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

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STLE Frontiers
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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.
Four general types of bearing materials:
- Steels (Corrosion resistant steels, martensitic, austenitic)
- Ceramics ($\text{Si}_3\text{N}_4$ 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).
  - 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.
### Technical Properties Comparison: Bearings

<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>
</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.**
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./\text{(load x distance)}\}

![Tribology Evaluation Diagram](image)
POD-Sliding Wear Results

Dry Sliding-Tribology Data Summary

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

<table>
<thead>
<tr>
<th>Pin Material</th>
<th>Disk Material/Surface Coating</th>
<th>Friction Coefficient</th>
<th>Pin Wear Factor, mm³/N-m</th>
<th>Surface Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP21 Polyimide</td>
<td>316L SS</td>
<td>0.29 +/- 0.07</td>
<td>1.9 +/- 0.7 x 10⁻⁶</td>
<td>Smooth</td>
</tr>
<tr>
<td>SP21 Polyimide</td>
<td>304 SS</td>
<td>0.34 +/- 0.08</td>
<td>0.7 +/- 0.2 x 10⁻⁶</td>
<td>Smooth</td>
</tr>
<tr>
<td>SP21 Polyimide</td>
<td>60NiTi</td>
<td>0.28 +/- 0.04</td>
<td>2.1 +/- 1.5 x 10⁻⁶</td>
<td>Smooth</td>
</tr>
<tr>
<td>60NiTi</td>
<td>60NiTi</td>
<td>0.18 +/- 0.03</td>
<td>8.3 +/- 3.2 x 10⁻⁶</td>
<td>Rough</td>
</tr>
<tr>
<td>60NiTi + SP21</td>
<td>60NiTi</td>
<td>0.15 +/- 0.03</td>
<td>3.1 +/- 1.9 x 10⁻⁶</td>
<td>Smooth</td>
</tr>
<tr>
<td>60NiTi*</td>
<td>PTFE DFL</td>
<td>0.15 +/- 0.02</td>
<td>184-348 km**</td>
<td>Smooth</td>
</tr>
<tr>
<td>60NiTi*</td>
<td>Graphite DFL</td>
<td>0.17 +/- 0.02</td>
<td>24-135 km**</td>
<td>Smooth</td>
</tr>
</tbody>
</table>

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

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

**Inner Race (ball) Drawing**

**Corrosion-Proof Rod bearings**

**Finished inner races**

**Proposed Project**
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

Bearing 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
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.
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!