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

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Aerospace Bearing Needs:
(Performance and attribute goals)

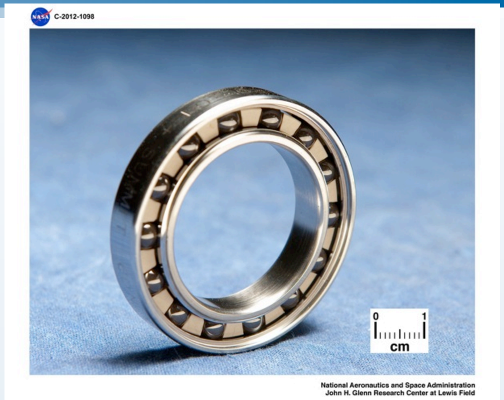
- Reduced weight propulsion and control systems:
  - Lighter weight materials
  - Higher power density designs
  - Higher transient load capability materials
- Corrosion Proof Components:
  - Exposed aircraft control surface hardware and bearings
  - Extreme environments (marine operation, search and rescue)
  - Long term storable bearings and components
  - Elimination of toxic coatings and expensive and complex processes
- Debris Tolerant Contacting Materials:
  - Bearings and gears not subject to secondary damage from debris.
  - Enable operation without coatings and super-clean oils.

Bearing Material: State-of-Art (SOA)
(Current suite of candidates is severely limited)

- Four general types of bearing materials:
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
  - Superalloys (e.g., jet turbine blade alloys)
  - Non-ferrous alloys (bronze, nylon etc.)
- Each of these has inherent shortcomings:
  - Hard steels are prone to rusting (even "stainless steels" like 440C)
  - Superalloys and austenitic stainless steels (304ss) are soft.
  - Ceramics have thermal expansion mismatch and dent steel races
  - Non-Ferrous materials are weak and lack temperature capabilities
- No known bearing material blends all the desired attributes:
  - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.

New approach: 60NiTi-Superelastic
(Hard but resilient material based upon shape memory alloys)

- **60NiTi Basics: market name NiTiNOL 60**
  - Invented by W.J. Buehler (late 1950's) at the Naval Ordnance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordnance Lab).
  - Casting (mix, melt, pour) was original process.
  - Contains 60 wt% Nickel and 40 wt% Titanium
  - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
  - A close cousin to the shape memory alloy, NiTiNOL 55, but 60NiTi is dimensionally stable.
  - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
  - Buehler found 60NiTi too difficult to manufacture but modern (ceramic) processing methods enable 60NiTi bearings with remarkable properties.



60NiTi ball bearings in production

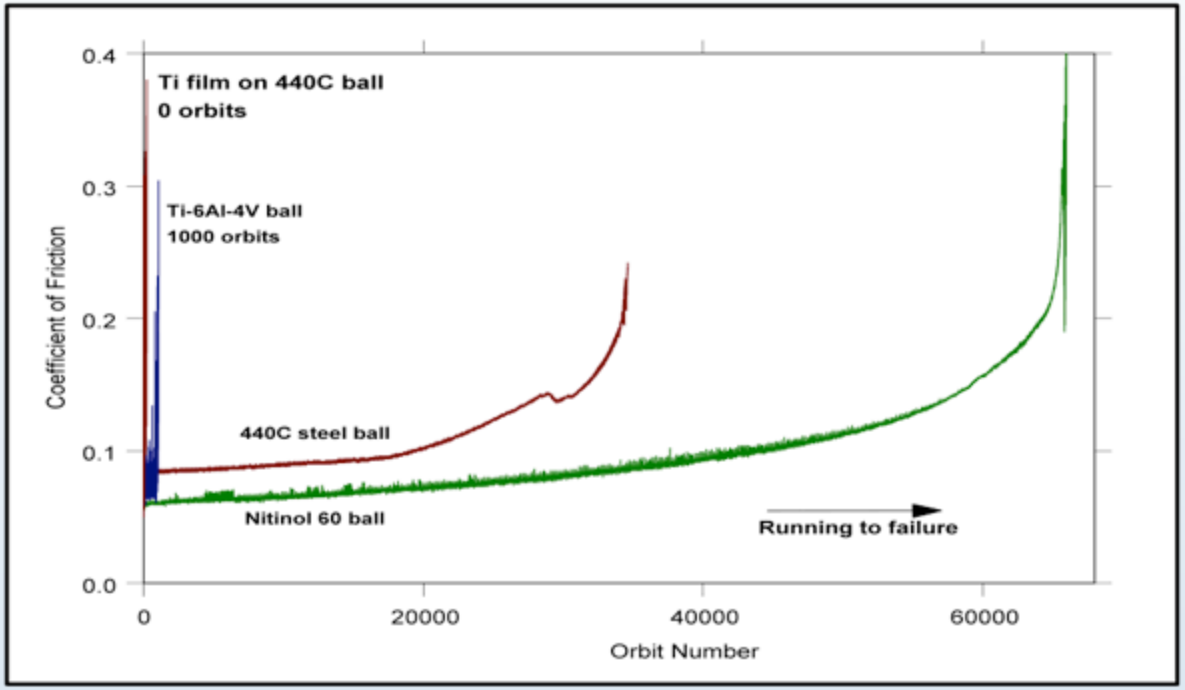
60NiTi Spherical Sliding Bearings Under Assessment: Present Study

Technical Properties Comparison: Bearings

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	24	33	~36
Thermal expansion	$\sim 11.2\times10^{-6}$/°C	10×10^{-6}/°C	2.6×10^{-6}/°C	$\sim 11\times10^{-6}$/°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	$\sim 1.04\times10^{-6}$ Ω-m	$\sim 0.60\times10^{-6}$ Ω-m	Insulator	$\sim 0.18\times10^{-6}$ Ω-m

- ***Primary Points***
  - ***Modulus is ½ that of steel, yet hardness is comparable.***
  - ***15% lighter than steel, corrosion resistance of a ceramic.***

60NiTi: Under Oil Lubrication



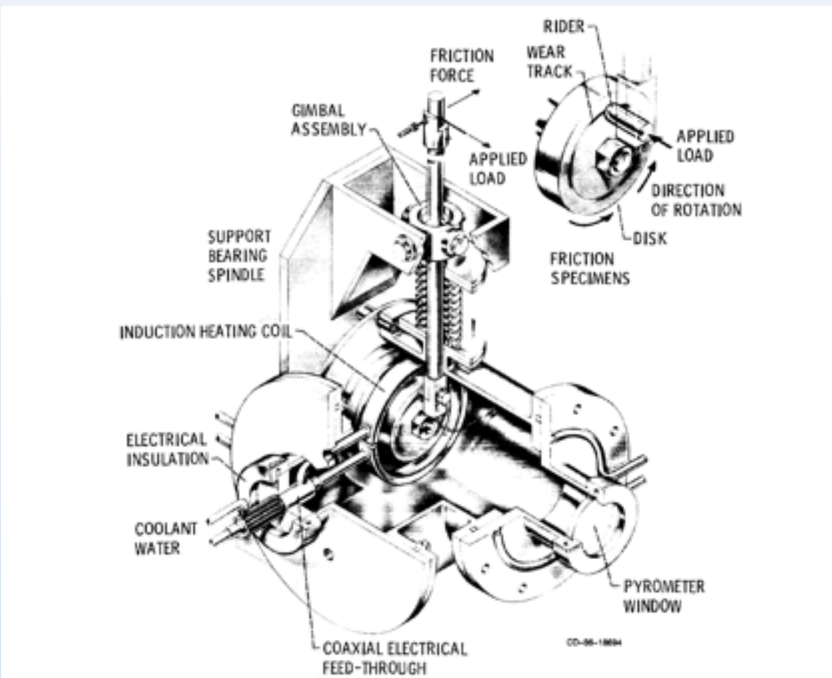
•60NiTi exhibits lower or comparable running friction than 440C stainless steel.

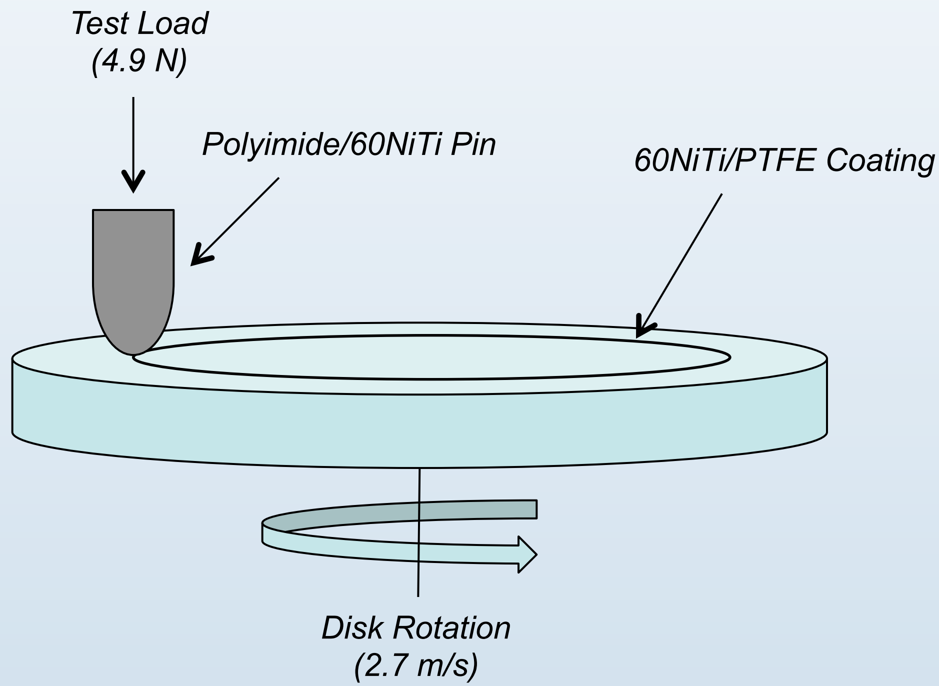
•60NiTi tends to provide longer lubricant life than 440C.

•60NiTi is also corrosion proof, non-magnetic and electrically conductive.

Tribology Evaluation: Dry sliding with solid lubricant

- *Pin-on-disk sliding test designed to mimic gear tooth-tooth contact.*
- *Load and speed chosen to bracket gear application.*
- *Survey-type experiments done over range of load-speed combinations to find pair that produces wear surfaces that match worn Polyimide/SS gear surfaces.*
- *Data output: friction coefficient, pin wear factor {wear vol./(load x distance)}*





Dry Sliding-Tribology Data Summary

POD-Sliding Wear Results

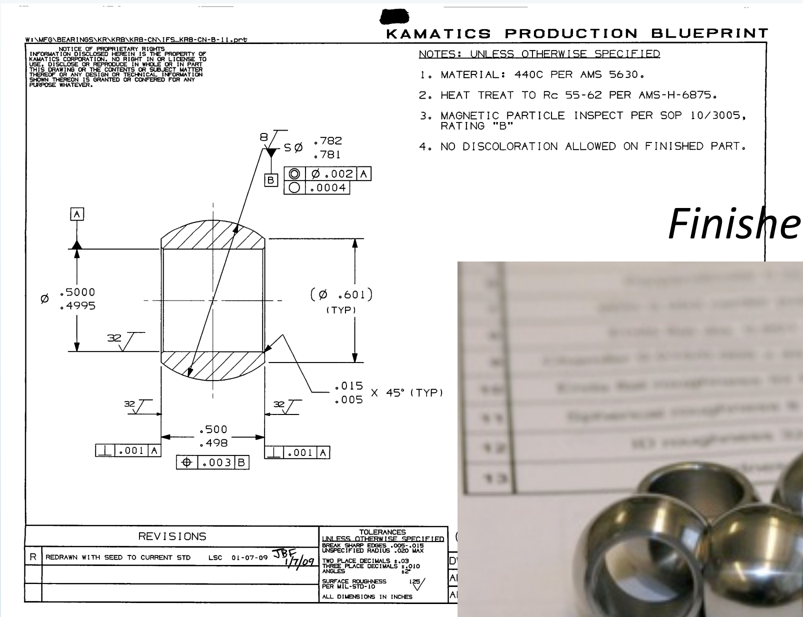
Table II-Friction and Pin Wear Data Summary
(Test Conditions: 4.9N load, 2.7m/s sliding speed, air at 25°C)

Pin Material	Disk Material/Surface Coating	Friction Coefficient	Pin Wear Factor, $mm^3/N\text{-}m$	Surface Appearance
SP21 Polyimide	316L SS	0.29 +/- 0.07	1.9 +/- 0.7 x 10^{-6}	Smooth
SP21 Polyimide	304 SS	0.34 +/- 0.08	0.7 +/- 0.2 x 10^{-6}	Smooth
SP21 Polyimide	60NiTi	0.28 +/- 0.04	2.1 +/- 1.5 x 10^{-6}	Smooth
60NiTi	60NiTi	0.18 +/- 0.03	8.3 +/- 3.2 x 10^{-6}	Rough
60NiTi + SP21	60NiTi	0.15 +/- 0.03	3.1 +/- 1.9 x 10^{-6}	Smooth
60NiTi*	PTFE DFL	0.15 +/- 0.02	184-348 km**	Smooth
60NiTi*	Graphite DFL	0.17 +/- 0.02	24-135 km**	Smooth

- **60NiTi accepts solid lubrication comparable to stainless steel.**
- **Would 60NiTi serve as a suitable self-aligning sliding bearing?**

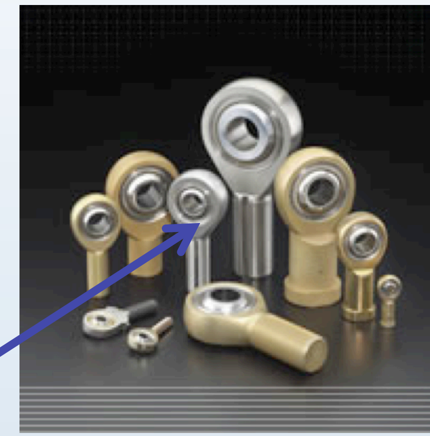
Spherical Bearing Project

Inner Race (ball) Drawing



Finished inner races

Corrosion-Proof Rod bearings



Status: Drilled 60NiTi balls (inner races) made and incorporated into bearings for testing.

Simplified Space Act Agreement

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

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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Email: christopher.dellacorte@nasa.gov

Kamatics Corporation
Name: Dr. Mark S. Broding
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

undersigned agrees to the above terms and conditions.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

____
Name: Christopher DellaCorte
Title: Senior Materials Research Engineer

Date: ______________________

Kamatics Corporation

____
Name: Dr. Mark S. Broding
Title: Director, Materials Science

Date: ______________________

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).

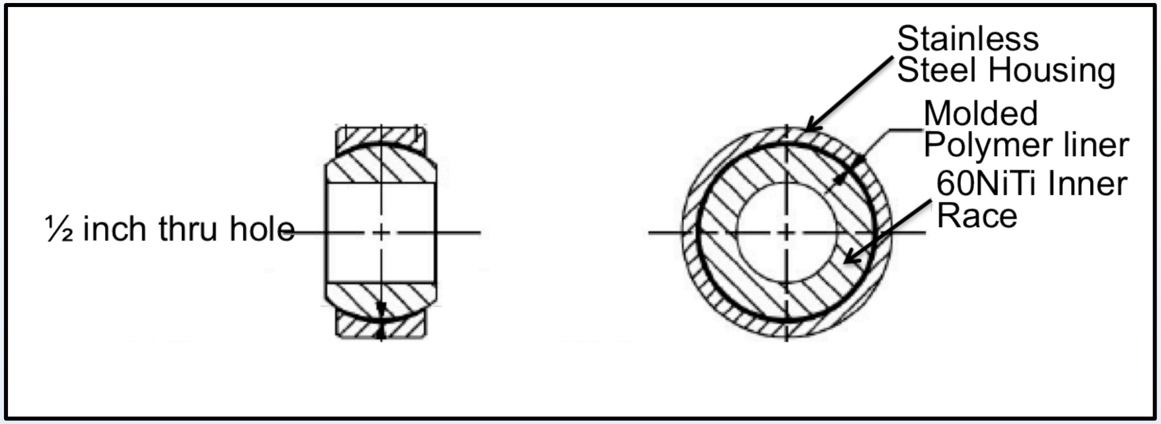
3. Liability and Risk of Loss
Each Party hereby waives any claim against the other Party, employees of the other Party, the other Party's Related Entities (including but not limited to contractors and subcontractors at any tier, grantees, investigators, customers, users, and their contractors or subcontractor 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

NASA provides finished balls and design properties, Kamatics builds and tests bearings, joint NASA publication of general results (w/o divulging proprietary details).

Test Bearings: 60NiTi balls, PTFE filled liner, 17-4 SS Outer Race



- SAE AS81820 test
- +/-25° Oscillation, 17cpm
- 10,400 pound load (dry)
- 7500 pound load (wet)
- 210 in-lb torque limit
- 0.006” radial wear limit

Results: 60NiTi Tribology

Table-II Spherical Bearing Data Summary
{Test Conditions: +/- 25° rotation, 17 cycles per minute, 0.3in^2 bearing area}

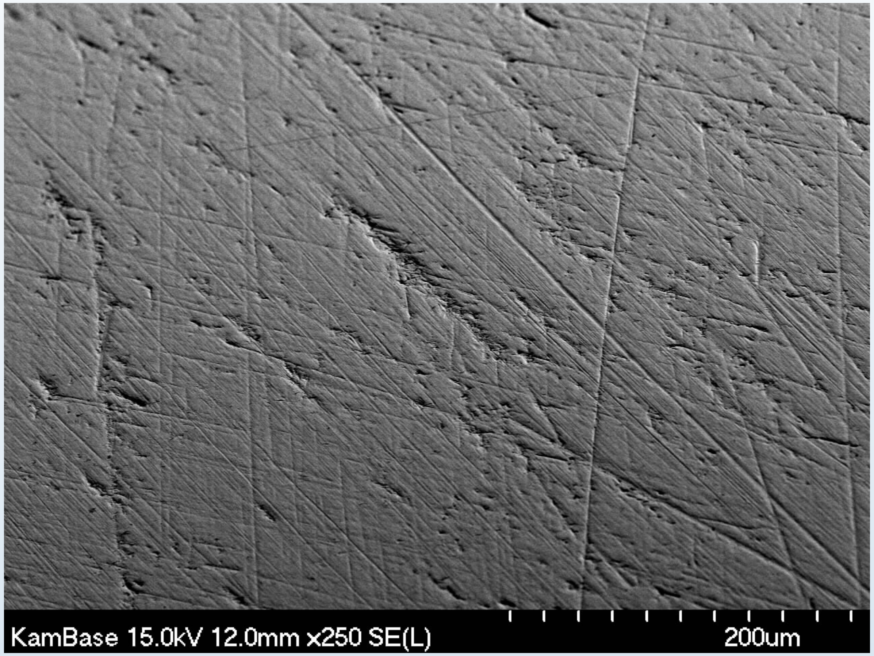
Bearing	Environment	Load (ksi)	#Total Cycles	Avg. Torque (in-lb)	Liner Wear (in)
60NiTi	Dry	34	25,000	193+/-11	0.0019+/-0.0007
60NiTi	Hydraulic Fluid	26	25,000	192+/-14	0.0026+/-0.0010
60NiTi	De-Icing Fluid	26	25,000	176+/-11	0.0019+/-0.0011
440C	Dry	34	25,000	188+/-19	0.0021+/-0.0009

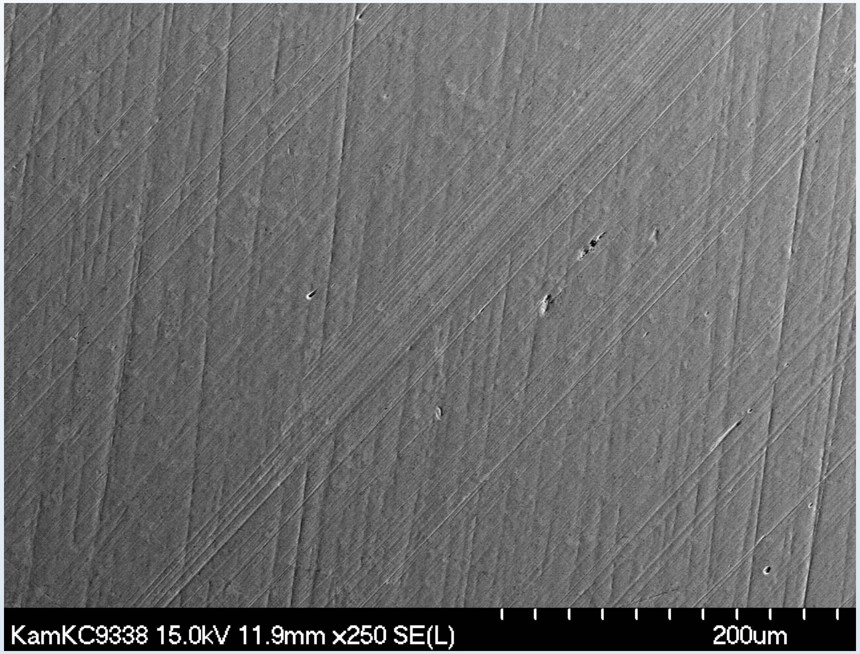
Bearings made with 60NiTi balls provide tribological response that is comparable to standard 440C steel ball bearings.

Result: 60NiTi Bearing After Test

Result: 60NiTi Ball Appearance After Test

Result: 60NiTi Wear Surfaces (SEM)

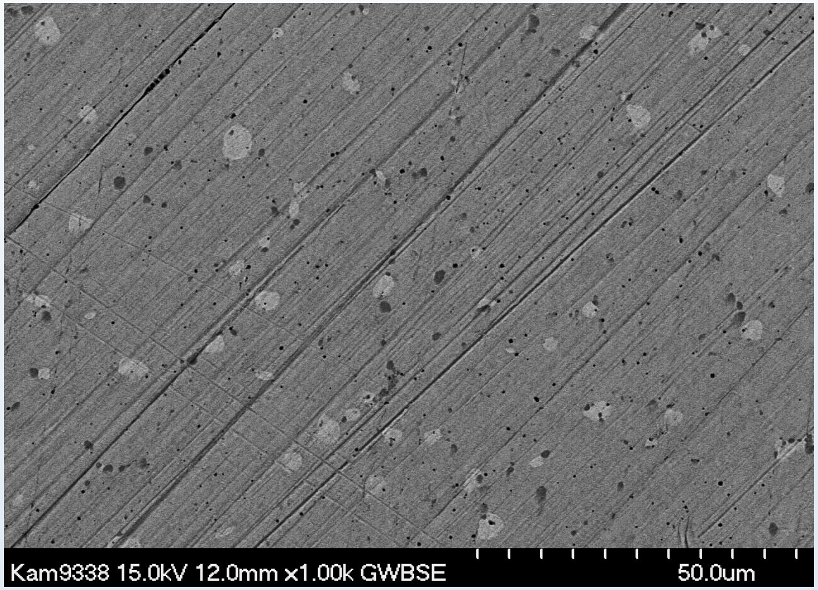




Pre-test 60NiTi inner race (ball) surface showing normal roughness features (250x).

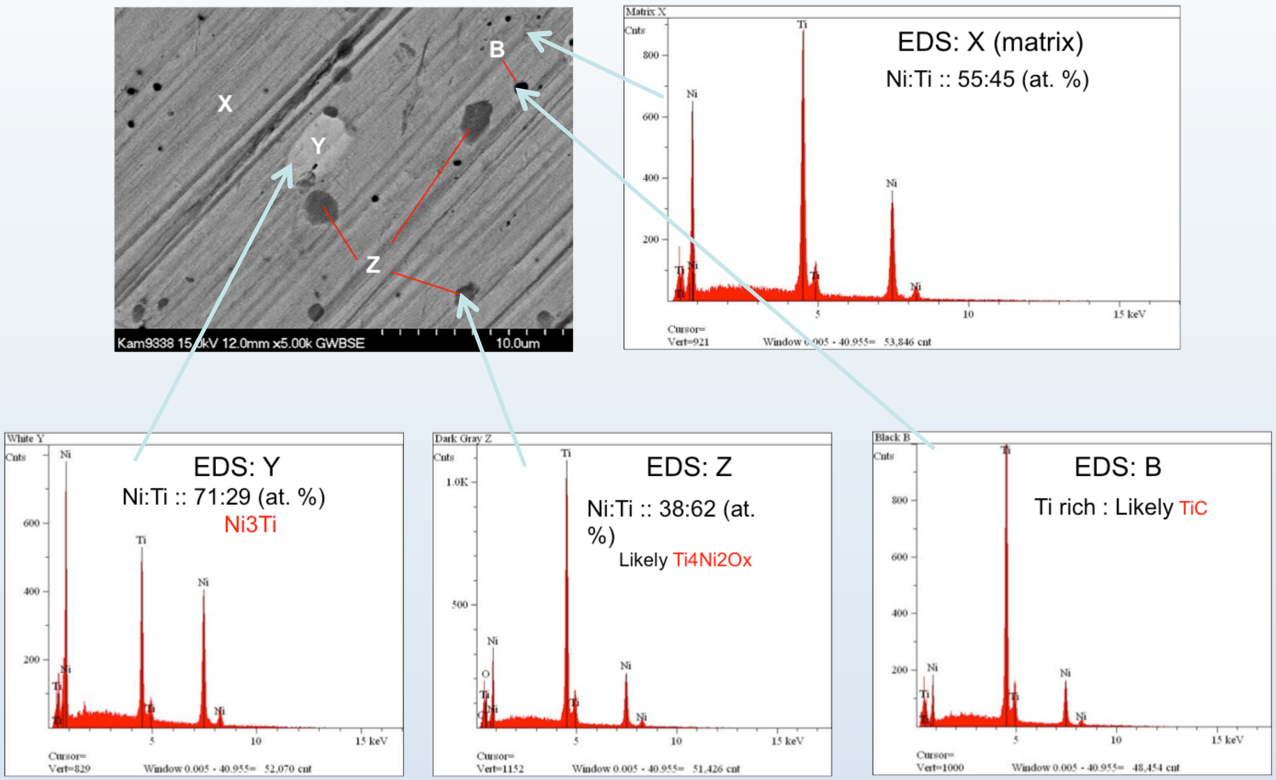
Post-test 60NiTi inner race (ball) surface showing that original machining marks remain (250x).

Result: 60NiTi Ball (Backscattered SEM)



- *Backscattered electron image of post-test 60NiTi inner race (ball) surface (1000x).*
- *Light spots are higher order phases (Ni_3Ti).*
- *Dark Spots are carbide tramp phases.*

Result: 60NiTi Surface Analyses

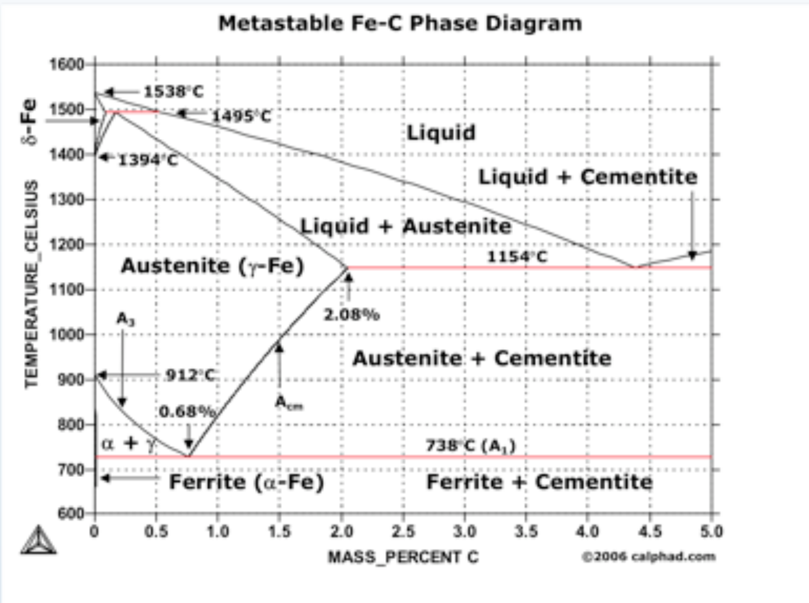


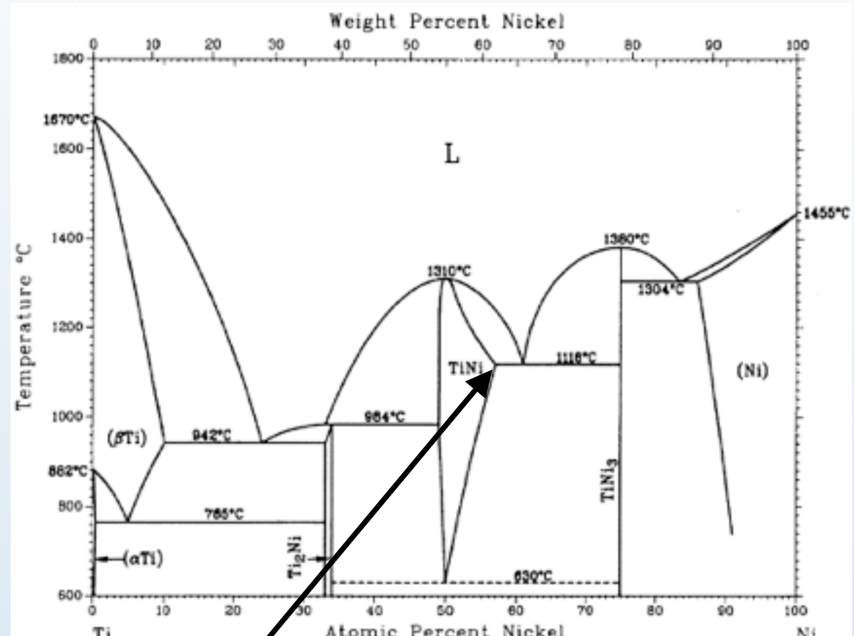
- ***Backscattered electron image and corresponding elemental spectra of post-test 60NiTi inner race (ball) surface (1000x).***

60NiTi Summary Remarks and Enabling Benefits

- 60NiTi can substitute for 440C steel in spherical bearings:
  - Friction and wear properties meet SAE requirements.
  - 60NiTi is not adversely affected by common aircraft contaminants (deicing and hydraulic fluids).
- Reduced weight propulsion and control systems:
  - Lighter weight materials: NiTi alloys weigh 15% less than steel.
  - High intrinsic transient load capability: reduce design margin
- Corrosion Proof Components:
  - Exposed aircraft control surfaces: NiTi alloys are rust-free
  - Elimination of toxic coatings and expensive and complex processes
  - Tests show tribological behavior is similar to stainless steel.
  - Corrosion performance exceeds steel capabilities.

Closing Thoughts: Materials Design Space





Fe-C system has yielded literally thousands of alloys and variants following centuries of development.

NiTi explorations to date have been limited to very narrow region.

Though much more R&D remains to commercialize 60NiTi and other superelastic intermetallic materials for use in bearings, gears and other mechanical systems, early indications are very promising.

Thank You!