Ni-Ti Next Generation Bearings for Space Applications

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Materials Requirements: NASA sets the bar high
(Aerospace challenges conventional bearing materials)

• Key Attributes sought:
  – Hard (Rockwell C58 or better)
  – Wear-resistant and compatible with existing lubricants
  – Resistant to rolling contact fatigue (RCF)
  – Fracture resistant
  – Corrosion resistant (preferably immune)
  – Capable of producing ultra-smooth surface finishes
Technical Challenge:
(Current suite of candidates is severely limited)

- Four general types of bearing and tribo-mechanical materials:
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si$_3$N$_4$ hybrid bearings)
  - Superalloys
  - 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 are non-conductive (and operate on steel raceways)
  - 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.
Superelastic Bearings: NiTi based intermetallics
(Hard but resilient material related to shape memory alloys)

- **60NiTi Basics: market name NiTiNOL 60**
  - W.J. Buehler invented NiTiNOL in the 1950’s. Acronym for Ni-Ti-Naval-Ordnance-Laboratory.
  - 60NiTi (60 wt% Ni) is the baseline composition. Alloying with Hf, Zr, and Ta improves microstructure and processing.
  - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
  - Closely related to the shape memory alloys, like NiTiNOL 55, but dimensionally stable.
  - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
  - Brinell damage threshold load (pounds, kgf) is significantly (3-5X) higher than steel.
### Technical Properties Comparison:

<table>
<thead>
<tr>
<th>Property</th>
<th>60NiTi</th>
<th>440C</th>
<th>Si₃N₄</th>
<th>M-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>6.7 g/cc</td>
<td>7.7 g/cc</td>
<td>3.2 g/cc</td>
<td>8.0 g/cc</td>
</tr>
<tr>
<td>Hardness</td>
<td>56 to 62 HRC</td>
<td>58 to 62 HRC</td>
<td>1300 to 1500 Hv</td>
<td>60 to 65 HRC</td>
</tr>
<tr>
<td>Thermal conductivity W/m-°K</td>
<td>~9 to 14</td>
<td>24</td>
<td>33</td>
<td>~36</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>~11.2×10⁻⁶/°C</td>
<td>10×10⁻⁶/°C</td>
<td>2.6×10⁻⁶/°C</td>
<td>~11×10⁻⁶/°C</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Non</td>
<td>Magnetic</td>
<td>Non</td>
<td>Magnetic</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Excellent (Aqueous and acidic)</td>
<td>Marginal</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>Tensile/(Flexural strength)</td>
<td>~1000(1500) MPa</td>
<td>1900 MPa</td>
<td>(600 to 1200) MPa</td>
<td>2500 MPa</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>~95 GPa</td>
<td>200 GPa</td>
<td>310 GPa</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>~0.34</td>
<td>0.3</td>
<td>0.27</td>
<td>0.30</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>~20 MPa/√m</td>
<td>22 MPa/√m</td>
<td>5 to 7 MPa/√m</td>
<td>20 to 23 MPa/√m</td>
</tr>
<tr>
<td>Maximum use temp</td>
<td>~400 °C</td>
<td>~400 °C</td>
<td>~1100 °C</td>
<td>~400 °C</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>~1.04×10⁻⁶ Ω-m</td>
<td>~0.60×10⁻⁶ Ω-m</td>
<td>Insulator</td>
<td>~0.18×10⁻⁶ Ω-m</td>
</tr>
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### Remarkable Points
- Modulus is ½ that of tool steel, yet hardness is comparable.
- Immune to rusting, non-magnetic, thermal expansion matches superalloys and steel structural materials.
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<td>60-65 HRC</td>
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<tr>
<td><strong>Indent Stress Limit, GPa</strong></td>
<td>3.0</td>
<td>2.3</td>
<td>Not applicable</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Thermal Conductivity W/m·°C</strong></td>
<td>18</td>
<td>24</td>
<td>33</td>
<td>~36</td>
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<td>600-1200MPa (Bend Strength)</td>
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<td>5-7 MPa/√m</td>
<td>20-23 MPa/√m</td>
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<td><strong>Maximum Use Temp</strong></td>
<td>~500°C</td>
<td>~400°C</td>
<td>~1100°C</td>
<td>~400°C</td>
</tr>
<tr>
<td><strong>Electrical Resistivity</strong></td>
<td>~80x10⁻⁶ Ω-cm</td>
<td>~36x10⁻⁶ Ω-cm</td>
<td>Insulator</td>
<td>~60x10⁻⁶ Ω-cm</td>
</tr>
</tbody>
</table>
Nitinol 60: Attribute Peculiarities

• Unexpected attributes and behavior:
  – Readily lubricated.
  – High resilience.
  – High Hardness.

• Questions:
  – **Tribology**: Titanium (and Nickel) alloys are notoriously difficult to lubricate. They gall, even with lubrication. Why does it lubricate “able”?
  – **Resilience**: NiTi is no harder than 440C. Why does it display superior dent resistance?
  – **Hardness**: NiTi has no carbide or other ceramic forming elements. Why is it hard?
SOT is a rolling tribology test with minimal lubricant that experiences a slight scrub against guide plate once per revolution. SOT mimics instrument ball bearings very well and is used to evaluate materials and lubricants. Tests typically run in vacuum to simulate space environment under boundary lubrication.
60NiTi: Friction and lubricant life testing

• Test confirms that pure titanium and conventional alloys (Ti-6Al-4V) are poor tribological materials.

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

• 60NiTi yields consistently longer lubricant life than 440C.

• 60NiTi is also corrosion proof, non-magnetic and electrically conductive.
The surface of 60NiTi is chemically benign to lubricant molecules but remains sufficiently active to foster boundary lubrication.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Initial Friction, µ</th>
<th>Steady-State Friction, µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castor Oil</td>
<td>0.12</td>
<td>0.008</td>
</tr>
<tr>
<td>Turbine Oil</td>
<td>0.09</td>
<td>0.2</td>
</tr>
<tr>
<td>Seed Oil</td>
<td>0.08</td>
<td>0.034</td>
</tr>
<tr>
<td>Paraffin Oil</td>
<td>0.13</td>
<td>0.037</td>
</tr>
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*Data taken from Zeng et. al (2014)
Nitinol 60: Material Peculiarities

- **Puzzling Mechanical Behavior:**
  - Measured elastic (stress-strain) properties exhibits nearly 10X more deflection than steel.
  - Conventional wisdom: hard and stiff go together yet despite its high hardness, 60NiTi is highly elastic (not so stiff).

- **Question:**
  - What are the reasons behind NiTi’s high hardness yet modest elastic stiffness?

- **Longer term potential:**
  - Could the unique combination (hard yet superelastic) yield new benefits?
  - Could the NiTi materials system be the basis for new applications?
Conventional Metals: Elastic Behavior

- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.
Conventional Metals: Elastic Behavior

Permanent deformation (dent) begins

Slope=$E_{\text{REX20}}$ is 234 GPa

Slope=$E_{\text{440C/52100}}$ is 205 GPa

Slope=$E_{\text{Ti-6V-4Al}}$ is 113 GPa

$\sigma$, stress, GPa

$\varepsilon$, strain, %
60NiTi: Stress-Strain Behavior

The graph shows the stress-strain behavior of various materials, including 440C or 52100 Bearing Steel, Ti-6V-4Al, REX20 Steel, and 60NiTi (E=95GPa). The slope of the 60NiTi line is indicated as 95 GPa. Contact points are high stress and where first permanent damage (dent) occurs.
Low Modulus + Hard: A Technical Opportunity

- **Surprising and relevant behavior:**
  - It is contrary to a century of experience with hard bearing materials!
  - Hard bearing materials are stiff and unforgiving and yield after small deformations.
  - Small contact points result in high stress and damage even under modest loads.
  - Brinell denting test can quantify resilience effect.

Balls touch races at small points causing race surface dents

Dents on race surface cause rough running and premature failure
Resilience: Can 60NiTi withstand high dent loads? (Static denting behavior)

- 60NiTi dent resistance
  - Threshold load to damage
  - Critical to launch vehicles and aircraft
Dent Depth vs. Hertz Contact Stress
(12.7 mm diameter Si₃N₄ ball against 60NiTi plate)

Quiet Running Dent Depth Limit
(dp/D = 0.00005)

σ̄_{avg}, contact stress, GPa

dp, dent depth, μm
60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!
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Nitinol 60: Microstructures - Optical Views

- **Microstructural Elements**
  - Annealed 60NiTi is largely NiTi with substantial Ni$_3$Ti precipitates.
  - Quenched (hardened) 60NiTi appears to be entirely NiTi but X-ray indicates Ni$_4$Ti$_3$. 

Heat treatment: 1000°C + Water Quench
NiTi Alloys: Hardened by naturally formed nanotechnology

• **Takeaway Points**
  - *In-situ* formation of hard nano-scale $Ni_4Ti_3$ particles hardens alloy.
  - Revealed by recent HAADF-STEM analyses.
Recent Advancements: Hf Additions

- **NiTi-Hf (just 1 atomic %)**
  - Same nano-scale $Ni_4Ti_3$ particles hardens alloy.
  - Hf slows down undesirable $Ni_3Ti$ precipitate formation, eliminates water quench and resulting residual stresses.
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Dent and Corrosion Resistant Ball Bearings

Finished 60NiTi-Hybrid Bearing
ISS DA Centrifuge Bearings: 60NiTi Application

Hub side
Motor side
Centrifuge
Compressor

Driver rotor: gear - motor side
Driven rotor: gear - motor side

Drive Motor
Pulleys
Tensioner and Compound
Bearing Testing:
(Warm, wet, slow conditions)

Speed, load, configuration, temperature and moisture match ISS application.
Bearing Testing:
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor

Over 10,000 operating hours has been demonstrated.
DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid

Test Results: 60NiTi bearings turn but don’t rust!
Opportunities: Superelastic Bearings

(ISS Wastewater purifier system offers technology “pull”)

• Superelastics enabling characteristics:
  – Impact load tolerance.
  – Intrinsic corrosion resistance (cannot rust)
  – High static load capability.
  – Non-magnetic but electrically conductive
  – Emerging manufacturing (M&P) database.

• ISS Urine Processor Pathfinder applications:
  – 50mm bore centrifuge bearings (wet, low speed, low load).
  – Compressor drive gears (dry lubed, damp, low load, high speed).
  – 12.7mm compressor bearings (moderate load, high speed, inaccessible location).

• Compressor Bearings
  – Support roots blower lobes.
  – 2000 rpm, high precision.
  – Moisture exposure.
  – Accessible for installation
  – Disassembly loads ball-race contact requiring bearing replacement.
Current Machine Design: Assembly: OK, Removal: Not OK

- Current Bearing: Deep Groove Instrument Design
  - Installation accomplished by pressing on both rings against tight fits.
  - Disassembly achieved by pulling on housings resulting in scrapped bearings.
Superelastic Bearing: Taking Advantage of NiTi Characteristics.

- 60NiTi has more load capability for given geometry:
  - Calculations, computer modeling and subsequent experiments led to a 60NiTi-hybrid bearing that withstands removal forces.
  - Does the bearing perform (life)?

![Press Fitting Practices Diagram]

![Graph showing dent depth vs indentation load for different materials]

Quiet running dent depth limit
(Dent depth = 0.00005 * Ball diameter)
Design Approach: Reusable NiTi R8 Compressor Bearing
(Leverage geometry and materials)

• Materials
  – 60NiTi has static stress limit of 3.1GPa. ~3x the static load capacity of steel.
  – Si$_3$N$_4$ balls match current baseline but reduce load capacity.

• Operating Conditions
  – Moderate speed (2000 rpm), low operating load.
  – Moisture exposure, 5000 hour life requirement.
  – 1.5-2.2kN installation/removal axial load.

• Bearing Geometry
  – Baseline bearing is deep groove ball bearing with conventional internal geometry.
The resulting modified bearing was manufactured by combination of in-house and specialty bearing firm.
• **Rig accurately duplicates materials, fits, loads, speed, and drive mechanism of flight compressor.**
• **Accelerometers on housings to capture vibration signatures for health monitoring.**
• Rig enables evaluation of load effects, speed effects, bearing performance before/after disassembly and re-installation trials.
• **Tests run (24/7) until vibration changes or 10,000 hours reached.**
Removable Superelastic Bearings: Experimental Work

Life Tests:

- 4 NiTi bearings underwent 10,000 hour life test.
- 1,700, 5,000 and 10,000 hour tear-down for visual inspection
  - No damage detected by vibration spectrum, by hand, or visual inspection.
10 000 hr: Bearings like new after 1200 M cycles
-60NiTi bearing races offer 2x (vs. Rex20) to 5x (440C) improvement.
-Adoption of NiTi bearings enables the elimination of half the ball bearings, reducing friction by half with considerable cost and weight savings.
Spherical Bearings: 60NiTi balls-PTFE Liner

Status: Performance tests confirm equivalence to steel with superior corrosion immunity and lower weight.
Summary: More than a Shape Memory Alloy

- Early NiTi investigations sought a better structural alloy and followed conventional evolutionary path.
- Structural properties of Ni-rich alloys were overshadowed by remarkable shape memory behavior. Buehler was visionary but also pragmatic.
- Recent material attribute revelations (dent and corrosion resistance) combined with modern PM processing has created a new market for bearing and mechanical system applications.
- Building upon a strong foundation of SMA knowledge, the structural engineering of Ni-rich alloys is rapidly advancing.
- It is expected that structural applications will grow the entire NiTi industry.
Fe-C system has yielded literally thousands of alloys and variants following centuries of development.

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.
Damage Threshold Load Capacity: Comparison
(1/2” Diameter ball pressed into plate)

Contact Load Capacity, lbs.

Low modulus + high hardness + superelasticity = extreme load capacity
Thank You!