLSS) Distillation Assembly (DA) (Ref. 7). However, when smaller instrument-class bearing manufacturing was attempted, 60NiTi bearings suffered from dimensional instability and high failure rates (catastrophic damaged parts) in machining trials. To achieve the high hardness required for bearing applications, the heat treatment process for 60NiTi includes a rapid quench, which it is believed results in high residual stress in the bulk material. The large residual stresses cause distortion and cracking in smaller parts when final machining is performed due to unbalanced stresses. For larger bearings, given that proportionally less material is removed after heat treatment compared to the total mass of the part, the residual stress unbalance is less significant. In a parallel effort taking place around the same time as the smaller part machining trials, a new alloy was being developed that, among other enhancements, requires a less aggressive heat treatment process. A major goal of this activity is to investigate if the new alloy enables small part manufacturing. The new alloy, informally called nickel-titanium-hafnium (designated NiTi-Hf or NiTiHf), is compositionally similar to 60NiTi but with the addition of 1 at% of Hf (approx. 57 percent Ni, 40 percent Ti, 3 percent Hf by weight) (Ref. 8).

The present work, which is funded by the NASA Glenn Research Center's Independent Research and Development (IRAD) program, has two objectives: (1) to manufacture small, precision-instrument bearings using the new NiTi-Hf material to demonstrate successful manufacturability of small parts and (2) to test NiTi-Hf materials to verify they retain the beneficial qualities of dent resistance and corrosion immunity previously demonstrated in 60NiTi.

Manufacturing of Miniature Precision Bearings

The manufacturability of miniature precision bearings using NiTi-Hf is crucial to their adoption in space mechanisms. As outlined in the preceding section, previous attempts to manufacture NiTi bearings with a bore smaller than about 12.5 mm (0.50 in.) resulted in poor dimensional precision and/or completely failed parts due to stress fractures. With the advent of NiTi-Hf, better precision and higher yield were anticipated. A competitive bid process resulted in two vendor selections to attempt manufacturing R4 bearings with a bore diameter of 6.35 mm (0.25 in.) using NiTi-Hf bulk material. One vendor chose to manufacture the bearings using a hard-turning method, in which bearing blanks were manufactured of annealed NiTi-Hf in near-net shapes. The blanks were then heat treated using the NASA-defined materials and processing methods (Ref. 9), which were modified slightly for NiTi-Hf. Final machining was carried out in the hardened state using a conventional turning method. The other

Figure 1.—Representative R4 NiTi-Hf bearings manufactured by two different vendors, one with rubber seals (left), one with metal shields (right).

vendor chose to use a grinding process. In similar fashion, blanks were manufactured from annealed NiTi-Hf to near-net shape. The blanks were then heat treated and finish ground to final dimensions.

Both vendors and methods were successful in manufacturing viable R4 bearings (Figure 1). Initial observations indicate the bearing groove surfaces of the hard-turned bearings appear somewhat less smooth than those of the ground bearings. However, to date, no testing has been completed to assess if that observation results in any measurable differences in performance.

Denting and Corrosion Testing

A major goal in the development of the new NiTi alloy containing Hf was better dimensional stability and easier material processing through adoption of a less aggressive heat treatment process while retaining the desirable characteristics of 60NiTi. The primary desirable traits are the superelasticity (or high elastic strain capability) and extremely high corrosion resistance. To verify that the new alloy retains both of these properties, a test campaign was undertaken to measure the dent resistance of NiTi-Hf compared to a subset of other common bearing materials in a manner similar to prior testing with 60NiTi. In addition, to assess the corrosion behavior of NiTi-Hf, a water exposure test was performed with NiTi-Hf bearings and 440C stainless steel as a screening test to verify retention of high corrosion resistance of NiTi-Hf. The corrosion test is not intended as a rigorous, comprehensive corrosion study but rather as a preliminary test to verify retention of superior corrosion performance in comparison to 440C.

Corrosion Test Method and Results

An existing test rig with a pair of rotating spindles was utilized for the corrosion test. The dual-spindle design enabled testing two sets of bearings simultaneously. One set of ball bearings consisted of hybrid stainless steel/ceramic (440C races with Si_3N_4 balls); the other set consisted of hybrid NiTi-Hf/ceramic (NiTi-Hf races with Si_3N_4 balls). Both bearing sets were the same size (R4, 6.35-mm/0.25-in. bore) with the hybrid ceramic bearings sourced from a standard bearing vendor, that is, commercial off-the-shelf (COTS) bearings. The hybrid NiTi-Hf bearings were sourced from one of the vendors discussed previously. The test spindles are a simple configuration, with a rotating shaft supported by a single bearing on each end, preloaded against each other with an axial wave spring. The preload was set to approximately 22 N (~5 lb). The shafts are driven by a belt drive system via a variable speed electric motor at a speed of 2,000 rpm. The motor had a double pulley system configured to drive both spindles at the same time with the belts oriented opposite one another to balance the side loads on the motor and ensure the speed was the same for both spindles. The radial belt preload was approximately 44.5 N (~10 lb) on each spindle. The clearance between the rotating shaft and the inner diameter of the housing was roughly 6.35 mm (0.25 in.) on a side. This gap was partially filled with plain tap water and the spindles were operated in a horizontal orientation for 100 h (Figure 2). When procured, the bearings all had rubber seals on both faces, but the seal facing inward was removed in all cases in order to expose the inner face to the wet environment inside the housing. A small amount of water leaked through the outer facing seal over the test duration, but there was still water in the housings upon disassembly, indicating that the bearings were exposed to a moist environment for the entirety of the test.

After 100 h (12 million revolutions), the test was stopped for inspection of the bearings. Upon disassembling the spindle with the ceramic hybrid bearings (440C races), one of the bearings fell apart as the shaft was removed from the housing. On further examination, it was observed that the ball retainer had broken at some point during the test. The outer seal likely helped keep the balls in place during the test, as all of the balls were still in the bearing, but when the preload was removed, the broken retainer and the balls were free to move excessively, and fell out of the bearing during removal from the housing. It is unknown if the retainer breakage was due to corrosion, but significant corrosion was observable on the bearing races and the housing spacers immediately adjacent to the bearings. In contrast, the hybrid Nitinol bearings exhibited no corrosion and were pristine upon removal. Figure 3 shows the spindle and one of the 440C hybrid ceramic bearings with the observed corrosion on both the bearing and the spindle. Figure 4 shows the analogous hardware from the NiTi-Hf bearing test with no corrosion observed on any of the parts. This qualitative performance test confirms that the NiTi-Hf material retains corrosion resistance superior to that of 440C stainless steel.

Denting Test Method and Results

The denting tests were designed to determine the effectiveness of the NiTi-Hf alloy in reducing the severity of bearing damage due to heavy radial loads compared to more conventional bearing materials like steels and ceramics. The test method was influenced by the work of Leveille and Murphy (Ref. 10), in which the authors were concerned with smooth running as it pertains to instrument-class aerospace bearings. The authors found that dents in a bearing raceway, such as those that could result from the vibratory environment during launch, should be limited to a maximum depth of 0.0005 times the ball diameter to ensure smooth running. Therefore, the dent depth ratio, defined as the depth of a dent divided by the diameter of the rolling element, should not exceed 0.0005. As such, the depth of dents in the raceway of a bearing is an important factor in assessing the fitness of a bearing material for use in critical aerospace bearings. Therefore, dent depth ratio in response to applied radial loading is used here to compare NiTi-Hf with conventional materials.

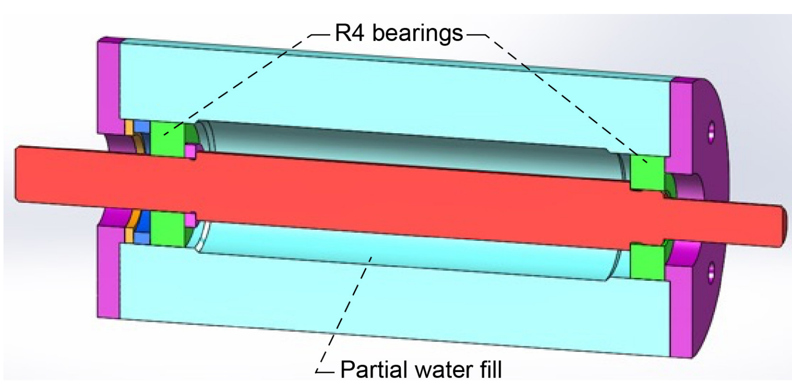

Figure 2.—Cross-sectional schematic of bearing corrosion test setup.

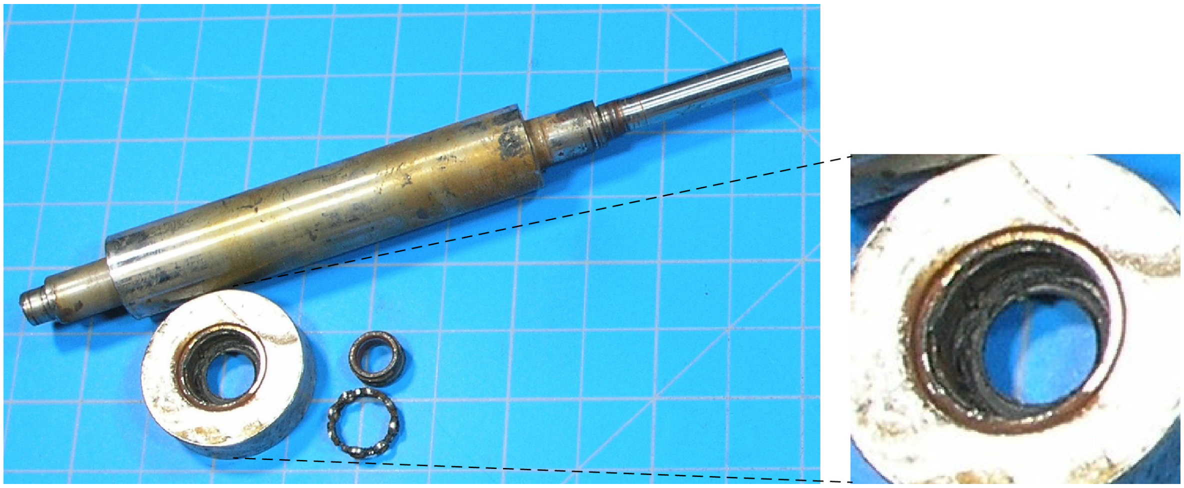

Figure 3.—Spindle and disassembled bearing from 440C 100-h corrosion test.

Figure 4.—Spindle and disassembled bearing from NiTi-Hf 100-h corrosion test.

To conduct the denting tests, COTS R8 size deep groove ball bearings (0.500-in./12.7-mm bore, 1.125-in./28.58-mm outer diameter (O.D.), and 0.325-in./8.26-mm width), with stainless steel (440C) races were procured. All bearings (Figure 5) had Si_3N_4 (silicon nitride) rolling elements (balls), polyether ether ketone (PEEK) retainers, and plastic grease shields as procured. The retainers were a snap-in design to facilitate disassembly and reassembly. Some of the bearings were disassembled, then reassembled, some with NiTi-Hf balls and some with 52100 steel balls. The rest were left with Si_3N_4 balls to create three lots of bearings, one with each ball material. A series of radial load tests were then performed as described in the following paragraph on the bearings with the three different ball materials with a range of loads to assess the severity of damage caused as a function of applied load and ball material.

To apply the radial load to the bearings under test, a fixture was manufactured to fit in NASA Glenn's small (5 kip) axial torsion load frame. Figure 6 is a schematic cross section of the load fixture, and Figure 7 is a photograph of the fixture in the load frame as tested. The fixture was designed to enable application of a controlled known radial load to two identical bearings while also allowing a small (44.5 N/10.0 lb) axial preload (applied via wave spring) to take up the clearance in the bearings before application of the radial load. The fixture is symmetric about the center to minimize any discrepancy between the load applied to the two bearings, such that the applied load on the test bearing is assumed to be half of the applied load. Due to limitations in the number of bearings available for test, one of the bearings in each test was sacrificial; that is, it was not inspected posttest, and was reused for all of the testing. The sacrificial bearing was identical to the test bearings except for the ball material, which was 52100 steel in all cases. Any effect on the load distribution due to differences in the deflection of the sacrificial bearing and the test bearing is negligible (deflections in all bearings are on the order of tens of microns). The distance between the bearings, the shaft diameter between the bearings, and the attachment of the loading bars was selected to minimize bending of the shaft as much as practical to avoid moment loads in the bearings. Order of magnitude calculations suggest the maximum angular tilt at the bearing locations should be less than 0.003 rad (0.172°), which is assumed to be insignificant.

As shown in Figure 5, each test bearing (outer and inner race) was laser etched with five (alternating long and short) radial tick marks over a 90° arc, such that each tick mark denotes 22.5°. The tick marks were used to position the bearings in the fixture such that one ball was at bottom dead center to aid in finding dents during posttest inspection. Each bearing had eight balls, so when the middle tick mark was aligned with a ball at bottom dead center during loading, the ball immediately to the left and to the right also aligned with a long tick mark, which made it much easier to find dents, especially very small ones.

Radial load was applied to each bearing only once to eliminate the possibility of damaging a given bearing in more than one location. A single test consisted of ramping the radial load up to the desired setpoint over 60 s, dwelling at that setpoint for 60 s, and then ramping down to zero load over 60 s. After each test, the bearing under test was removed from the fixture, and disassembled for inspection and measurement of any dents observed.

Only inner races were used for inspection and measurement for two reasons. First, given that the damage for inner races is on the O.D. of the part, it is much more amenable to nondestructive evaluation. Second, stress is always higher on the inner race for a given load condition due to the convex race geometry (nonconformal) in the circumferential direction compared to the concave (conformal) race geometry on the outer race. Therefore, for a nonrotating bearing and a given applied load, damage in the inner race is always expected to be more severe than in the outer race.

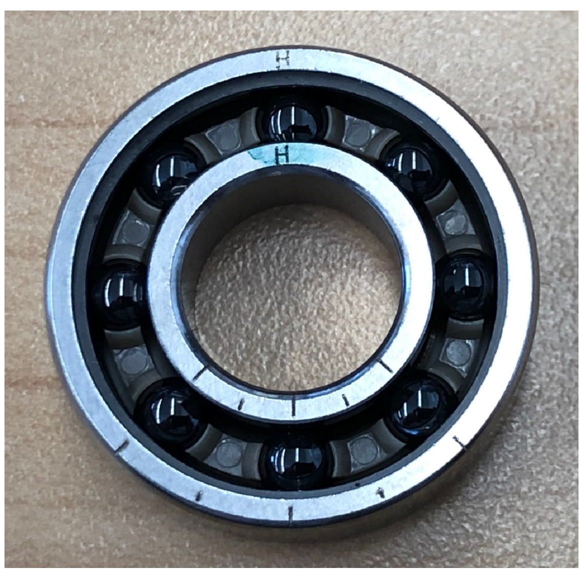

Figure 5.—Hybrid 440C/NiTi-Hf R8 bearing, showing laser etch marks for indexing/positioning.

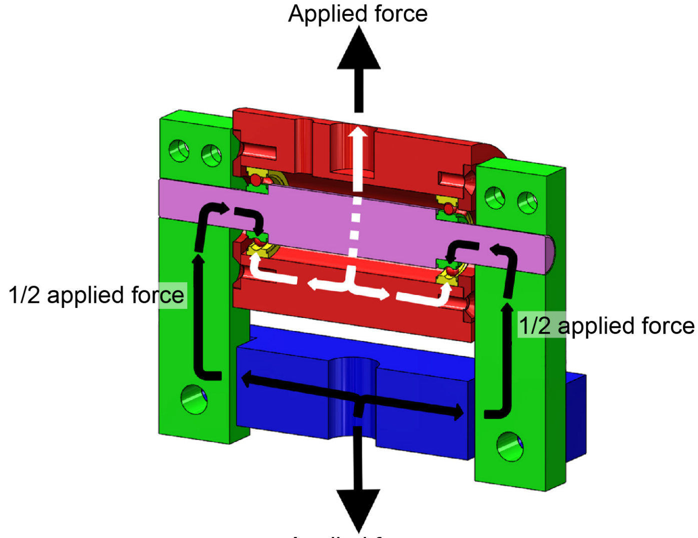

Figure 6.—Cross-sectional schematic of bearing load fixture showing bearing arrangement and load path for applied radial load.

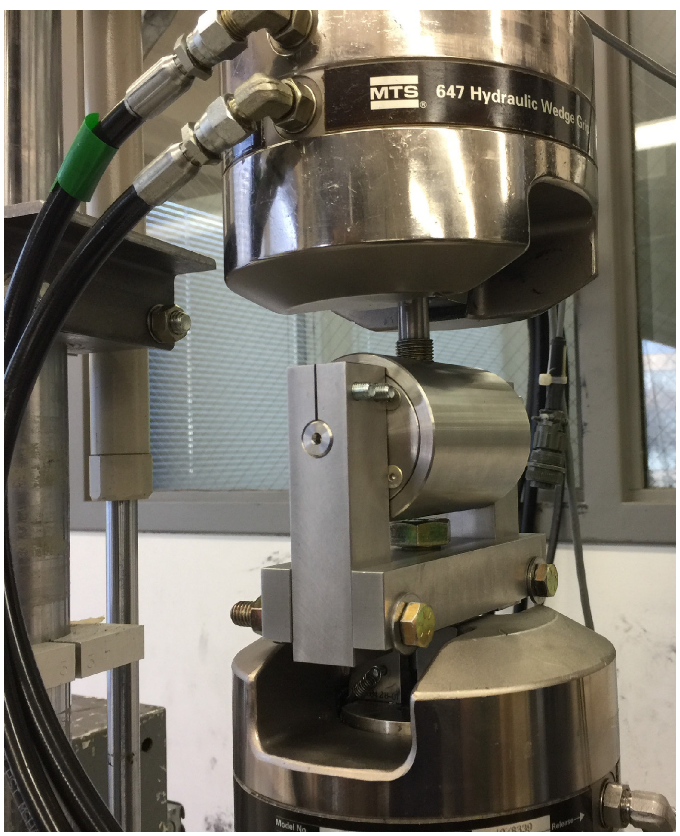

Figure 7.—Bearing load fixture mounted in NASA Glenn's 5-kip axial torsion load frame.

Dent measurements were made using a coherence scanning interferometric three-dimensional 3D optical profilometer. The optical profilometer provides a large vertical focal range via image stacking and has a high dynamic range and image averaging to produce high-fidelity images and measurements over a large dynamic range and vertical depth of field with low to moderate magnification.

A visual inspection (under low magnification from ×2 to ×10, depending on the dent size) was first conducted with an optical microscope to locate any observable dents and record their approximate location relative to the closest tick mark. Bearings were then inspected using the 3D optical profilometer to quantify the size of the dent (max. depth).

The following technique was used to quantify the dent depth using the 3D optical profilometer. The inner raceway of each bearing was mounted on a glass microscope slide using mounting clay so that the location of the dent (found as described in the previous paragraph) faced upward, that is, toward the 3D optical profilometer's objective lens. The profilometer was then used to take an image of the bearing inner raceway using a long (140 µm/0.0055 in.) vertical scan length and image stacking with a ×2.75 objective lens, two averages to reduce noise, and high dynamic range to reduce exposure issues. The setup is approximated in the sketch in Figure 8(a). The dent depth is typically not obvious in the resulting 3D contour plot because the three-dimensionality of the raceway curvatures dwarfs the depth of the dents. Therefore, the curvature of the raceway is removed numerically in the circumferential and axial directions to effectively flatten the global three-dimensionality of the raceway, a technique often called form removal. The curvatures are approximated by high-order polynomials. A third-order polynomial fit was found to be effective at flattening the curvatures without distorting the dents significantly. Figure 8(b) and (c) illustrate the technique qualitatively.

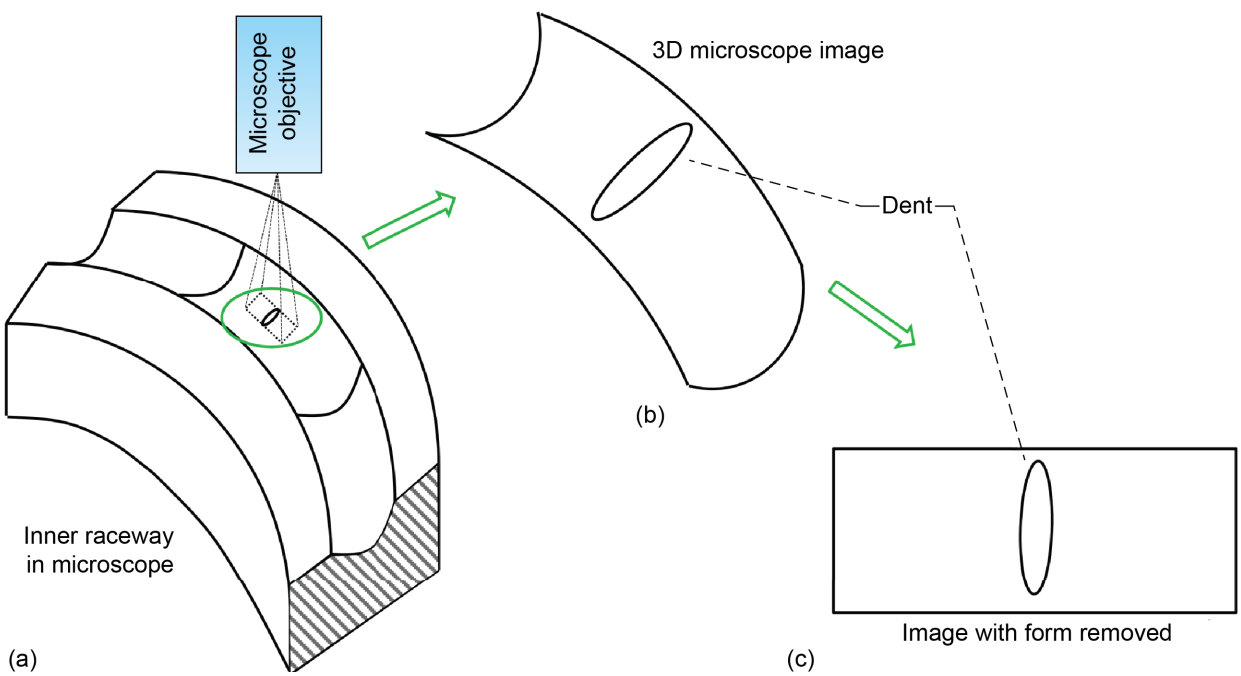

Figure 8.—Conceptualization of 3D microscope imaging technique. (a) Inner raceway under microscope objective. (b) 3D microscope scan with dent near the center of the scan envelope. (c) Flattened image with form removed.

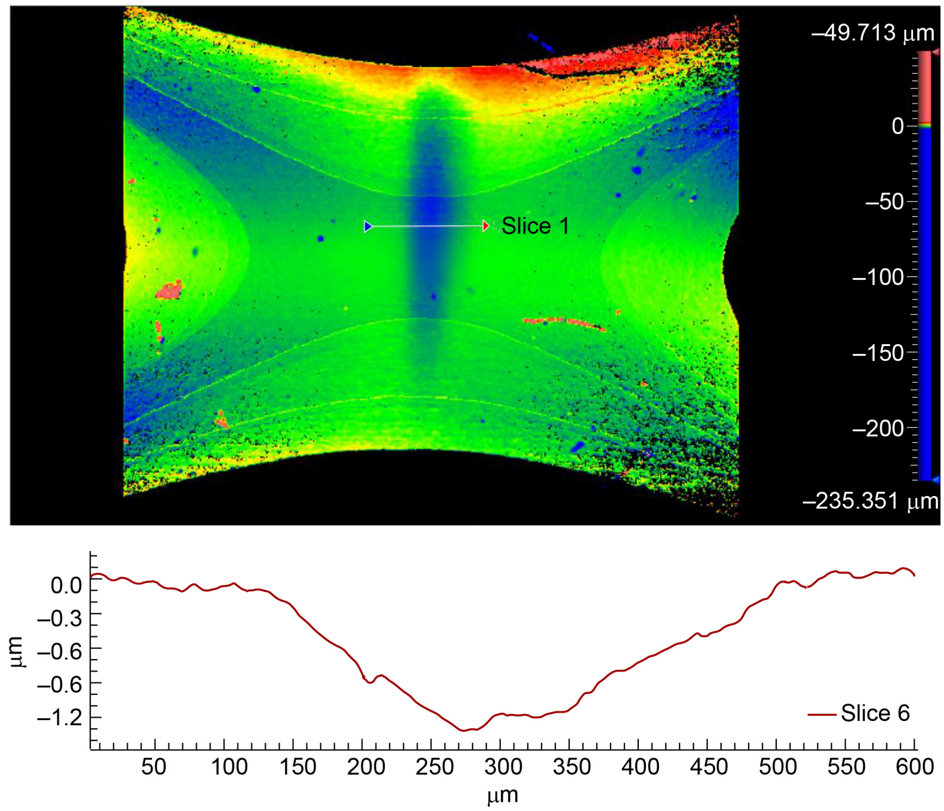

Figure 9.—Sample 3D microscope contour image showing dent and depth measurement.

When this technique is applied, the depth of the dent can be readily measured at any location by comparing it to the surrounding material. In general, the deepest dent depth occurs where the dent is the widest in the circumferential direction. A cursor (line) is superimposed on the image with endpoints selected by the user to obtain a two-dimensional (2D) depth scan. The cursor is moved manually along the length of the dent until the maximum depth is found. Figure 9 is representative of the type of contour image and measurements obtained. The color represents height, while the line plot below the contour is the quantitative measurement obtained by the cursor line, which can be seen as the horizontal white line approximately in the center of the blue oval dent depression. The small blue triangle on the left end of the line corresponds to the left extreme of the line plot; the small red triangle on the right end of the line corresponds to the right extreme of the line plot.

Following this measurement process with three bearings for a similar load case (one each with Si_3N_4 balls, 52100 balls, and NiTi-Hf balls) produced the three images in Figure 10(a) to (c). The bearing in Figure 10(a) had Si_3N_4 balls, and the maximum dent depth for this load case was approximately 1.3 µm (0.051 in.). The bearing in Figure 10(b) had 52100 steel balls, and the dent depth for this load case was approximately 0.60 µm (0.024 in.). Lastly, the bearing in Figure 10(c) had NiTi-Hf balls, and the dent depth for this load case was approximately 0.15 µm (0.0059 in.). The race material for all bearings was 440C stainless steel; the applied load was similar (2,200 N/490 lb for the bearing in Figure 10(a) and 1,800 N/400 lb for bearings in Figure 10(b) and (c)). For this load case, one can observe that the dent depth is a strong function of the ball material, with Si_3N_4 balls yielding the deepest dent and NiTi-Hf the shallowest dent. This process was repeated for various load cases for each ball material to identify the load required to achieve a 0.0005 dent depth ratio (dent depth/ball diam. as defined in Ref. 10); therefore, different numbers of tests were required for each material because the necessary applied load

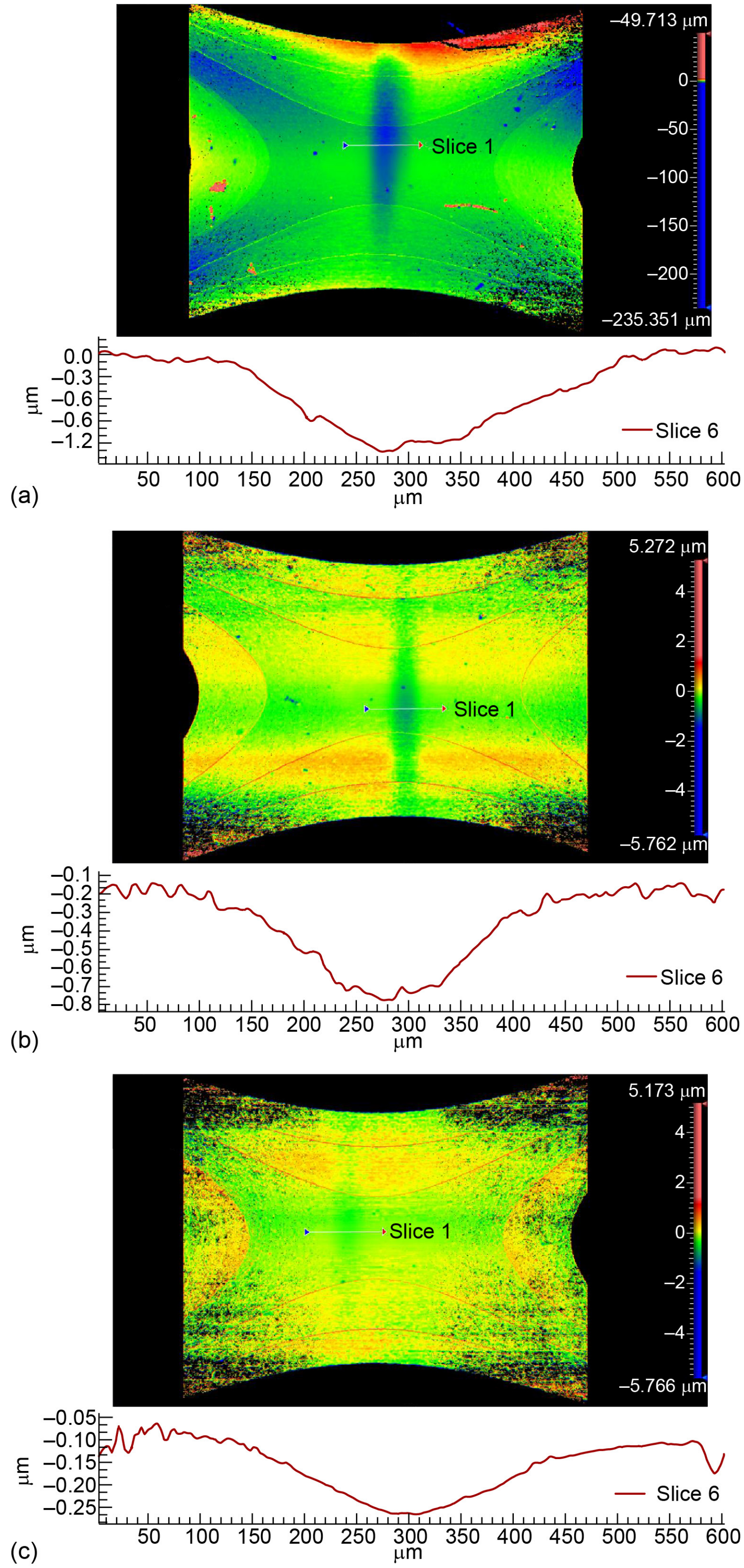

Figure 10.—3D microscope contours of three bearings with different ball materials, 2,000 N applied load. (a) Si_3N_4. (b) 52100. (c) NiTi-Hf.

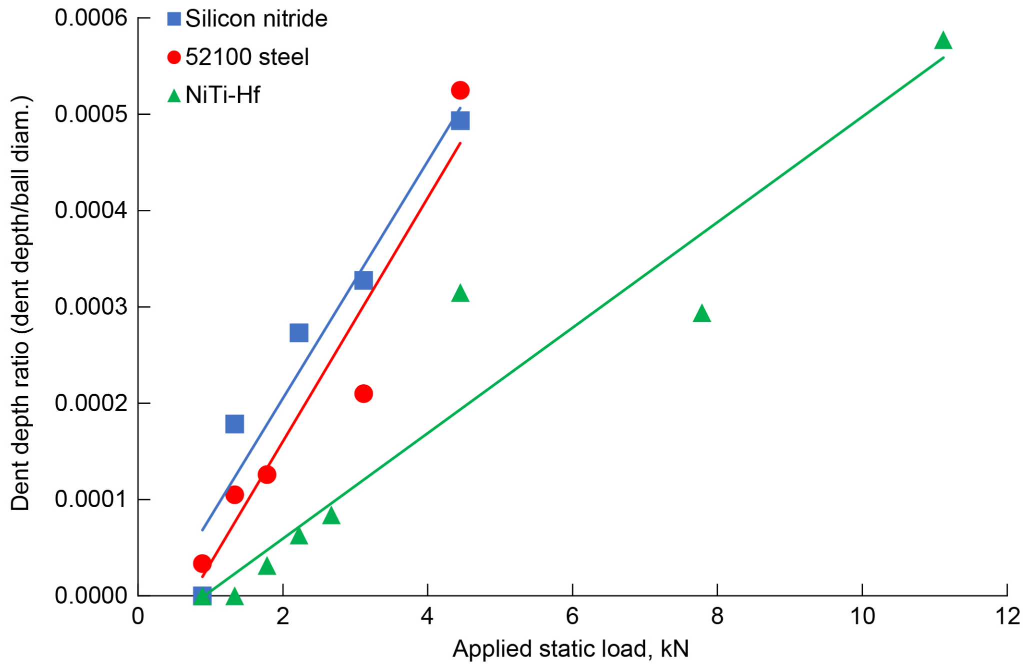

Figure 11.—Dent depth ratio versus applied radial load for Si_3N_4, 52100, and NiTi-Hf balls.

was unknown a priori. In general, the dent depth trend follows the previous example, in which the NiTi-Hf balls resulted in the least severe denting (in terms of depth), followed by 52100 balls and, lastly, Si_3N_4 balls. Figure 11 shows the resulting dent depth versus load plot. The load needed to produce a given dent depth with the NiTi-Hf balls is roughly twice as high as the load needed to produce the same dent depth for 52100 and Si_3N_4 balls, with the load for Si_3N_4 balls being slightly lower than for 52100 balls. The implication of these results is that NiTi-Hf balls can reduce damaging brinnelling for a given load condition, effectively increasing load capacity.

Conclusions

A relatively new class of bearing material, nickel-titanium alloy (NiTi or Nitinol), has previously been demonstrated to provide potential for high load capacity and significant improvements in corrosion resistance compared to conventional bearing materials. A new alloy of NiTi, NiTi-Hf (57 wt% Ni, 40 wt% Ti, and 3 wt% Hf), has been shown to retain the beneficial characteristics of the base NiTi alloy (60NiTi) while allowing for a less aggressive heat treatment process and simpler material processing. In the present work, the new alloy has been shown to enable manufacturing of smaller precision bearings than was previously possible. The successful manufacturing of smaller parts is believed to be due to the lower residual stresses, but further investigation would be required to verify the causality. The combination of high load capacity, corrosion immunity, and small precision manufacturability combine to make NiTi-Hf a viable material choice for extreme aerospace bearing applications where these characteristics are potentially beneficial. Examples of potential uses in currently challenging NASA applications include reaction wheel bearings that require high launch load capability, fluid process pump bearings subjected to corrosive liquids such as in spacesuit cooling pumps, and lunar and martian surface mechanism bearings subjected to particulate ingestion, to name a few.

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