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
• 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>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^{-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).
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Earlier investigations

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Question #1: Can we make 60NiTi gears?
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
Method: Wire Electrode Discharge Machining (EDM)

Water submerged electrode

Modern computer controlled (EDM) with gear tooth program

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.
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  - 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 {wear vol./(load x distance)}
1. Introduction

With growing awareness of engineering polymers, there is increasing application of polymers and polymeric composites to machine elements. The ability to economically manufacture and run un lubricated contacts at increasing temperatures through the use of high temperature polymers such as poly-ether-ether-ketone (PEEK) is making their application more desirable.

The majority of published work on the tribology and wear of non-conformal polymer pairs relate to the performance of gears. For a pair of gears, the dominant operating parameters such as sliding velocity and load, and the geometry of the contacting surfaces vary with the contact position on the tooth profile. Consequently, gear action is a very complicated process to understand. An alternative method of studying gear action is to apply the same load and speed conditions to a much simpler geometry. An example of such a simulation is the use of cylindrical discs rubbing against each other in edge-to-edge contact, each rotating at different speeds. By varying the relative speeds of the discs (i.e. changing the ratio of sliding to rolling velocity conditions) one can study the influence of these factors on the frictional force and torque generated by the contact.

**INFLUENCE OF A NON-STANDARD GEOMETRY OF PLASTIC GEAR ON SLIDING VELOCITIES**

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**ABSTRACT**

In this paper the sliding velocities of plastic non-conventional gears are analyzed. The main aim was to take into account when metal gear pairs are replaced by polymer pairs to analyze the influence of the non-conventional gears on the sliding velocity. Different rubbing angles between the non-standard teeth cause the influence of the tooth geometry on sliding velocity variation, a particular criteria for a further study on the optimization of the gear geometry.

**KEYWORDS:** Non-standard curved face width spur gear, plastic gear, sliding velocity

**1. INTRODUCTION**

Curved face width spur gears, with variable tooth height along the gear face width [1] are especially designed for plastic gears in order to increase their transmissible power level. The advantages of these gears, compared to standard spur gears are:
- higher contact ratio for a given size of gear and number of teeth;
- lower bending and contact stresses;
- better noise and smoother running conditions.

In this paper the authors analyzed the modified tooth geometry of the curved face width spur gears, with modified geometry, pointed out the peculiar thermal behavior of the non-standard gears. The sliding velocity of the gear pair was taken into account as a variable factor which affects the gear temperature. It was shown that the use of curved teeth reduced the gear temperature and increased the life of the gear pair. The authors also noted that the non-standard gears were more resistant to wear compared to the standard gears.

**Experimental work carried out by the authors on the running curved face width spur gears, with modified geometry, pointed out the peculiar thermal behavior of the non-standard gears.** With these non-standard gears, running at high loads where conventional spur gears would fail, the gear surface temperature increased at an extremely high rate. It was recommended that the manufacturer should consider using the curved teeth geometry for high-speed applications.
Selection of sliding conditions: 4.9 N load, 2.7 m/s velocity
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 \(\text{wear vol.}/(\text{load} \times \text{distance})\)

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

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

<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>
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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.
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)

**Polyimide Idler Gear (Lubricant Source)**

**60NiTi Pin**

**Test Load**

**Lubricant Deposition** (Light Load)

**Polyimide Pin**

**Disk Rotation**

*Polyimide idler gear proposed if DFL life proves inadequate.*
**POD-Sliding Wear Results**

*Tests initiated with pre-worn pin (~3mm dia. Wear scar).
**Tests terminated when DFL wore through to substrate. No additional pin wear was observed.*

GEARS-Tribology Data Summary

**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>
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<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>
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<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>
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<tr>
<td>60NiTi + SP21</td>
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<td>0.15 +/- 0.03</td>
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<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>
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Recommendation: 60NiTi gear set with PTFE-based DFL

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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!