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

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STLE Frontiers
October 25th, 2015
Denver, Colorado
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 ($\text{Si}_3\text{N}_4$ 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 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.
• 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 \(\text{wear vol.}/(\text{load} \times \text{distance})\)
Dry Sliding-Tribology Data Summary

**POD-Sliding Wear Results**

<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.
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, 0.3in² bearing area}

<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>

*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$_3$Ti).**
- **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.