Tribological Evaluation of Candidate Gear Materials Operating under Light Loads in Highly Humid Conditions

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Opportunities: Superelastic Bearings and Gears

( ISS Wastewater purifier system offers technology “pull” )

- **Required characteristics:**
  - Impact load tolerance.
  - Intrinsic corrosion resistance (cannot rust)
  - High static load capability.
  - No toxic materials.

- **ISS Urine Processor Pathfinder applications:**
  - 50mm bore centrifuge bearings (wet, low speed, low load).
  - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).
  - Compressor drive gears (dry lubed, damp, low load, high speed).

**Earlier Investigations**

- Compressor Gears
  - Drives roots blower lobes.
  - 2000 rpm, high precision.
  - Moisture exposure.
  - Contacts process stream (must be non-toxic).
Technical Requirements:
(Material properties needed for bearings/gears)

- Bearing and gear materials must be:
  - Hard (Rockwell C58 or better)
  - Wear-resistant and compatible with existing lubricants
  - Resistant to 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
Mechanical Component Materials: State-of-Art (SOA)
(Current suite of candidates is severely limited)

- **Four general types of bearing and gear 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.
Superelastics: NiTi based intermetallics
(Hard but resilient material related to shape memory alloys)

- **60NiTi Basics: market name NiTiNOL 60**
  - W.J. Buehler invented NiTiNOL in the 1950’s. Acronym for Ni-Ti-Naval-Ordnance-Laboratory.
  - 60NiTi (60 wt% Ni) is the baseline composition. Alloying with Hf, Zr, and Ta improves microstructure and processing.
  - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
  - Closely related to the shape memory alloys, like NiTiNOL 55, but dimensionally stable.
  - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
  - Brinell damage threshold load (pounds, kgf) is significantly (3-5X) higher than steel.
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</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>

- **Modulus is ½ that of steel, yet hardness is comparable.**
- **Tensile strength akin to ceramics.**
- **Does not rust. Enhanced static load capacity.**
Opportunities: Superelastic Bearings and Gears (ISS Wastewater purifier system offers technology “pull”)

- Superelastic enabling characteristics:
  - Impact load tolerance.
  - Intrinsic corrosion resistance (cannot rust).
  - High static load capability.
  - Non-magnetic but electrically conductive.
  - Emerging manufacturing (M&P) database.

- ISS Urine Processor Pathfinder applications:
  - 50mm bore centrifuge bearings (wet, low speed, low load).
  - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).
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Earlier investigations:

- 60NiTi gears

Question #1: Can we make 60NiTi gears?

Compressor Gears
- Drives roots blower lobes.
- 2000 rpm, high precision.
- Moisture exposure.
- Contacts process stream (must be non-toxic).
Gear Manufacturing: Multi-step process

- **Ingot:** Hot Isostatic Press (HIP) of pre-alloyed powder
  - Wire EDM slice to gear thickness.
  - Take metallography samples for QC
  - Heat treat QC samples and verify hardness and microstructure
  - EDM drill wire starter holes.
  - Cut rough gear tooth shape.
  - Emerging manufacturing (M&P) database.

60NiTi Ingot

60NiTi Ingot Slice

Wire Cut Blanks

M&P-QC
Metallography

Microstructure and quality verified.
Method: Wire Electrode Discharge Machining (EDM)

Modern computer controlled (EDM) with gear tooth program

Water submerged electrode

Wire slowly moves through ingot slice like a cheese cutter
Method: Wire Electrode Discharge Machining (EDM)
Turning: Carbide tool turning (lathe) to near finish dimensions
Fixtures: Lathe jaws machined in place to maximize accuracy

**Approach:** Jaw pins “between teeth” used to locate gear

**Next Steps:** Drill through holes and heat treat to harden.

**Question #2:** Can we solid lubricate 60NiTi gears?
Challenges: Gear Problems
(Drive gears are life-limiting component)

• Gear requirements:
  – Run without oil & grease lubrication.
  – Withstand moist, acidic environment.
  – High dimensional precision and stability.
  – Low wear, no toxic materials.
  – Baseline is stainless steel meshed with polyimide gear.

• Approach:
  – Simulate stainless-polyimide tooth mesh contact with pin-on-disk.
  – Evaluate 60NiTi as a hard, corrosion immune candidate gear material.
  – Establish feasibility of using dry film lubricant (DFL) to mitigate friction and wear.

• Compressor Gears
  – Drives roots blower lobes.
  – 2000 rpm, high precision.
  – Moisture exposure.
  – Contacts process stream (must be non-toxic).
GEARS-Tribology Simulation

• 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})\}

![Diagram of test setup]

- **Test Load**: (TBD N)
- **Polyimide Pin**
- **300 series SS Disk**
- **Disk Rotation**: (TBD m/s)
Influencing the sliding velocity of plastic non-conventional gear spur gears is essential. There are two main factors that determine the friction force generated: the contact area and sliding velocity. One method that has been used to determine the influence of the contact area, and the effect of varying sliding velocity with and without lubrication is called the pin-on-disc test. This test involves sliding a cylindrical pin against a flat disc under controlled conditions. The friction force generated is then measured, and the sliding velocity is varied to determine its effect on the friction force.

The pin-on-disc test is a simple and widely used method for determining the influence of sliding velocity on the friction force. However, it has some limitations. First, the contact area is fixed, and the contact pressure is not constant. Second, the test is conducted under dry conditions, which may not accurately represent real-world conditions. Therefore, it is important to consider the influence of other factors, such as lubrication and contact pressure, to determine the true influence of sliding velocity on friction force.

This study aims to investigate the influence of sliding velocity on the friction force of non-conventional gear spur gears under lubricated conditions. The test was conducted under varying sliding velocities, and the friction force was measured. The results showed that the friction force increased with increasing sliding velocity, and the effect was more pronounced at lower contact pressures. This suggests that sliding velocity is a critical factor in determining the friction force of non-conventional gear spur gears, and it should be considered when designing such gears.

In conclusion, the study demonstrated that sliding velocity is a significant factor in determining the friction force of non-conventional gear spur gears. However, future studies should consider the influence of other factors, such as lubrication and contact pressure, to better understand the friction force behavior. This knowledge can help in designing more efficient and reliable gear systems.

*Three related papers offer analyses and equations to estimate sliding velocity and load.*
*Selected sliding conditions: 4.9N load, 2.7m/s velocity
• 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)}\}

*Selected sliding conditions: 4.9N load, 2.7m/s velocity
**GEARS-Tribology Simulation**

*Selected sliding conditions: 4.9N load, 2.7m/s velocity*

### Table I-Test Condition Evaluation-Friction and wear surface appearance

(Air at 25°C, 50-60% relative humidity)

<table>
<thead>
<tr>
<th>Trial Load (N)</th>
<th>Trial Speed (m/s)</th>
<th>Friction Range</th>
<th>Surface Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>1.35</td>
<td>0.18-0.25</td>
<td>Smooth</td>
</tr>
<tr>
<td>4.9</td>
<td>2.70</td>
<td>0.25-0.36</td>
<td>Smooth</td>
</tr>
<tr>
<td>9.8</td>
<td>1.35</td>
<td>0.2-0.30</td>
<td>Rough to smooth</td>
</tr>
<tr>
<td>9.8</td>
<td>2.70</td>
<td>0.5-0.6</td>
<td>Rough</td>
</tr>
<tr>
<td>14.7</td>
<td>1.35</td>
<td>0.5-0.9</td>
<td>Rough</td>
</tr>
<tr>
<td>14.7</td>
<td>2.70</td>
<td>0.3-0.5</td>
<td>Rough</td>
</tr>
</tbody>
</table>

**Test Load**

(4.9, 9.8, 14.7N)

**Polyimide Pin**

**300 Series SS Disk**

**Disk Rotation**

(500, 1000rpm)

{1.35, 2.70m/s}
Solid Film Lubrication Concept

• Deposit special purpose dry film lubricant (DFL) onto gear teeth after grinding.
• Technique common practice in space mechanisms.
• Life must be determined through test.
• Use of non-galling gear materials (i.e., 60NiTi in place of 316SS) recommended.

Diagram:
- Test Load
- Overcoat 60NiTi surface with solid film lubricant
- Disk Rotation
Transfer Film Lubrication: COMPRESSOR GEARS

Transfer Film Concept

- Polyimide idler gear to replenish DFL
- Added if DFL alone doesn’t yield adequate gear life.

*1964 Bowen Paper shows idler gear lubrication
Transfer Film Solid Lubrication Concept

• Similar to bearing lubrication via transfer from the cage.

• Technique well described in early space mechanism literature but its current use is largely unknown.
Transfer Film + Solid Lubrication Concept

Proposed Approach*: 60NiTi Gear (Coated with DFL)

Pin-on-Disk Simulation:
DFL coated 60NiTi Disk (Polyimide transfer from pin)

60NiTi Pin
Test Load
Lubricant Deposition (Light Load)

Polyimide Pin

*Polyimide idler gear proposed if DFL life proves inadequate.
GEARS-Tribology Data Summary

**POD-Sliding Wear Results**

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>
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<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>
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<tr>
<td>SP21 Polyimide</td>
<td>304 SS</td>
<td>0.34 +/- 0.08</td>
<td>0.7 +/- 0.2 x 10⁻⁶</td>
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<tr>
<td>SP21 Polyimide</td>
<td>60NiTi</td>
<td>0.28 +/- 0.04</td>
<td>2.1 +/- 1.5 x 10⁻⁶</td>
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<td>60NiTi</td>
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<td>0.18 +/- 0.03</td>
<td>8.3 +/- 3.2 x 10⁻⁶</td>
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<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>
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*Tests initiated with pre-worn pin (~3mm dia. Wear scar).

**Tests terminated when DFL wore through to substrate. No additional pin wear was observed.*
**Recommendation:** 60NiTi gear set with PTFE-based DFL

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

- Pin-on-disk testing was a rapid and convenient method to simulate polymer-metal gear tribology under lightly loaded conditions.
- Literature based models yielded test conditions that gave smooth tribo-surface characteristics representative of the target application.
- The polyimide material exhibited self-lubricating behavior in sliding against stainless steel and 60NiTi.
- PTFE based dry film lubricant coatings provided long-life, low friction performance superior to graphite based coatings but comparable to the polyimide.
- The use of a sacrificial polyimide slider for transfer film lubrication may be an effective means to replenish lubricant to the primary gear tooth surfaces.
- Full-scale gear tests are now needed to corroborate the pin-on-disk tests leading to an engineering decision point.
Thank You!