Ni-Ti Alloys for Aerospace Bearing Applications

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Aerospace Bearing Needs:

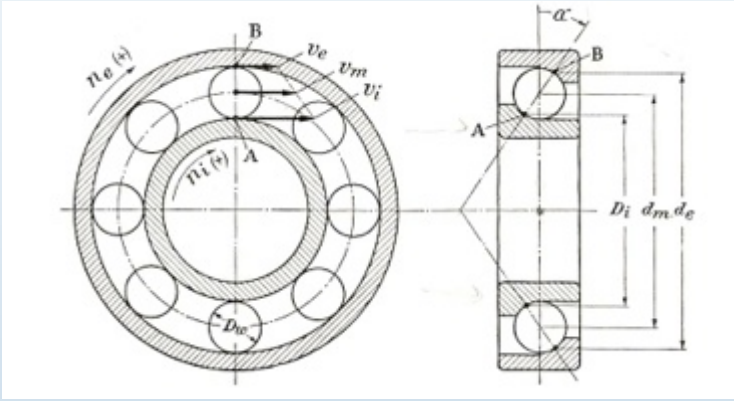
(Performance and attribute goals)

- Reduced weight propulsion and control systems:
  - Lighter weight materials
  - Higher power density designs
  - Higher transient load capability materials
- Corrosion Proof Components:
  - Exposed aircraft control surface hardware and bearings
  - Extreme environments (marine operation, search and rescue)
  - Long term storable bearings and components
  - Elimination of toxic coatings and expensive and complex processes
- Debris Tolerant Contacting Materials:
  - Bearings and gears not subject to secondary damage from debris.
  - Enable operation without coatings and super-clean oils.

Materials Requirements: NASA sets the bar high

(Space challenges conventional technology)

- **Attributes sought:**
  - 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 centrifugal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture



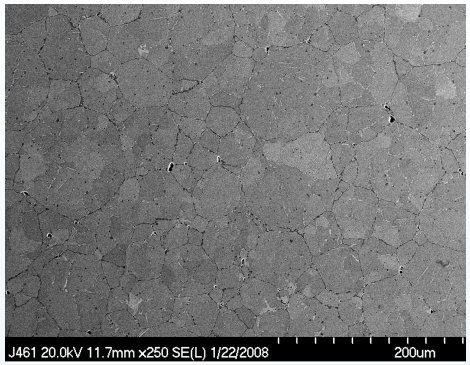
Bearing Material: State-of-the-Art (SOA)
(Current suite of candidates is severely limited)

- Four general types of bearing materials:
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_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).
  - 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.



60NiTi microstructure

Highly polished 60NiTi bearing balls

Technical Properties Comparison: Bearings

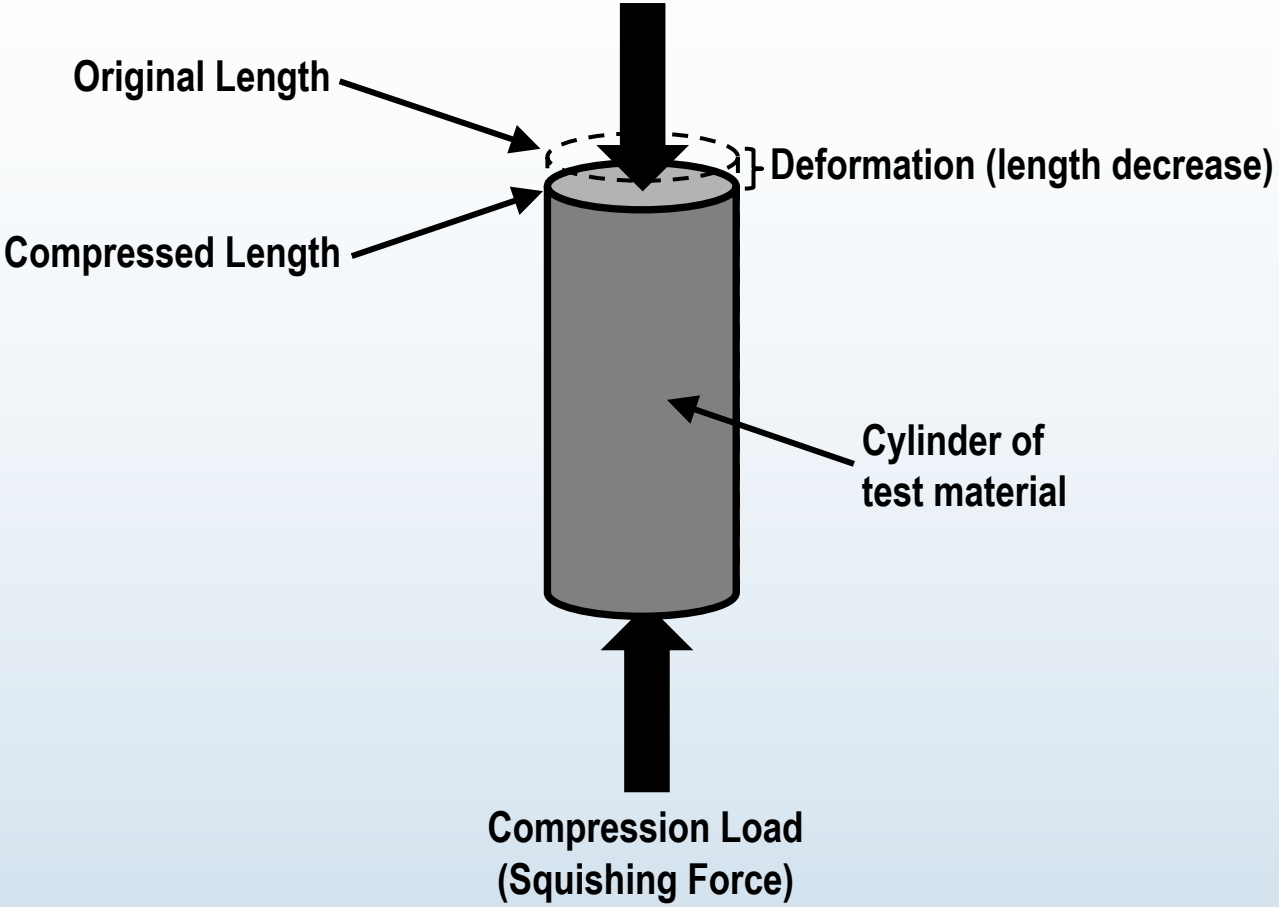
Property	60NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m-°K	~9 to 14	24	33	~36
Thermal expansion	~11.2×10^{-6}/°C	10×10^{-6}/°C	2.6×10^{-6}/°C	~11×10^{-6}/°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	~1.04×10^{-6} Ω-m	~0.60×10^{-6} Ω-m	Insulator	~0.18×10^{-6} Ω-m

- ***Primary Points***
  - ***Modulus is ½ that of steel, yet hardness is comparable.***
  - ***15% lighter than steel, corrosion resistance of a ceramic.***

Nitinol 60: Material Peculiarities

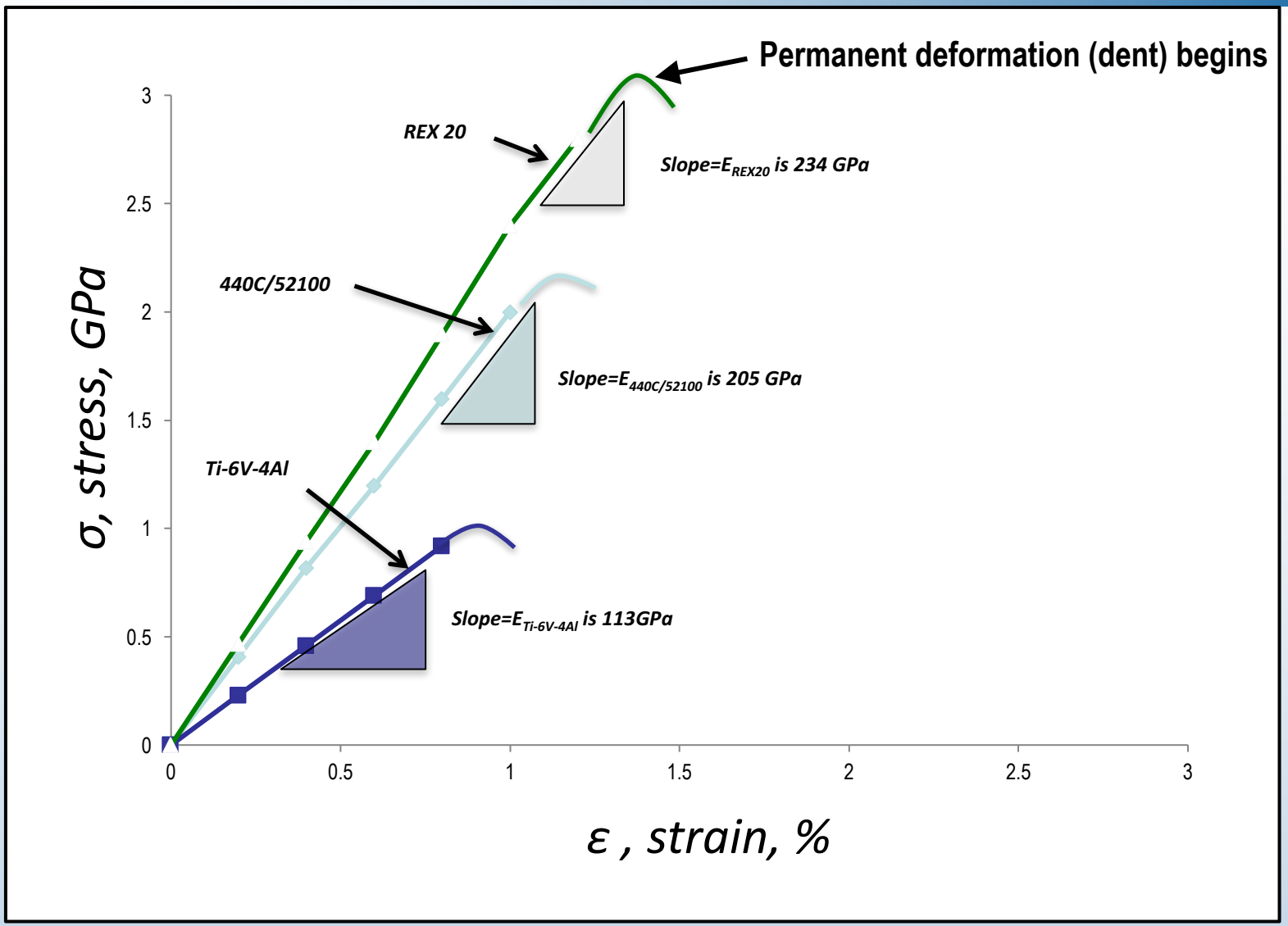
- **Puzzling Mechanical Behavior:**
  - Measured elastic (stress-strain) properties exhibits nearly 10X more deflection than steel.
  - Conventional wisdom: hard and stiff go together yet despite its high hardness, 60NiTi is highly elastic (not so stiff).
- **Question:**
  - What are the reasons behind NiTi's high hardness yet modest elastic stiffness?
- **Longer term potential:**
  - Could the unique combination (hard yet superelastic) yield new benefits?
  - Could the NiTi materials system be the basis for new applications?

Conventional Metals: Elastic Behavior

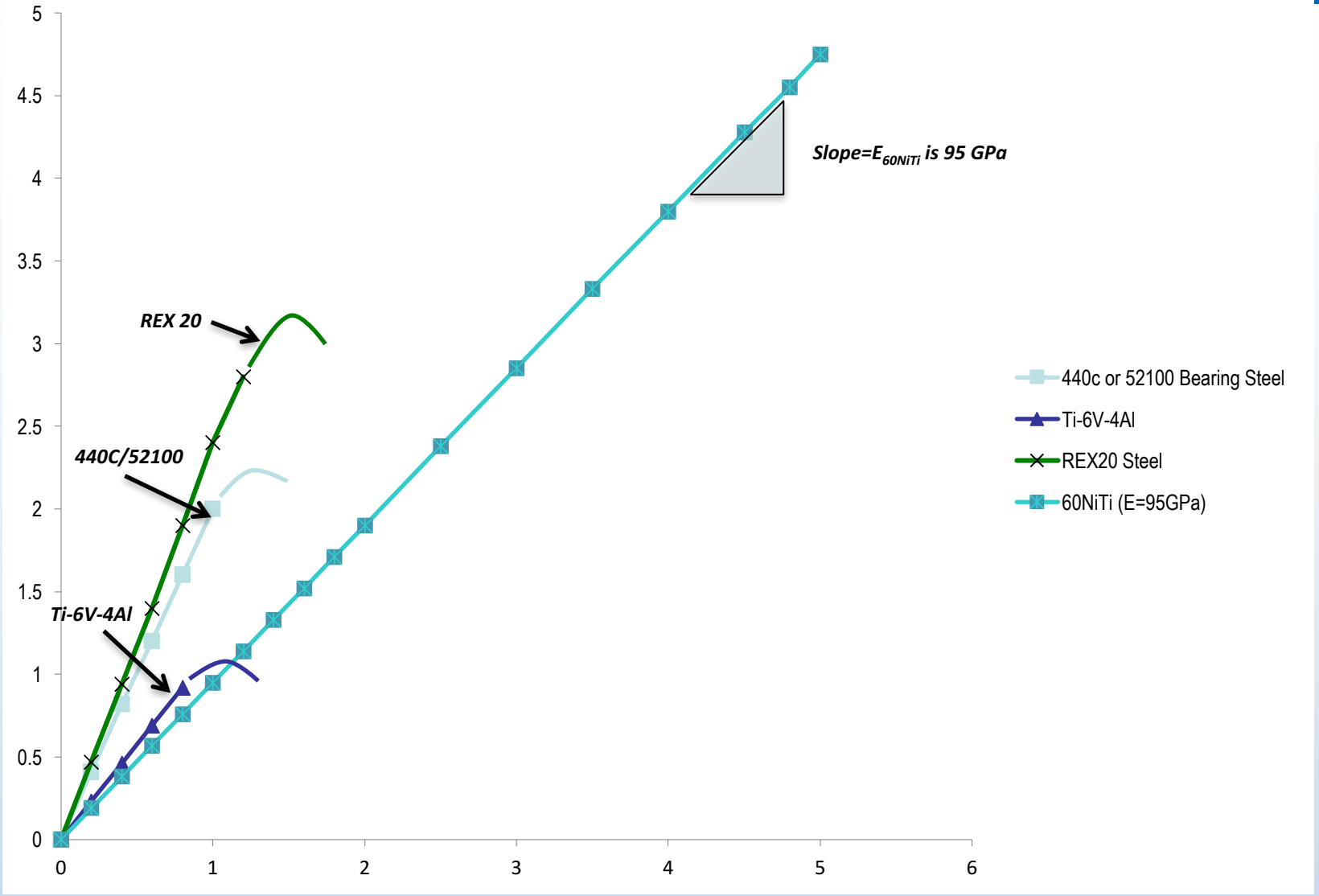


- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior



60NiTi: Stress-Strain Behavior



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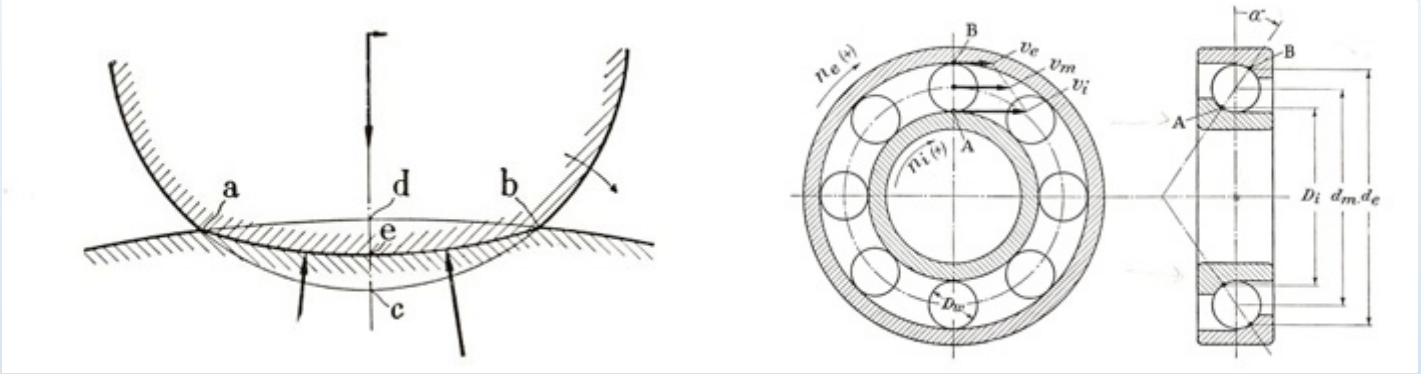
Low Modulus + Hard: A Technical Opportunity

- **Surprising and relevant behavior:**
  - **It is contrary to a century of experience with hard bearing materials!**
  - **Hard bearing materials are stiff and unforgiving and yield after small deformations.**
  - **Small contact points result in high stress and damage even under modest loads.**
  - **Brinell denting test can quantify resilience effect.**



Balls touch races at small points causing race surface dents

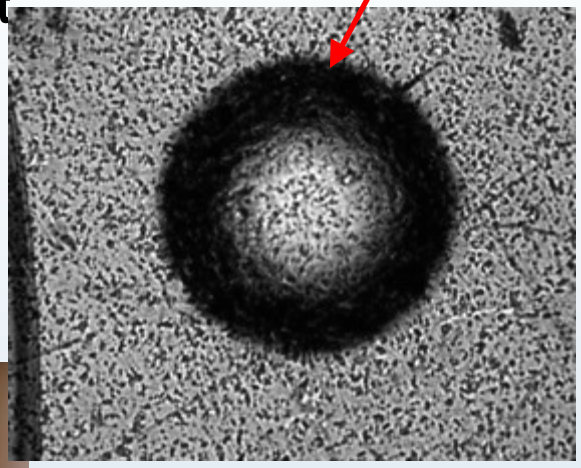
Dents on race surface cause rough running and premature failure

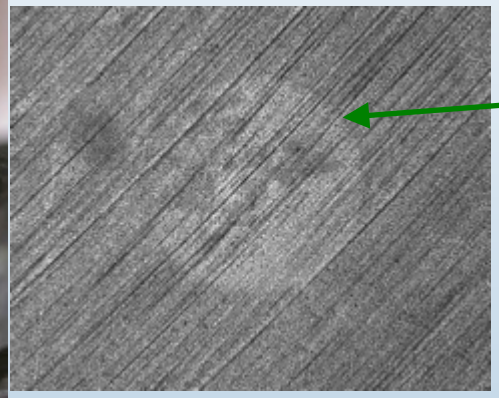
Resilience: Can 60NiTi withstand high dent loads?

(Static denting behavior)

- 60NiTi dent resistance
  - Threshold load to damage
  - Critical to launch vehicles and aircraft

Deep Brinell dent.



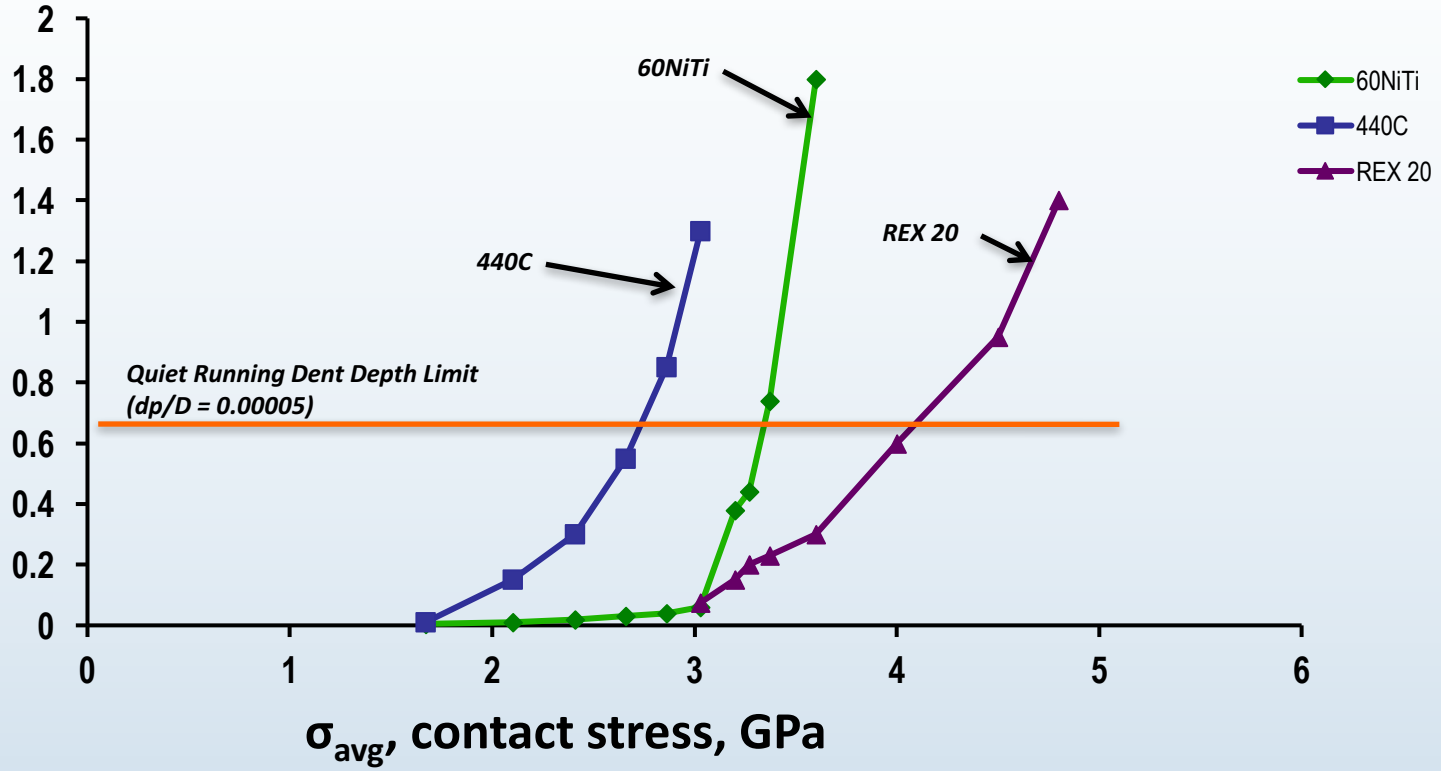


Threshold load visible dent.

Dent Depth vs. Hertz Contact Stress

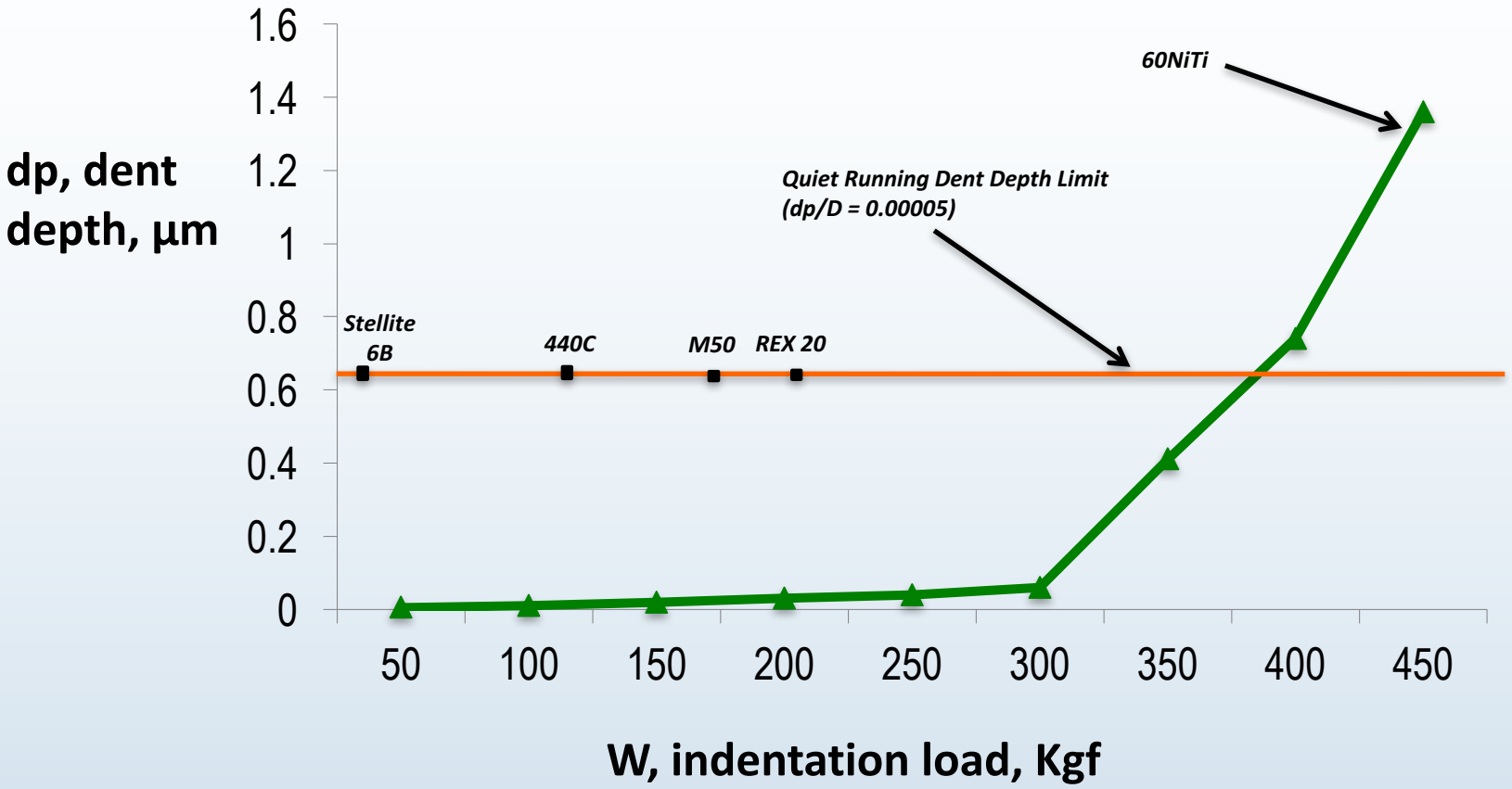
(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)

dp, dent depth, µm



Dent Depth vs. Load

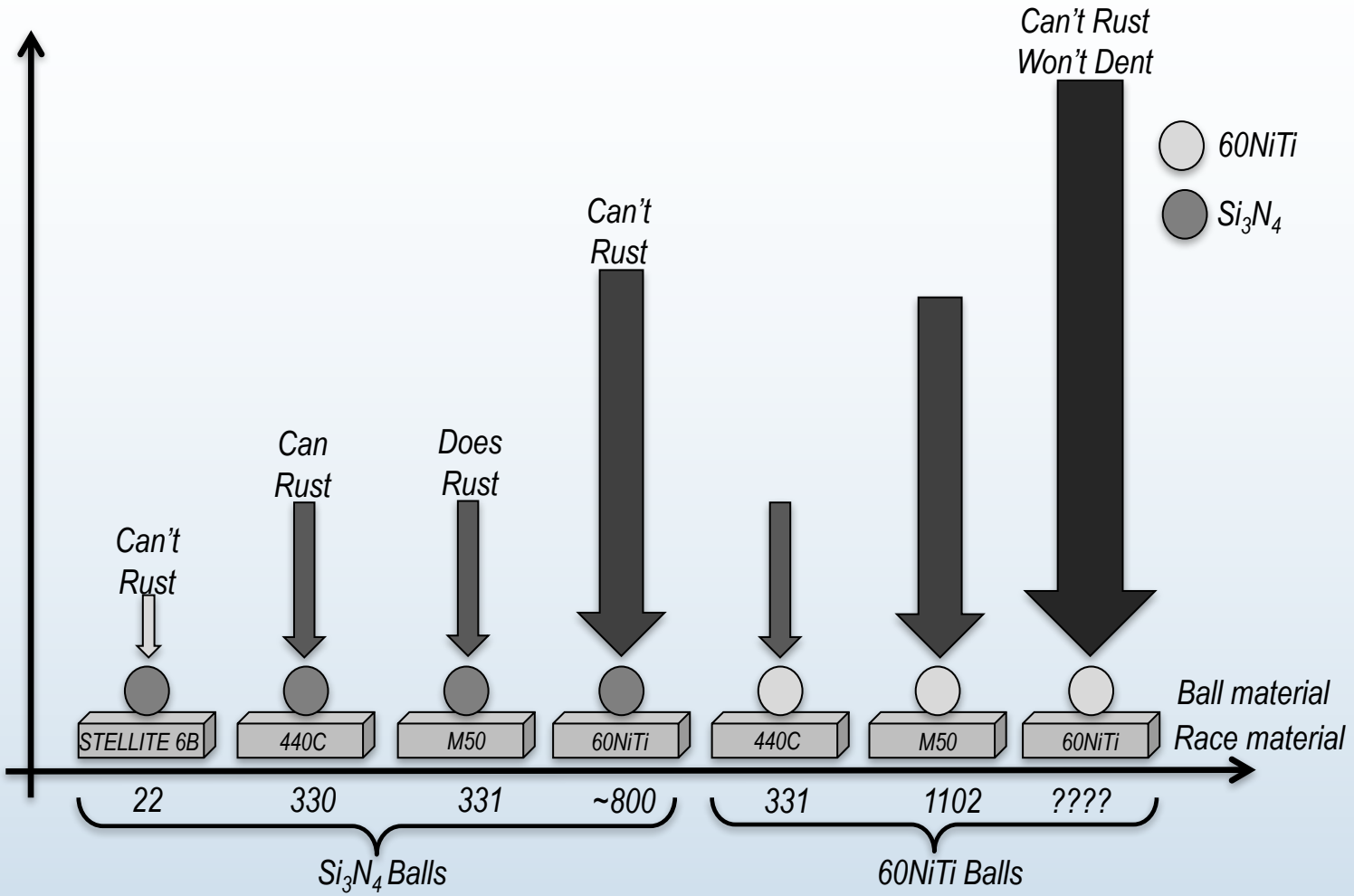
(Si_3N_4 ceramic ball pressed against 60NiTi plate)



60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!

Damage Threshold Load Capacity: Comparison
(1/2" Diameter ball pressed into plate)

Indent test



Low modulus + high hardness +superelasticity = extreme load capacity

Dent and Corrosion Resistant Ball Bearings

Finished 60NiTi-Hybrid Bearing

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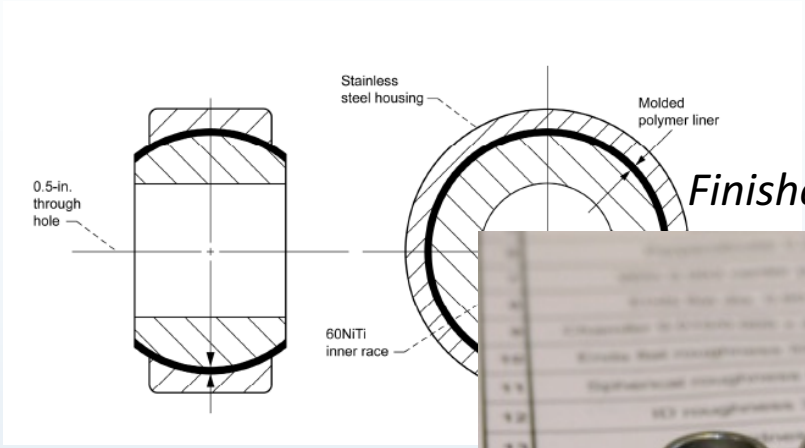
Spherical Bearing Project

Inner Race (ball) Sketch



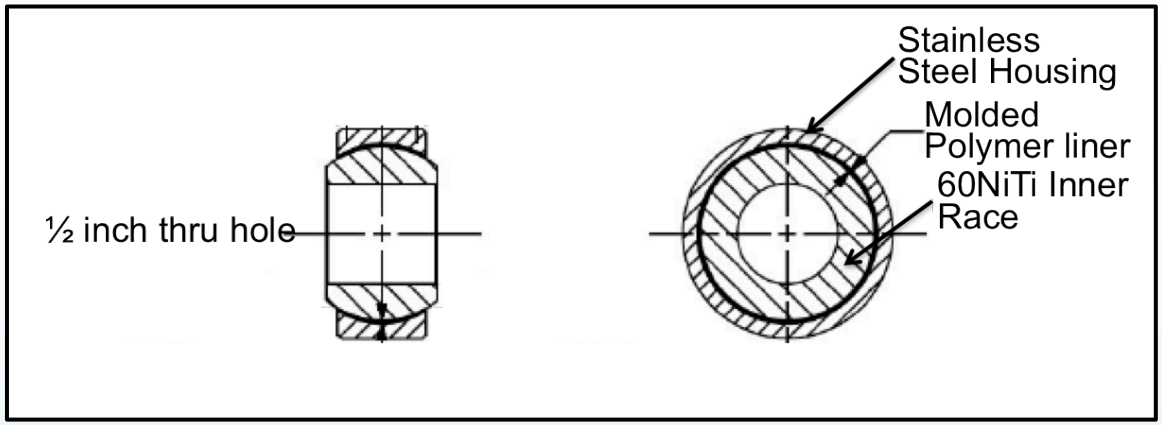
Finished inner races

Proposed Project

Corrosion-Proof Rod bearings

Status: Drilled 60NiTi balls (inner races) made and incorporated into bearings for testing.

Test Bearings: 60NiTi balls, PTFE filled liner, 17-4 SS Outer Race



- SAE AS81820 test
- +/-25° Oscillation, 17cpm
- 10,400 pound load (dry)
- 7500 pound load (wet)
- 210 in-lb torque limit
- 0.006” radial wear limit

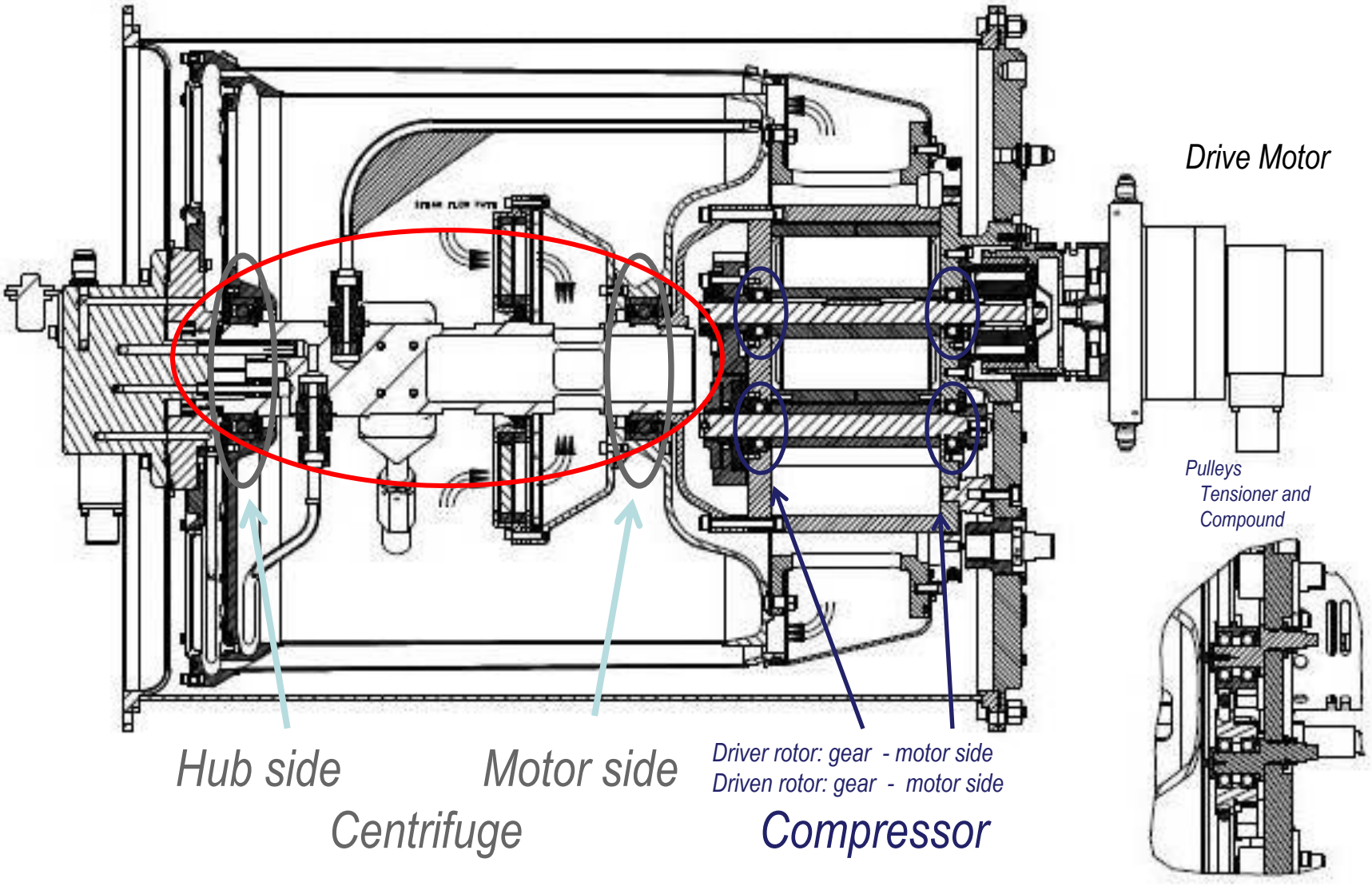
Results: 60NiTi Tribology

Table-II Spherical Bearing Data Summary {Test Conditions: +/- 25° rotation, 17 cycles per minute, 0.3in² bearing area}					
Bearing	Environment	Load (ksi)	#Total Cycles	Avg. Torque (in-lb)	Liner Wear (in)
60NiTi	Dry	34	25,000	193+/-11	0.0019+/-0.0007
60NiTi	Hydraulic Fluid	26	25,000	192+/-14	0.0026+/-0.0010
60NiTi	De-Icing Fluid	26	25,000	176+/-11	0.0019+/-0.0011
440C	Dry	34	25,000	188+/-19	0.0021+/-0.0009

Bearings made with 60NiTi balls provide tribological response that is comparable to standard 440C steel ball bearings.

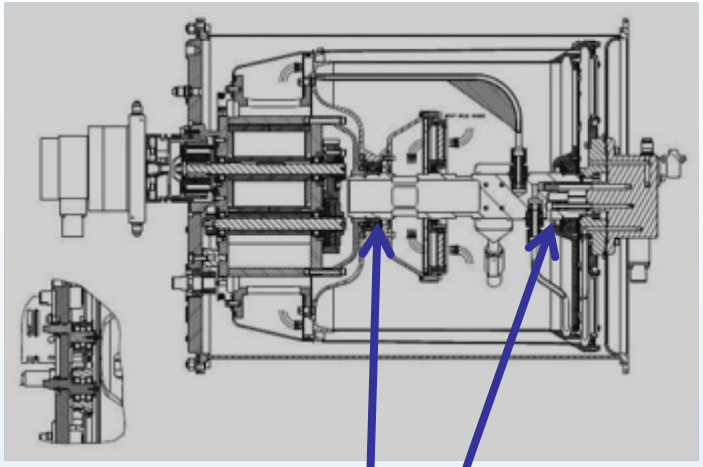
Result: 60NiTi Bearing After Test

ISS DA Centrifuge Bearings: 60NiTi Application

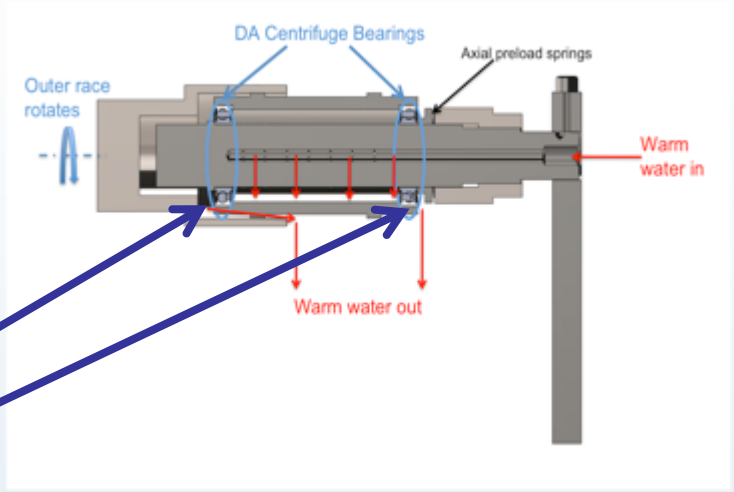


Bearing Testing:
(Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator

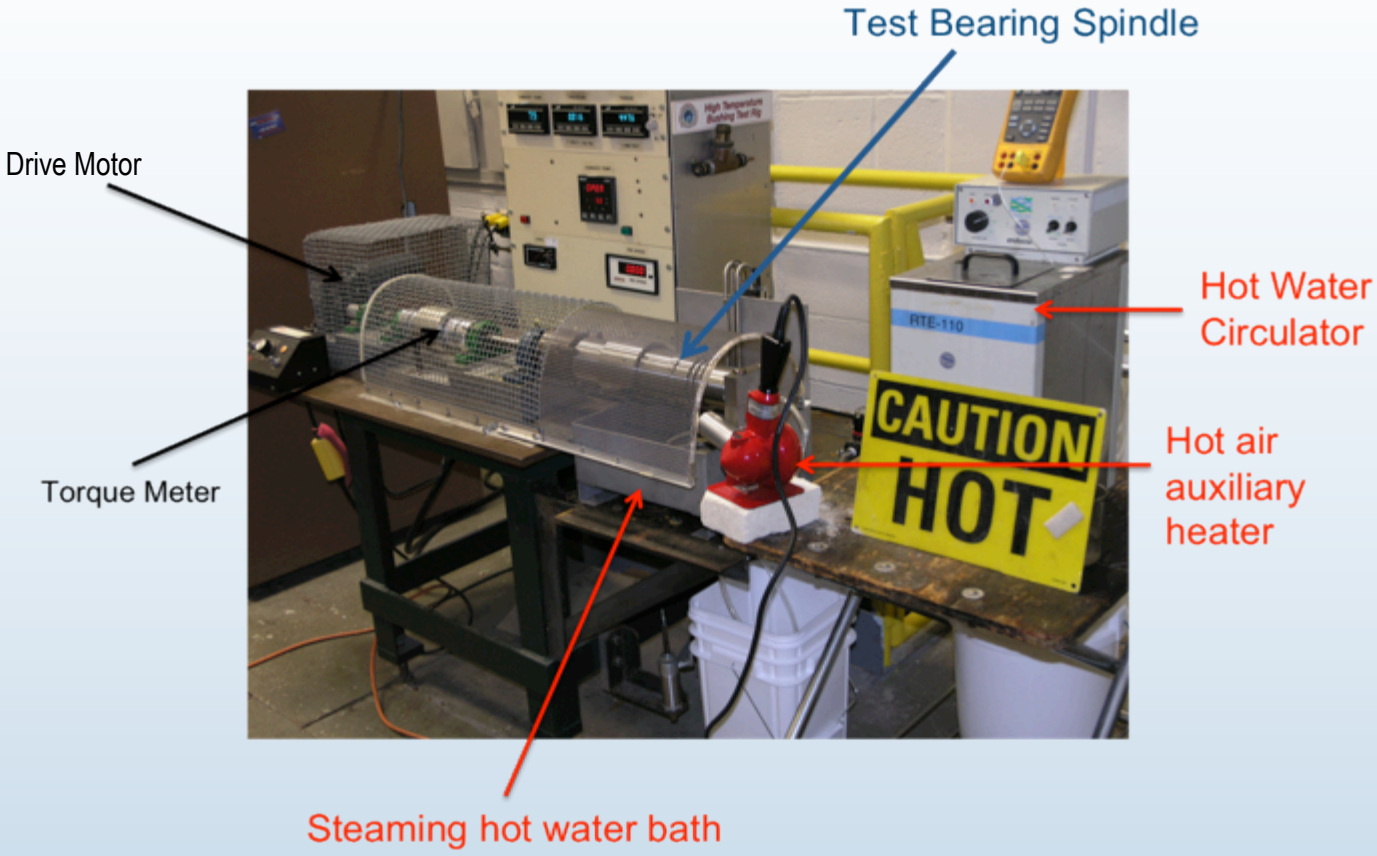


DA Centrifuge Bearing Test Rig
Spindle Components

Speed, load, configuration, temperature and moisture match ISS application.

Bearing Testing:
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor



Over 10,000 operating hours has been demonstrated.

DA Bearing: 60NiTi-Hybrid (50mm)

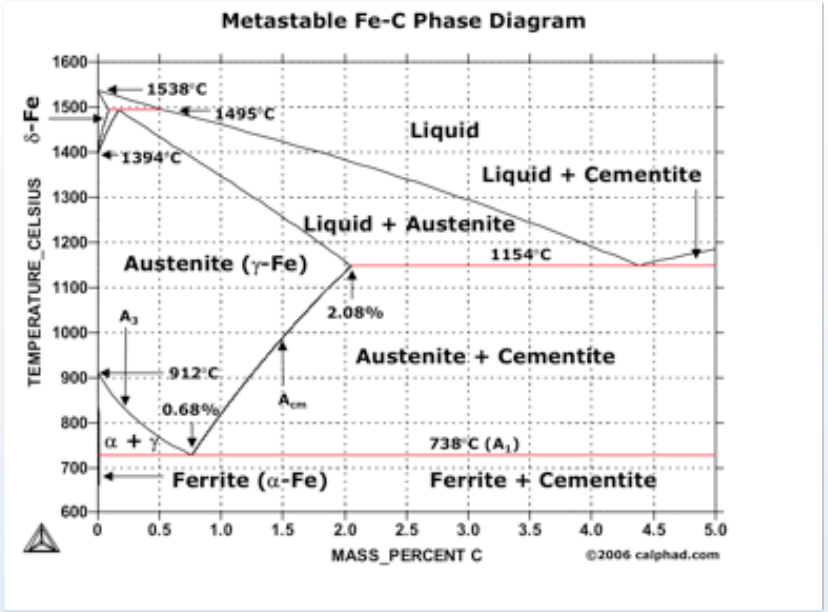
Post-Test Steel vs. 60NiTi-Hybrid

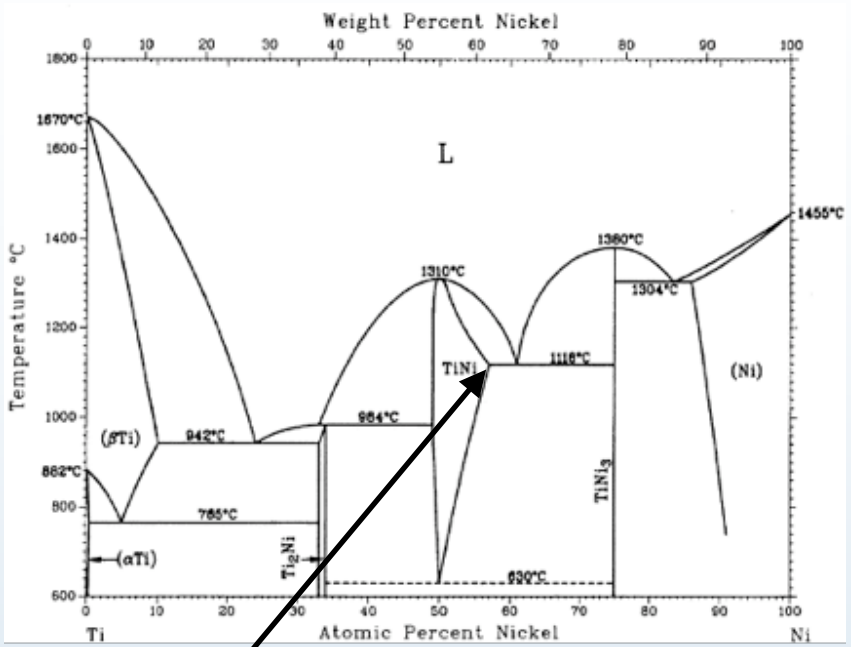
Test Results: 60NiTi bearings turn but don't rust!

Summary: NiTi for Aerospace Bearings

- Nickel-rich NiTi alloys for bearing applications are emerging from a long period of R&D dormancy.
- Recent material attribute revelations (dent and corrosion resistance) combined with modern PM processing has created a new market for bearing and mechanical system applications.
- Building upon a strong foundation of SMA knowledge, the structural engineering of Ni-rich alloys is rapidly advancing.
- Proof of concept demonstrations in spherical sliding bearings and ball bearings in wet applications illustrate the benefits of this new alloy system.
- More applications are anticipated as the technology matures.

Future View: Materials Design Space





Fe-C system has yielded literally thousands of alloys and variants following centuries of development.

NiTi explorations to date have been limited to a very narrow region.

Though much more R&D remains to commercialize 60NiTi and other superelastic intermetallic materials for use in bearings, gears and other mechanical systems, early indications are very promising.

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