The Effect of Indenter Radius on the Static Load Capacity of the Superelastic 60NiTi for Rolling Element Bearings

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Motivation: the ride into space can be rough
(Vibration/loads impact bearings and components)

- Bearing and component materials must be:
  - 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 centripetal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture
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.
Ball-Race Static Load Capacity: Leveille & Murphy
(Dent depth vs. running torque noise)

- Classic 1973 paper on dent depth/ball diameter (dp/D) effects
  - Showed that dp/D~0.0001 criterion too aggressive for precision bearings with respect to torque ripple. Proposed dp/D~0.00003 to 0.00005
Contact Engineering: Geometry, Loads and Materials

• Engineering Mitigations
  – Reduce loads through vibration isolation.
  – Reduce the stresses through margin additions such as increased bearing size and increased ball-race conformity.
  – Use harder materials less prone to denting.

• Implications
  – Load reduction and vibration isolation can add mass.
  – Bearing design and material changes introduce other complications.
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 (Si₃N₄ 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 Ordinance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordinance 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:

<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 (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</td>
<td>10</td>
<td>2.6</td>
<td>~11</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 (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>

**Primary Points**

- *Modulus is $\frac{1}{2}$ that of steel, yet hardness is comparable.*
- *Tensile strength akin to ceramics.*
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

Conventional Metals: Elastic Behavior
60NiTi: Stress-Strain Behavior

Slope = $E_{60\text{NiTi}}$ is 95 GPa

440C or 52100 Bearing Steel
Ti-6V-4Al
REX20 Steel
60NiTi (E=95GPa)
Brinell Test: Elucidates static load capacity

- How well does 60NiTi resist dents?
  - Brinell number
  - 12.7mm diameter Si$_3$N$_4$ ball
  - dp/D vs. stress (Leveille)
Typical Result: 60NiTi-Superelastic
(Dent barely visible to unaided eye)

1500Kg (3300lb) load on 12.7mm diameter Si$_3$N$_4$ ball yields dent that is barely visible to the unaided eye but clearly defined by profilometry.
Dent Depth vs. Hertz Contact Stress
(12.7 mm diameter Si₃N₄ ball against 60NiTi plate)

dp, dent depth, μm

σ_{avg}, contact stress, GPa

Quiet Running Dent Depth Limit
(dp/D = 0.00005)
Dent Depth vs. Load
(12.7 mm diameter Si₃N₄ ball against 60NiTi plate)

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

W, indentation load, Kgf

dp, dent depth, µm
Damage Threshold Load Capacity: Comparison
(12.7mm diameter ball pressed into plate)

**Indent test**

- **Can’t Rust**
  - STELLITE 6B
  - Si$_3$N$_4$ Balls
  - Contact Load Capacity, lbs. 22
- **Can’t Rust**
  - 440C
  - 60NiTi Balls
  - Contact Load Capacity, lbs. 60NiTi 331
- **Does Rust**
  - M50
  - Contact Load Capacity, lbs. 331
- **~800**
  - 440C
  - Contact Load Capacity, lbs. 440C 331
- **331**
  - M50
  - Contact Load Capacity, lbs. 1102
- **22**
  - 60NiTi
  - Contact Load Capacity, lbs. 60NiTi ????

**Ball material**

- **Can’t Rust**
  - 60NiTi
- **Won’t Dent**
  - Si$_3$N$_4$

**Race material**

Low modulus + high hardness + superelasticity = extreme load capacity
Brinell Test: Effect of ball diameter?

- Do the dent limit results extend beyond a 12.7mm ball?
- Do the Hertz relations apply to superelastic materials?
Indent Plates: Cast 60NiTi-Superelastic (Heat treated to ~60 Rockwell C)

As-received 60NiTi (lighter phase is Ni₃Ti). Heat-treated 60NiTi.

Clean and uniform microstructure yields highly polished, flat plate test specimens on which even small dents not readily visible can be measured.
Test Set-Up: Cast 60NiTi-Superelastic
(Provides repeat experiments)

Carefully planned “dent” map and specimen numbering and fixture system allowed location of dents possible.
Tabular Results: 60NiTi-Superelastic
(Si3N4 indenters from 6.35 to 12.7mm)

<table>
<thead>
<tr>
<th>Load, Kg</th>
<th>6.35mm (1/4”) ball</th>
<th>7.94mm (5/16”) ball</th>
<th>9.52mm (3/8”) ball</th>
<th>12.7mm (1/2”) ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Stress, GPa</td>
<td>Dent Depth (dp), μm</td>
<td>dp/D x10^-3</td>
<td>Mean Stress, GPa</td>
</tr>
<tr>
<td>50</td>
<td>2.65</td>
<td>0.11</td>
<td>0.017</td>
<td>2.3</td>
</tr>
<tr>
<td>100</td>
<td>3.35</td>
<td>0.56</td>
<td>0.088</td>
<td>2.9</td>
</tr>
<tr>
<td>150</td>
<td>3.83</td>
<td>1.50</td>
<td>0.236</td>
<td>3.3</td>
</tr>
<tr>
<td>200</td>
<td>4.20</td>
<td>2.30</td>
<td>0.365</td>
<td>3.6</td>
</tr>
<tr>
<td>250</td>
<td>4.54</td>
<td>3.60</td>
<td>0.564</td>
<td>3.9</td>
</tr>
<tr>
<td>300</td>
<td>4.83</td>
<td>5.30</td>
<td>0.84</td>
<td>4.15</td>
</tr>
<tr>
<td>350</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>400</td>
<td>---</td>
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<tr>
<td>450</td>
<td>---</td>
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<tr>
<td>500</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>550</td>
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</tr>
</tbody>
</table>

Dent load ranges differed with indenter size to target stress range of interest (2.0-4.0GPa).
Effects of Indenter Diameter

Dent Depth vs. Stress: 6.4 to 12.7mm $Si_3N_4$ indenter balls

- Implications
  - Hertz stress relations work well for hard balls against flat plates.
  - Data curve can be used to guide bearing detailed design.
• 60NiTi has been successfully fabricated into precision bearing balls and races.
• 60NiTi is hard yet has a low elastic modulus and large elastic deformation range enabling high static load capacity.
• Combination of aqueous corrosion immunity, non-magnetic and electrical conductivity not found in any other hard bearing material.
• Low modulus and high elasticity of superelastic gives it more load capacity than that inferred from hardness alone.
• Carefully planned and conducted denting experiments quantify stress-damage relationship.
• Results can be used to guide detailed bearing design.
Thank You!