Ni-Ti Alloys for Aerospace Bearing 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.
Materials Requirements: NASA sets the bar high
(Space challenges conventional technology)

- 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)
  - Low density (to reduce centrifugal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture
Bearing Material: State-of-the-Art (SOA)
(Current suite of candidates is severely limited)

• Four general types of bearing materials:
  – Steels (Corrosion resistant steels, martensitic, austenitic)
  – Ceramics (Si$_3$N$_4$ 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).
  - 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.
Technical Properties Comparison: Bearings

<table>
<thead>
<tr>
<th>Property</th>
<th>60NiTi</th>
<th>440C</th>
<th>Si$_3$N$_4$</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>
</tbody>
</table>

- **Primary Points**
  - Modulus is $\frac{1}{2}$ that of steel, yet hardness is comparable.
  - 15% lighter than steel, corrosion resistance of a ceramic.
Nitinol 60: Material Peculiarities

- **Puzzling Mechanical Behavior:**
  - Measured elastic (stress-strain) properties exhibit 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=$E_{REX20}$ is 234 GPa

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

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

ε, strain, %

σ, stress, GPa

440C/52100

Ti-6V-4Al

REX 20
60NiTi: Stress-Strain Behavior

\[ \sigma, \text{stress, GPa} \]

\[ \varepsilon, \text{strain, \%} \]

Slope = \( E_{60\text{NiTi}} \) is 95 GPa
Nitinol 60: Material Peculiarities

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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

Deep Brinell dent.

Threshold load visible dent.
Dent Depth vs. Hertz Contact Stress (12.7 mm diameter Si₃N₄ ball against 60NiTi plate)

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

σ_{avg}, contact stress, GPa

dp, dent depth, μm

Graph showing the relationship between dent depth and contact stress for different materials: 60NiTi, 440C, and REX 20.
60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!
Damage Threshold Load Capacity: Comparison
(1/2” Diameter ball pressed into plate)

Contact Load Capacity, lbs.

Low modulus + high hardness + superelasticity = extreme load capacity
Dent and Corrosion Resistant Ball Bearings

Finished 60NiTi-Hybrid Bearing
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Spherical Bearing Project

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

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

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Environment</th>
<th>Load (ksi)</th>
<th>#Total Cycles</th>
<th>Avg. Torque (in-lb)</th>
<th>Liner Wear (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60NiTi</td>
<td>Dry</td>
<td>34</td>
<td>25,000</td>
<td>193+/-11</td>
<td>0.0019+/-0.0007</td>
</tr>
<tr>
<td>60NiTi</td>
<td>Hydraulic Fluid</td>
<td>26</td>
<td>25,000</td>
<td>192+/-14</td>
<td>0.0026+/-0.0010</td>
</tr>
<tr>
<td>60NiTi</td>
<td>De-Icing Fluid</td>
<td>26</td>
<td>25,000</td>
<td>176+/-11</td>
<td>0.0019+/-0.0011</td>
</tr>
<tr>
<td>440C</td>
<td>Dry</td>
<td>34</td>
<td>25,000</td>
<td>188+/-19</td>
<td>0.0021+/-0.0009</td>
</tr>
</tbody>
</table>
Result: 60NiTi Bearing After Test
ISS DA Centrifuge Bearings: 60NiTi Application

Hub side
Motor side
Centrifuge
Compressor

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

Drives 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!
Summary: NiTi for Aerospace Bearings

- Nickel-rich NiTi alloys for bearing applications are emerging from a long period of R&D dormancy.
- 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.
- Proof of concept demonstrations in spherical sliding bearings and ball bearings in wet applications illustrate the benefits of this new alloy system.
- More applications are anticipated as the technology matures.
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.
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