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

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71st STLE Annual Meeting
May 17th, 2016
Las Vegas, CA
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>Si₃N₄</th>
<th>M-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density g/cc</td>
<td>6.7</td>
<td>7.7</td>
<td>3.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Hardness HRC</td>
<td>56 to 62</td>
<td>58 to 62</td>
<td>1300 to 1500</td>
<td>60 to 65</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 10⁻⁶/°C</td>
<td>~11.2×10⁻⁶</td>
<td>10×10⁻⁶</td>
<td>2.6×10⁻⁶</td>
<td>~11×10⁻⁶</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</td>
<td>Marginal</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>Tensile/(Flexural strength)</td>
<td>~1000(1500)</td>
<td>1900</td>
<td>(600 to 1200)</td>
<td>2500</td>
</tr>
<tr>
<td>Young’s Modulus GPa</td>
<td>~95</td>
<td>200</td>
<td>310</td>
<td>210</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 MPa/√m</td>
<td>~20</td>
<td>22</td>
<td>5 to 7</td>
<td>20 to 23</td>
</tr>
<tr>
<td>Maximum use temp °C</td>
<td>~400</td>
<td>~400</td>
<td>~1100</td>
<td>~400</td>
</tr>
<tr>
<td>Electrical resistivity Ω-m</td>
<td>~1.04×10⁻⁶</td>
<td>~0.60×10⁻⁶</td>
<td>Insulator</td>
<td>~0.18×10⁻⁶</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
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 V-Preliminary rolling contact fatigue (RCF) life for 60NiTi rods (loaded against M50 steel balls, 3600 rpm, mineral oil lubricant).

<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>
Rolling Contact Fatigue:
Early cast 60NiTi rod microstructure

• 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)
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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.7 GPa</td>
</tr>
<tr>
<td></td>
<td>2.5 GPa</td>
</tr>
<tr>
<td></td>
<td>3.3 GPa</td>
</tr>
<tr>
<td></td>
<td>4.1 GPa</td>
</tr>
<tr>
<td>PM-60NiTi (Baseline)</td>
<td>&gt;800 hr</td>
</tr>
<tr>
<td></td>
<td>18-847 hr</td>
</tr>
<tr>
<td></td>
<td>&lt;20 hr (tests ongoing)</td>
</tr>
<tr>
<td></td>
<td>&lt;0.3 hr</td>
</tr>
<tr>
<td>PM-60NiTi (With inclusions)</td>
<td>131-800 hr</td>
</tr>
<tr>
<td></td>
<td>11-800 hr</td>
</tr>
<tr>
<td></td>
<td>0.2 to &lt;236 hr</td>
</tr>
<tr>
<td></td>
<td>------</td>
</tr>
<tr>
<td>60NiTi (Cast &amp; hot-rolled)</td>
<td>13-800 hr</td>
</tr>
<tr>
<td></td>
<td>&lt;5 hr</td>
</tr>
<tr>
<td></td>
<td>&lt;5 hr</td>
</tr>
<tr>
<td></td>
<td>------</td>
</tr>
<tr>
<td>59NiTi + X alloy (Cast)</td>
<td>&gt;800 hr</td>
</tr>
<tr>
<td></td>
<td>&gt;800 hr</td>
</tr>
<tr>
<td></td>
<td>0.1 to 970 hr</td>
</tr>
<tr>
<td></td>
<td>------</td>
</tr>
<tr>
<td>59NiTi + X Alloy (Cast and extruded)</td>
<td>&gt;800 hr</td>
</tr>
<tr>
<td></td>
<td>400 to 800+ hr</td>
</tr>
<tr>
<td></td>
<td>0.1 to &lt;31 hr</td>
</tr>
<tr>
<td></td>
<td>------</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?
Life Test: 50mm Hybrid NiTi Bearing

- 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
Life Test #2: High Quality 60NiTi-1100 hours

- 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.
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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