Microstructural and Material Quality Effects on Rolling Contact Fatigue of Highly Elastic Intermetallic Ball Bearings

Christopher DellaCorte, S. Adam Howard, Fransua Thomas, and Malcolm K. Stanford
NASA, Glenn Research Center
Cleveland, Ohio

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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$_3$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).
  - 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:

<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^{-8} Ω-m</td>
<td>~0.60×10^{-8} Ω-m</td>
<td>Insulator</td>
<td>~0.18×10^{-8} Ω-m</td>
</tr>
</tbody>
</table>

- **Modulus is ½ that of steel, yet hardness is comparable.**
- **Ultra-high static load capacity.**
- **Tensile strength akin to ceramics.**
- **NiTi alloys are brittle but do not rust.**
Contact Engineering: Ball-Race

- **When hard surfaces contact**
  - Forces are transmitted at small, concentrated contact points (Hertz).
  - Resulting stresses cause deformations that help “spread the load”.
  - Contact area is a function of the geometry, material stiffness and load.
  - High stiffness (modulus) inhibits deformations leading to small contact area and high stresses (contrast with a tire contacting the ground).

- **Hard surfaces can dent**
  - *Even modest loads can exceed stress capability limits.*
  - *Bearing raceways are particularly prone to Brinell dent damage.*
• **60NiTi** combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically.

• But what about rolling contact fatigue, **RCF**?
Rolling Contact Fatigue
(Accelerated Test Protocol: 3 Ball-on-Rod)

• 3-Ball test allows for RCF evaluation of new materials prior to investing in the manufacture of full-scale bearings.

Figure 7.4-9. Rolling Contact Fatigue (RCF) Specimen Arrangement in which Steel Bearing Balls are Loaded against a Rotating NiTi Rod. Tests are run until rod damage is detected or 800 hours of operation is reached.
Early Rolling Contact Fatigue: Cast 60NiTi

Modern bearing steels yield long life at 500 ksi (~3.5GPa).

Cast 60NiTi’s life-threshold stress varies widely.

Results linked to material quality.

<table>
<thead>
<tr>
<th>RCF Stress Level, Ksi</th>
<th>Wear Track Width, µm</th>
<th>RCF Life, hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>429</td>
<td>850 +/- 18</td>
<td>5.7 +/- 3.2</td>
</tr>
<tr>
<td>356</td>
<td>701 +/- 25</td>
<td>5.4 (typical)</td>
</tr>
<tr>
<td>266</td>
<td>540</td>
<td>13.8 to 841 (no failure)</td>
</tr>
</tbody>
</table>
• Internal defects such as precipitates and voids are fracture initiation sites for hard bearing materials and must be eliminated through processing and alloying.

• Newly emerging processing expected to lead to enhanced RCF life.
Rolling Contact Fatigue: PM Material?

Powder Metallurgy 60NiTi has fine, uniform microstructure
Rolling Contact Fatigue
(PM Rod Specimen: represents bearing race)

Bearing race surface finish
Rolling Contact Fatigue
(Updated test results: more representative materials)

Modern bearing steels yield long life to at least 3.5GPa.

60NiTi begins to exhibit permanent dents at stresses above ~3.0GPa.

60NiTi’s life limiting fatigue stress is lower (~2GPa) but is adequate for some applications. RCF results highly dependent upon material quality.

<table>
<thead>
<tr>
<th>Rod Specimen</th>
<th>Peak Contact Stress (GPa)</th>
<th>Baseline</th>
<th>Continuous</th>
<th>Stress Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-60NiTi (Baseline)</td>
<td>1.7 GPa</td>
<td>&gt;800 hr</td>
<td>18-847 hr</td>
<td>&lt;20 hr (tests ongoing)</td>
</tr>
<tr>
<td>PM-60NiTi (With inclusions)</td>
<td></td>
<td>131-800 hr</td>
<td>11-800 hr</td>
<td>0.2 to &lt;236 hr</td>
</tr>
<tr>
<td>60NiTi (Cast &amp; hot-rolled)</td>
<td></td>
<td>13-800 hr</td>
<td>&lt;5 hr</td>
<td>&lt;5 hr</td>
</tr>
<tr>
<td>59NiTi + X alloy (Cast)</td>
<td></td>
<td>&gt;800 hr</td>
<td>&gt;800 hr</td>
<td>0.1 to 970 hr</td>
</tr>
<tr>
<td>59NiTi + X Alloy (Cast and extruded)</td>
<td></td>
<td>&gt;800 hr</td>
<td>400 to 800+ hr</td>
<td>0.1 to &lt;31 hr</td>
</tr>
</tbody>
</table>
Rolling Contact Fatigue: PM 60NiTi rod

PM 60NiTi rod running surface after test.
Improperly formed 60-NiTi showing unconsolidated particle boundaries.

Flawed PM60NiTi
1.7GPa RCF Stress Limit

Baseline PM60NiTi
~2.5GPa RCF Stress Limit

Nominal 60-NiTi showing well bonded prior particle boundary

- Microstructure affects RCF stress capability in the 3-Ball test
- Does the effect of quality translate to full-scale bearings?
Centrifuge Bearings: 50mm bore 60NiTi Hybrid

Two batches of bearings fabricated

- Low Quality 60NiTi (2011)
- High Quality 60NiTi (2013)

- Quality level affected 3-ball RCF stress capability.
- Does the effect of quality translate to full-scale bearings?
Pair of 50mm hybrid (60NiTi races, Si$_3$N$_4$ balls) ball bearings, 90 pound axial preload (~1.1 GPa stress).

- 200 rpm, continuous turning, torque measurements.
- Accelerometer with hourly vibe spectrum data capture used for health monitoring.
- Tests continued (24/7) until vibration changes or 5000 hours reached.
Life Test #1: Low Quality 60NiTi, 1156 hours

- Test began normally, low torque, smooth operation.
- Inspection after 600 hours. Bearing surfaces and lubricant in as-new condition.
- At 1156 hours, rig making noise. Full inspection of bearings.
- Fatigue damage, debris contaminated grease.

Inner race pit

Outer race pit and cross-race crack
Life Test #1: Low Quality 60NiTi

Outer race crack propagation through entire race.
Life Test #2: High Quality 60NiTi
Life Test #2: Vibration plot at 1100 hours

- Typical vibration cascade plot for three day period shown below:

- 3.2 Hz-shaft rpm
- 22 Hz-rig support brg
- 24 Hz-ball pass frequency
- 37 Hz-rig support brg
• 1100 hour inspection-all surfaces and lubricant in as-new condition
• Bearings re-greased and returned to test.
Life Test #2: Inspection at 5000 hours

- Lubricant grease looks new, no visible wear or damage on races.
Bearing Life Test: Inspection at 5000 hours

- Inner race surfaces shiny and without any apparent wear or other signs of contact damage.
Bearing Life Test: Inspection at 5000 hours

- Outer race looks fine too.

- Bearings were cleaned, visually inspected, re-greased and re-started.
- Health monitoring (torque and vibration) used to indicate failure.
- Tests to be halted at 10,000 hours.
Summary Remarks

• Sub-component RCF tests indicate relation between material quality and stress capability.
• Full-scale bearing life tests corroborate the sub-component tests.
• High quality 60NiTi, largely free from inclusions and other flaws can provide long running life under modest continuous stress levels.
• NiTi bearing materials offer several unique attributes (high static load capability and corrosion resistance) that make them attractive candidates for space mechanisms.
• As the technology matures, the growing knowledge-base coupled with alloy improvements will enable expanded use of these new materials allowing designers to take advantage of NiTi’s unique capabilities.
Thank You!
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