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60NiTi Intermetallic Material Evaluation for Lightweight and Corrosion Resistant Spherical Sliding Bearings for Aerospace Applications

Report on NASA-Kamatics SAA3–1288

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November 2015

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Abstract

Under NASA Space Act Agreement (SAA3–1288), NASA Glenn Research Center and the Kamatics subsidiary of the Kaman Corporation conducted the experimental evaluation of spherical sliding bearings made with 60NiTi inner races. The goal of the project was to assess the feasibility of manufacturing lightweight, corrosion resistant bearings utilizing 60NiTi for aerospace and industrial applications. NASA produced the bearings in collaboration with Abbott Ball Corporation and Kamatics fabricated bearing assemblies utilizing their standard reinforced polymer liner material. The assembled bearings were tested in oscillatory motion at a load of 4.54 kN (10,000 lb), according to the requirements of the plain bearing specification SAE AS81820. Several test bearings were exposed to hydraulic fluid or aircraft deicing fluid prior to and during testing. The results show that the 60NiTi bearings exhibit tribological performance comparable to conventional stainless steel (440C) bearings. Further, exposure of 60NiTi bearings to the contaminant fluids had no apparent performance effect. It is concluded that 60NiTi is a feasible bearing material for aerospace and industrial spherical bearing applications.

Introduction

Materials that are suitable for use in bearings are generally limited to four broad categories each of which have advantages and disadvantages. The four categories are: (1) hardening steels, (2) superalloys and austenitic stainless steels, (3) ceramics and lastly, (4) non-ferrous alloys which include copper, zinc, and plastics. The hardening steels, such as M50 tool steel and 440C are inexpensive and have high hardness but generally poor corrosion resistance. Superalloys like Inconel and Stellite and austenitic stainless steels like 304LC, exhibit excellent corrosion resistance but low hardness. Ceramics such as silicon nitride are hard and chemically inert but are brittle and difficult to incorporate into machine designs because of their extreme rigidity and low thermal expansion coefficients. Finally, the non-ferrous alloys are inexpensive to produce but are weak and lack high temperature capability (Refs. 1 to 3). In most instances, design accommodations can be made to account for a bearing material's shortcomings. In some instances, however, benefits could be realized through the use of a material that simultaneously provides high hardness, corrosion resistance, ease of manufacture and design incorporation into mechanical systems. Since 2004, the potential to realize such benefits has motivated NASA to research and develop NiTi intermetallics for bearing applications (Refs. 2 to 8). The concept, however, began much earlier in another government laboratory.

The consideration of NiTi alloys for bearings can be traced to the pioneering work of William J. Buehler and his colleagues at the Naval Ordnance Laboratory (NOL) during the late 1950s (Refs. 9 and 10). The designation NITINOL often used for these alloys is an abbreviation for Nickel-Titanium Naval Ordnance Laboratory. At that time, research was underway to develop high temperature, non-magnetic alloys for missile cone applications. Buehler's early efforts identified both the 55 and 60 Nitinol alloys, which contained 55 and 60-weight percent nickel, respectively. 55 Nitinol, referred to hereafter as 55NiTi, is soft and exhibits remarkable shape memory effects while 60 Nitinol (60NiTi) is hard and is dimensionally stable. Both alloys have apparent moduli comparable to titanium. Buehler abandoned work on the hard 60 Nitinol because it was very difficult to process and machine and it had the tendency to spontaneously fracture upon cooling after casting. By applying advanced manufacturing methods, bearing quality balls and races have been routinely produced opening the potential for bearings that exhibit excellent corrosion resistance and tribological behavior (Ref. 11).

The nominal material properties of 60NiTi are shown alongside traditional bearing materials in Table 1. All of these materials have high hardness, above 55HRC, which assures good wear resistance. They all have high strength and temperature capability. Compared to the two metals 440C and M-50 tool steel, 60NiTi is about 15 percent lighter, has comparable thermal expansion coefficient, similar fracture toughness and Poisson's ratio. 60NiTi has much lower (half) elastic stiffness (Young's) modulus than the steels and one-third that of the ceramic silicon nitride. Like the ceramic, 60NiTi is immune to atmospheric corrosion. This blend of properties is unique and leads to a number of performance benefits with regards to bearings that are not immediately apparent from a cursory review of the properties alone.

For instance, when used in a highly stressed, concentrated contact like a ball bearing, 60NiTi can withstand higher loads without suffering from permanent damage (e.g., denting) as might a conventional all steel bearing. The basis for this behavior lies within the contact mechanics of the ball-race interface. 60NiTi has a reduced modulus and yet is hard. These properties lead to a broadened contact area, reduced stresses and higher load capacity (Refs. 2 and 5). Figure 1 shows this effect.

Thus from a design standpoint, the use of 60NiTi and other emerging hard superelastic, low modulus alloys for bearings is enabling. Higher loads, smaller sizes and intrinsic corrosion resistance are all positive side effects of replacing iron-based alloys (steels). Of course, for the purposes of the present investigation on conforming-contact sliding bearings, the contact mechanics of 60NiTi and its variants are not specifically relevant. For the current work, sliding friction and wear behavior is primary. Nonetheless, if it is shown that 60NiTi tribologically performs well in the spherical bearing application and in the presence of fluid contaminants (hydraulic and deicing fluids), it may be beneficial to consider other aircraft applications involving highly stressed contacts such as ball bearings and gears.

TABLE 1.—NOMINAL PROPERTIES FOR 60NiTi AND Si_3N_4 TEST SPECIMENS AND CONVENTIONAL BEARING STEELS

Property	60NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 HV	60 to 65 HRC
Thermal conductivity W/m-°K	9 to 14	42	22	~26
Thermal expansion	11×10^{-6}/°C	11×10^{-6}/°C	3×10^{-6}/°C	12×10^{-6}/°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	~1.04×10^{-6} Ω·m	~0.60×10^{-6} Ω·m	Insulator	~0.18×10^{-6} Ω·m

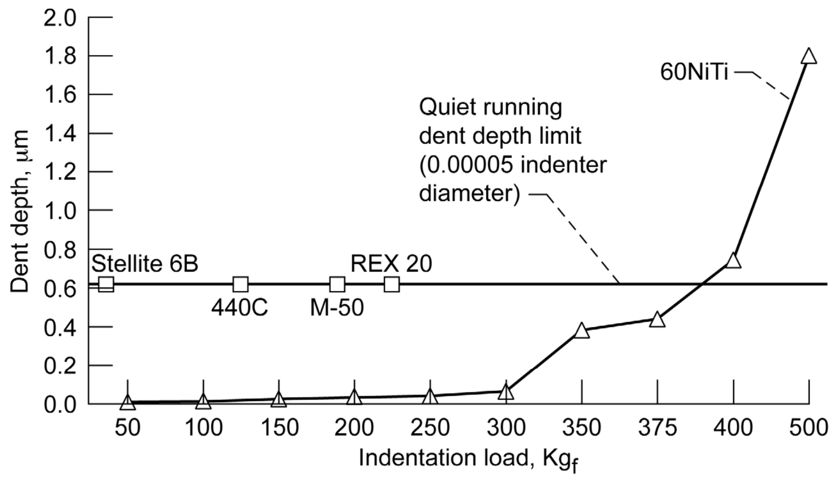

Figure 1.—Dent depth versus indentation load for 12.7 mm diameter Si_3N_4. Ball pressed onto flat plate specimens. (Data from Ref. 5).

Figure 2.—Typical linkage rod-end bearings that utilize spherical inner race drilled balls.

Figure 3.—Test bearings that utilize spherical inner race drilled balls made from 60NiTi.

In the current report, highly loaded spherical sliding bearings are fabricated incorporating 60NiTi inner races (drilled balls) into conventional commercial aerospace grade reinforced polymer lined outer races (shells) made of stainless steel. These types of self-aligning slider bearings are used throughout the aerospace industry for the transmission of forces and motions in mechanisms such as airframe control surface actuator links (Ref. 12). Such applications are depicted in Figure 2 and a photograph of a 60NiTi (inner race) bearing is shown in Figure 3.

These bearings are subjected to oscillatory motion under radial load according to the endurance test described by Aerospace Standard SAE AS81820 (Ref. 13). Bearings were tested in three groups, dry, contaminated with hydraulic fluid and contaminated with deicing fluid. The friction (torque) and wear results were collected and compared to conventional bearings made with 440C stainless steel balls (inner races).

Test Articles/Procedures

A lot of 25 spherical bearing assemblies were fabricated by Kamatics incorporating 60NiTi inner race balls with a 0.78-in. nominal outer diameter and 0.5-in. through hole bore. The ball is held inside a 17-4PH stainless steel sleeve in which reinforced PTFE liner is molded in place. Figure 4 shows the Kamatics drawing for the spherical bearing assembly. Further details about the design, testing and use of spherical bearings are contained in the Kamatics design guide (Ref. 12).

The lot of bearings were dispensed in the following manner: two bearings were destructively disassembled (cut) to confirm the molded liner uniformity, 14 bearings were subjected to oscillating sliding tests and then further measured and analyzed, and the remaining 9 bearings were retained for additional testing and characterizations.

Six of the 14 test bearings were tested dry, with no fluid contamination. These six were subjected to 25,000 oscillation (±25°) cycles at a rate of 17 cycles per minute, in ambient air under a load of 10,400 lb. This load corresponds to an average contact stress of 34 ksi and represents a fairly high load level intended to accelerate the wear and rapidly evaluate the bearing capabilities.

Eight bearings were tested under a reduced (75 percent) load of 7800 lb (26 ksi) following contamination with either Skydrol 500B hydraulic fluid or AS8243 Anti-icing fluid. The contamination procedure includes a 24-hr soak in the contamination fluid, removal of the bearing from the fluid and the initiation of testing within 30 min. Four bearings each were tested in each of the two fluids. The test duration and oscillating rate were the same as the dry case. Only the test load was reduced to compensate for the fluid contamination. In all tests, the rotational breakaway torque limit was 210 in.-lb.

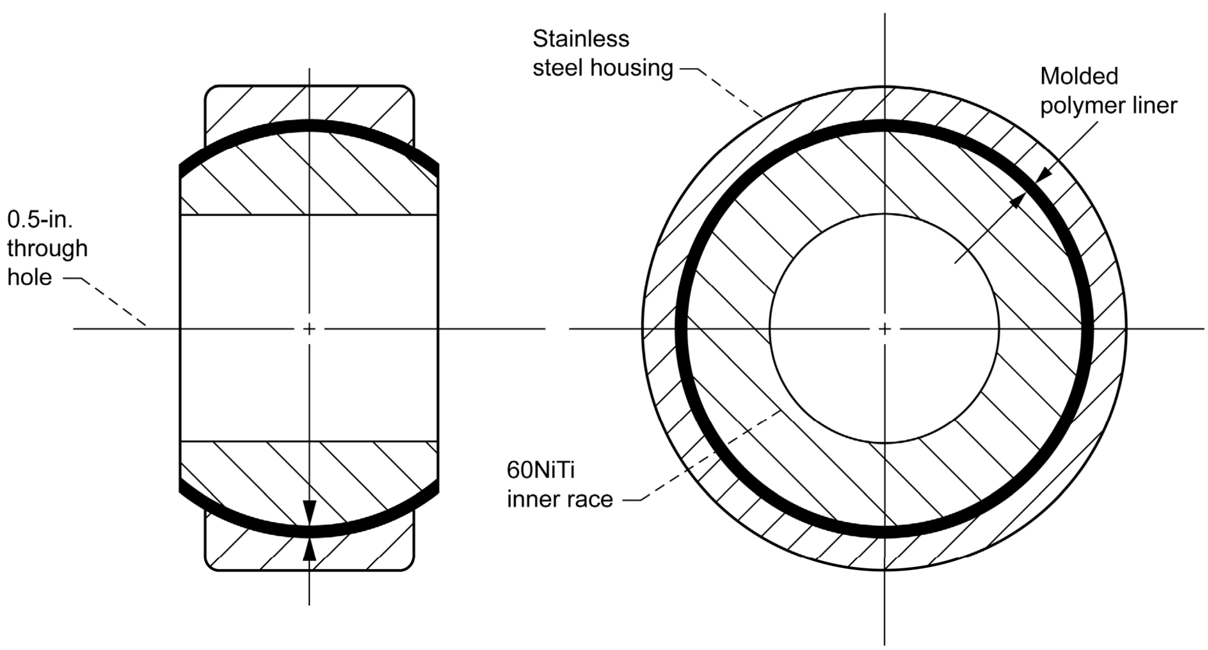

Figure 4.—Kamatics test bearing drawing.

Test Results and Discussion

The tribology test data, shown in Table 2, consists of the breakaway torque and the liner wear. The torque and wear data averages are based upon six repeat tests for the dry conditions and four repeat tests for the contaminated conditions. The error represents one standard deviation. Liner wear was measured during and after testing by measuring the radial movement between the ball and liner in accordance to SAE 808120 (Ref. 13). An examination of the data shows clear comparability of the 60NiTi bearings and the baseline 440C bearing.

The performance of the 60NiTi bearings is well within the torque limit (210 in.-lb) for this bearing and also well within the liner wear limit (0.006 in.). The photos shown in Figures 5 and 6 clearly illustrate that the 60NiTi surface is well lubricated by the PTFE filled liner material. The ball wear surfaces are smooth and free from deep gouges and wear patches. The wear behavior can be described as mild polishing type wear. Interestingly, the stainless steel bearing housing (outer surface) shows gouge marks from being pressed into and out of the test rig fixture. These gouges are considered normal and do not affect the bearing.

Several bearings were disassembled after testing to more closely examine the 60NiTi surface wear characteristics and metallurgy. Figures 7 and 8 show representative wear surfaces and features before and after sliding. In these figures one can readily see the grinding marks remaining from the ball manufacturing process. These marks (scratches and gouges) can be reduced through polishing. This is standard procedure for rolling element bearings. However, for the spherical sliding bearings tested in the present study, the unpolished, ground surface generally performs better in sliding against the polymer liner. This may be because the ball surface topography encourages the transfer of liner material and the formation of a solid lubricant film.

Figures 9 and 10 show ball surfaces after the sliding tests. These surface images were made after the full 25,000 sliding cycle test sequence was completed. Comparing Figures 9 and 10 to Figures 7 and 8, one can see that that a mild polishing-type wear process has occurred. No deep gouging or material pullout from the ball surface is observed. In the following figures, a backscattered electron image and subsequent elemental x-ray analyses is presented which shows that only the normal phases and constituents of the 60NiTi are present. This is consistent with a benign, polishing wear process. For comparative purposes, the spectra in Figure 11 coincides with spectra reported previously for fracture surfaces of 60NiTi (Ref. 7, Fig. 15) again indicating the present bearing testing does not alter the 60NiTi material.

The surface analyses of specimens that were tested following exposure to deicing fluid or hydraulic fluid are essentially the same as for the uncontaminated samples. From these results, we can conclude that the 60NiTi performs well tribologically in this application.

TABLE 2.—SPHERICAL BEARING DATA SUMMARY
[Test conditions: ±25° rotation, 17 cycles per minute, 0.3 in.^{2} bearing area.]

Bearing	Environment	Load, ksi	No. total cycles	Average torque, in.-lb	Liner wear, in.
60NiTi	Dry	34	25,000	193±11	0.0019±0.0007
60NiTi	Hydraulic fluid	26	25,000	192±14	0.0026±0.0010
60NiTi	De-icing fluid	26	25,000	176±11	0.0019±0.0011
440C	Dry	34	25,000	188±19	0.0021±0.0009

Figure 5.—Post-test Kamatics bearing assembly.

Figure 6.—Kamatics test bearings.

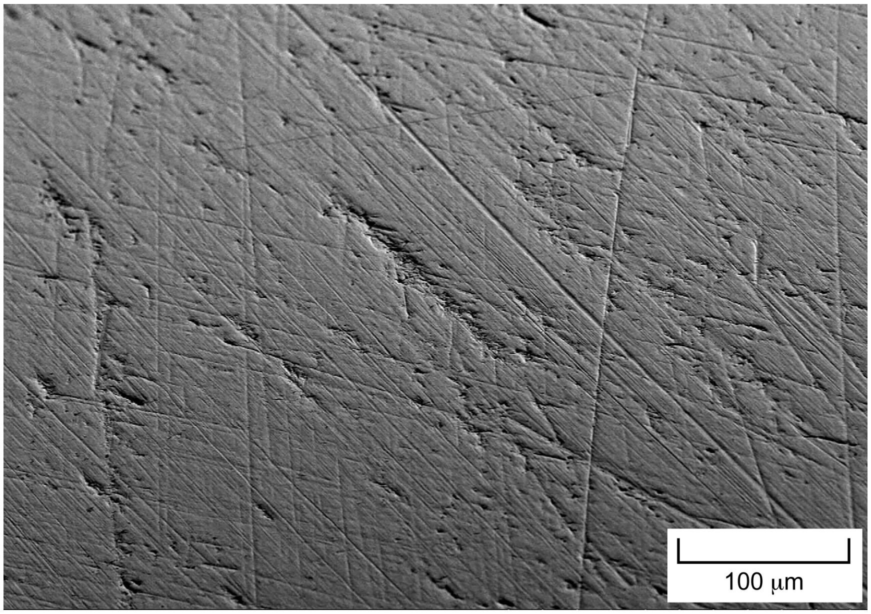

Figure 7.—Pre-test 60NiTi inner race (ball) surface showing normal roughness features (250×).

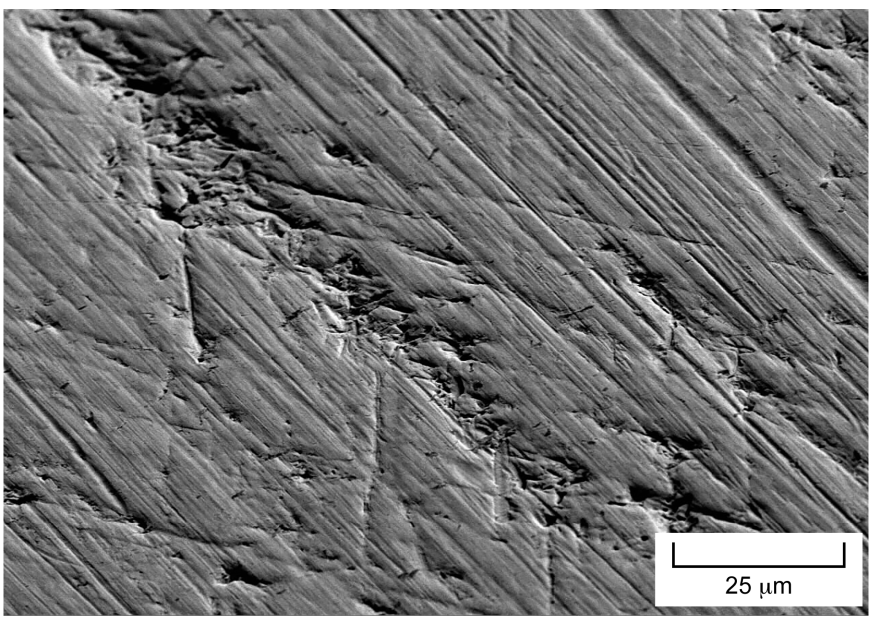

Figure 8.—Pre-test 60NiTi inner race (ball) surface showing normal roughness features (1000×).

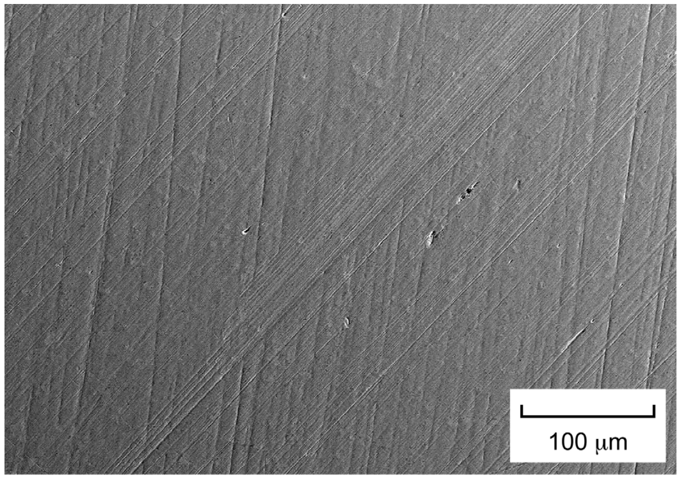

Figure 9.—Post-test 60NiTi inner race (ball) surface showing that original machining marks remain (250x).

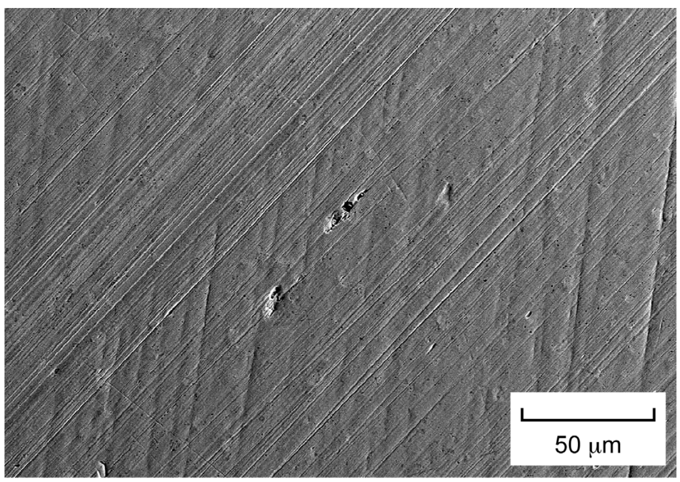

Figure 10.—Higher magnification post-test 60NiTi inner race (ball) surface (500x).

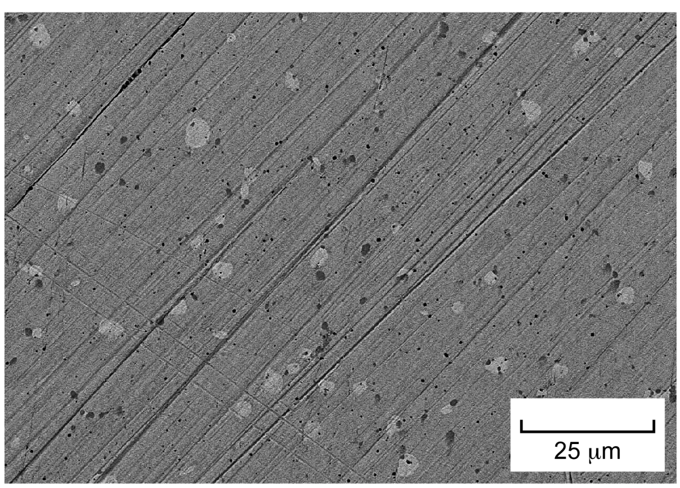

Figure 11.—Backscattered electron image of post-test 60NiTi inner race (ball) surface (1000x).

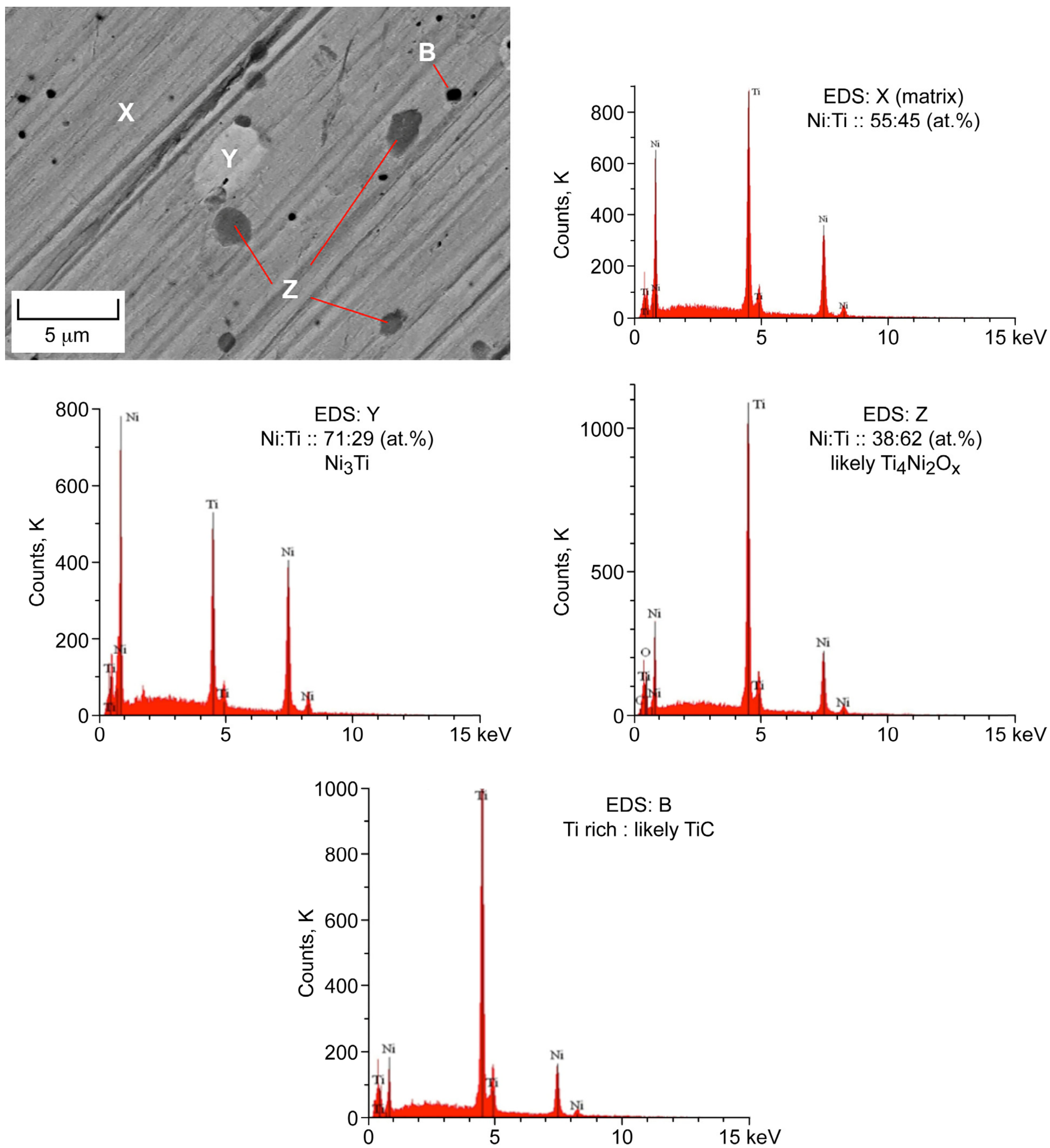

Figure 12.—Backscattered electron image and corresponding elemental spectra of post-test 60NiTi inner race (ball) surface (1000×).

Summary Remarks

The results of this Space Act Agreement clearly demonstrate that 60NiTi can be utilized for spherical bearings. Drilled balls were successfully fabricated from the baseline composition 60NiTi and these fully met the dimensional requirements set forth by Kamatics and the SAE specification. From a tribological performance perspective, the 60NiTi bearings exhibit comparable behavior to the more conventional 440C stainless steel bearings.

The use of 60NiTi carries advantages and disadvantages that must be considered prior to entering any commercialization development. 60NiTi has no iron content and therefore is both non-magnetic and not susceptible to rusting. Therefore it is well suited for wet and exposed corrosive applications where the use of a protective anti-corrosion oil or grease is impractical. Bearings for external locations on aircraft, marine machinery, submerged locations and food processing equipment are potential applications. 60NiTi has 15 percent lower density than steel and this can be helpful for mass critical applications. 60NiTi and its alloys are superelastic and can withstand concentrated loads to a higher level than steels without denting. Thus there may be an advantage to using 60NiTi in conforming contacts like the spherical bearings tested in this project and for conventional, high load capacity ball and roller bearings which are more sensitive to Brinell damage.

60NiTi has characteristics that should be viewed as disadvantages as well. 60NiTi is made from high cost constituents. The NiTi processing route is intrinsically high cost. Elemental powders must first be pre-fused and then consolidated. Even in high-volume mass production, the material cost for 60NiTi will far exceed that of high quality bearing steel, typically by an order of magnitude. Following the current production path, 60NiTi bearings cost approximately five times more than comparable high-grade steel bearings. In full production the price is expected to drop perhaps by a factor of two. Thus the applications for 60NiTi must be in systems in which conventional steels cannot be used effectively. Based upon these considerations, 60NiTi and its variants are promising materials for highly loaded, highly corrosive, weight sensitive applications.

Appendix—Visual Facsimile of the Signed Space Act Agreement

The following three pages are a visual facsimile of the signed space act agreement.

NONREIMBURSABLE SIMPLIFIED TECHNOLOGY
TRANSFER AGREEMENT
SPACE ACT AGREEMENT NUMBER SAA3- 1288

1. PURPOSE AND AGENCY COMMITMENT

The primary purpose of this agreement is to conduct a joint research and development project between NASA and Kamatics in which a NASA developed corrosion resistant and shockproof superelastic NiTi bearing alloy will be evaluated in an aerospace spherical bearing application. If successful, the results will be disseminated in a NASA report and it is expected that doing so will accelerate the commercialization of the technology for aerospace and industrial applications.

2. RESPONSIBILITIES

A. NASA will provide up to 25-cored 60NiTi balls made using the patented NASA-Abbott process (patent #8182741) to Kamatics for incorporation into SAE standard (AS 81820) spherical bearing assemblies. The balls have been previously manufactured to Kamatics specifications. NASA will also provide engineering data and technical guidance and consulting to Kamatics in order for them to successfully engineer and test the 60NiTi balls in their bearing assemblies. At the conclusion of testing, NASA will conduct forensic analyses of selected worn bearing assemblies and combine the results of these analyses with the bearing performance data provided by Kamatics into a co-authored NASA report.

B. Kamatics will accept delivery of the cored 60NiTi balls and incorporate them into their standard (SAE AS81820) test bearings. Kamatics will conduct a test program to evaluate the performance and suitability of the 60NiTi ball material for use in aerospace and industrial spherical bearings. Kamatics will provide the bearing performance data (friction, wear rate, torque) and relevant observations along with comparative data collected previously using industry standard ball materials tested under the same conditions. The data provided to NASA is not to include proprietary or restricted information. Kamatics will deliver at least 5 but not more than 10 tested spherical bearing assemblies to NASA for evaluation and advocacy purposes. Kamatics will retain any remaining bearing assemblies for further evaluations and for their advocacy purposes. If needed, Kamatics will assist NASA in co-authoring the NASA report describing the project.

3. POINTS OF CONTACT

NASA Glenn Research Center
Name: Dr. Christopher DellaCorte
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Fax: 216-433-5170
Email: christopher.dellacorte@nasa.gov

Kamatics Corporation
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Address: 1330 Blue Hills Ave., Bloomfield, CT 06002
Phone: 860-243-9704
Fax: 860-243-7993
Email: mark.broding@kaman.com

4. TERM, SCHEDULE AND MILESTONES

This Agreement becomes effective upon the date of the last signature below and shall remain in effect until the completion of all obligations of both Parties hereto, or one year from the date of the last signature, whichever comes first. Attached hereto and incorporated herein are the Terms and Conditions for the subject Agreement.

The Schedule and Milestones for this Agreement is as follows:
NASA will deliver cored bearing balls to Kamatics within two weeks of the effective date of the agreement.
Kamatics will manufacture spherical test bearings within four months of the effective date of this agreement.
Kamatics will test the bearing assemblies within 7 months of the effective date of this agreement.
Kamatics will deliver test data and worn bearing assemblies to NASA within 9 months of this agreement.
NASA will prepare a draft report describing the results within 12 months of the date of this agreement.

5. SIGNATORY AUTHORITY

The signatories to this Agreement covenant and warrant that they have authority to execute this Agreement. By signing below, the

Page 1 of 3

undersigned agrees to the above terms and conditions.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION	Kamatics Corporation
Name: Jih-Fen Lei	Name: Mr. Mark S. Broding
Title: Director, Research &Technology	Title: Director, Materials Science
Date: 3/8/13	Date: 3/5/13

NONREIMBURSABLE SIMPLIFIED TECHNOLOGY TRANSFER AGREEMENT
TERMS AND CONDITIONS

1. Authority. In accordance with the National Aeronautics and Space Act (51 U.S.C. § 20113), this Agreement is entered into by the National Aeronautics and Space Administration, John H. Glenn Research Center, located at 21000 Brookpark Road, Cleveland, Ohio 44135 (hereinafter referred to as "NASA" or "NASA GRC") and Kamatics Corporation located at 1330 Blue Hills Ave., Bloomfield, CT 06002 (hereinafter referred to as "Partner"). NASA and Partner may be individually referred to as a "Party" and collectively referred to as the "Parties."

2. Financial Obligations
There will be no transfer of funds between the Parties under this Agreement and each Party will fund its own participation. All activities under or pursuant to this Agreement are subject to the availability of funds, and no provision of this Agreement shall be interpreted to require obligation or payment of funds in violation of the Anti-Deficiency Act, (31 U.S.C. § 1341).

3. Liability and Risk of Loss
Each Party hereby waives any claim against the other Party, employees of the other Party, the other Party's Related Entities (including but not limited to contractors and subcontractors at any tier, grantees, investigators, customers, users, and their contractors or subcontractor at any tier), or employees of the other Party's Related Entities for any injury to, or death of, the waiving Party's employees or the employees of its Related Entities, or for damage to, or loss of, the waiving Party's property or the property of its Related Entities arising from or related to activities conducted under this Agreement, whether such injury, death, damage, or loss arises through negligence or otherwise, except in the case of willful misconduct.

4. Rights in Data
(A) Definitions. "Data," means recorded information, regardless of form, the media on which it is recorded, or the method of recording. Data exchanged under this Agreement is exchanged without restriction except as otherwise provided herein. "Proprietary Data," means Data embodying trade secrets developed at private expense or commercial or financial information that is privileged or confidential, and that includes a restrictive notice, unless the Data is:

(i) known or available from other sources without restriction;
(ii) known, possessed, or developed independently, and without reference to the Proprietary Data;
(iii) made available by the owners to others without restriction; or
(iv) required by law or court order to be disclosed.

(B) Data First Produced by Partner under the Agreement. If Data first produced by Partner or its Related Entities under this Agreement is given to NASA and the Data is Proprietary Data, and it includes a restrictive notice, NASA will use reasonable efforts to protect it. The Data will be disclosed and used (under suitable protective conditions) only for U.S. Government purposes.
(C) Data First Produced by NASA Under the Agreement
If Partner requests that Data first produced by NASA or its Related Entities under this Agreement be protected and NASA determines it would be Proprietary Data if obtained from Partner, NASA will mark it with a restrictive notice and use reasonable efforts to protect it for one (1) year after its development. During this restricted period the Data may be disclosed and used (under suitable protective conditions) for U.S. Government purposes only, and thereafter for any purpose. Partner must not disclose the Data without NASA's written approval during the restricted period. The restrictions placed on NASA do not apply to Data disclosing a NASA-owned invention for which patent protection is being considered.

5. Patent Rights.

Title to inventions made (conceived or first actually reduced to practice) under this Agreement remain with the respective inventing party(ies). No invention or patent rights are exchanged or granted under this Agreement. NASA and Partner will use reasonable efforts to report inventions made jointly by their employees (including employees of their Related Entities). The Parties will consult and agree on the responsibilities and actions to establish and maintain patent protection for joint invention and on the terms and conditions of any license or other rights exchanged or granted between them.

6. Right to Terminate
Either Party may unilaterally terminate this Agreement by providing thirty (30) calendar days written notice to the other Party.

7. Applicable Law
U.S. Federal law governs this Agreement for all purposes, including, but not limited to, determining the validity of the Agreement, the meaning of its provisions, and the rights, obligations and remedies of the Parties.

8. Disclaimer of Warranty
Goods, services, facilities, or equipment provided by NASA under this Agreement are provided "as is." NASA makes no express or implied warranty as to the condition of any such goods, services, facilities, or equipment, or as to the condition of any research or information generated under this Agreement, or as to any products made or developed under or as a result of this Agreement including as a result of the use of information generated hereunder, or as to the merchantability or fitness for a particular purpose of such research, information, or resulting product, or that the goods, services, facilities or equipment provided will accomplish the intended results or are safe for any purpose including the intended purpose, or that any of the above will not interfere with privately-owned rights of others. Neither the government nor its contractors shall be liable for special, consequential or incidental damages attributed to such equipment, facilities, technical information, or services provided under this Agreement or such research, information, or resulting products made or developed under or as a result of this Agreement.

9. Dispute Resolution
All disputes concerning questions of fact or law arising under this Agreement shall be referred by the claimant in writing to the appropriate person identified in this Agreement for purposes of the activities undertaken in the Agreement. The persons identified as the "Points of Contact" for NASA and the Partner will consult and attempt to resolve all issues arising from the implementation of this Agreement. If they are unable to come to agreement on any issue, the dispute will be referred to the signatories to this Agreement, or their designees, for joint resolution. If the Parties remain unable to resolve the dispute, then the NASA signatory or that person's designee, as applicable, will issue a written decision that will be the final agency decision for the purpose of judicial review.

10. Data Subject to Export Control
Whether or not marked, technical data subject to the export laws and regulations of the United States provided to Partner under this Agreement must not be given to foreign persons or transmitted outside the United States without proper U.S. Government authorization.

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