Ni-Ti Next Generation Bearings for Space Applications

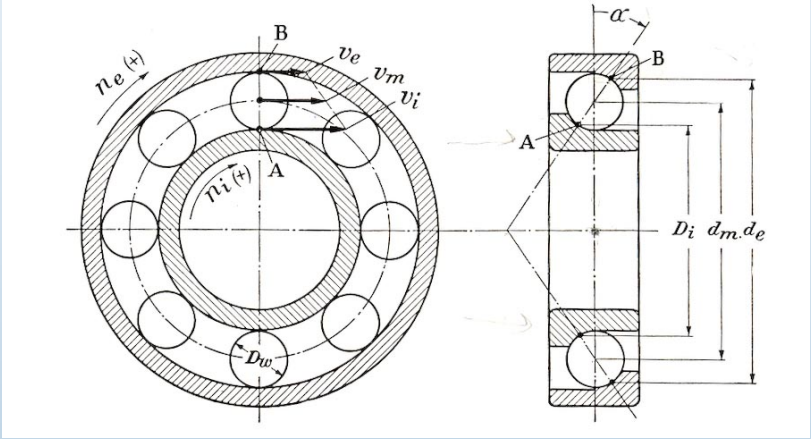
Christopher DellaCorte
NASA, Glenn Research Center
Cleveland, Ohio

(January 24th, 2018)
Schaeffler International Bearing Conference
Herzogenaurach, Germany

Materials Requirements: NASA sets the bar high

(Aerospace challenges conventional bearing materials)

- **Key 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)
  - Capable of producing ultra-smooth surface finishes



Technical Challenge:

(Current suite of candidates is severely limited)

- **Four general types of bearing and tribo-mechanical materials:**
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_4 hybrid bearings)
  - Superalloys
  - 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 are non-conductive (and operate on steel raceways)
  - 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.

Superelastic Bearings: 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, kg_f) is significantly (3-5X) higher than steel.

Highly polished 60NiTi bearing balls

60NiTi-Si_3N_4 Hybrid Bearing

Technical Properties Comparison:

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

- ***Remarkable Points***
  - ***Modulus is ½ that of tool steel, yet hardness is comparable.***
  - ***Immune to rusting, non-magnetic, thermal expansion matches superalloys and steel structural materials.***

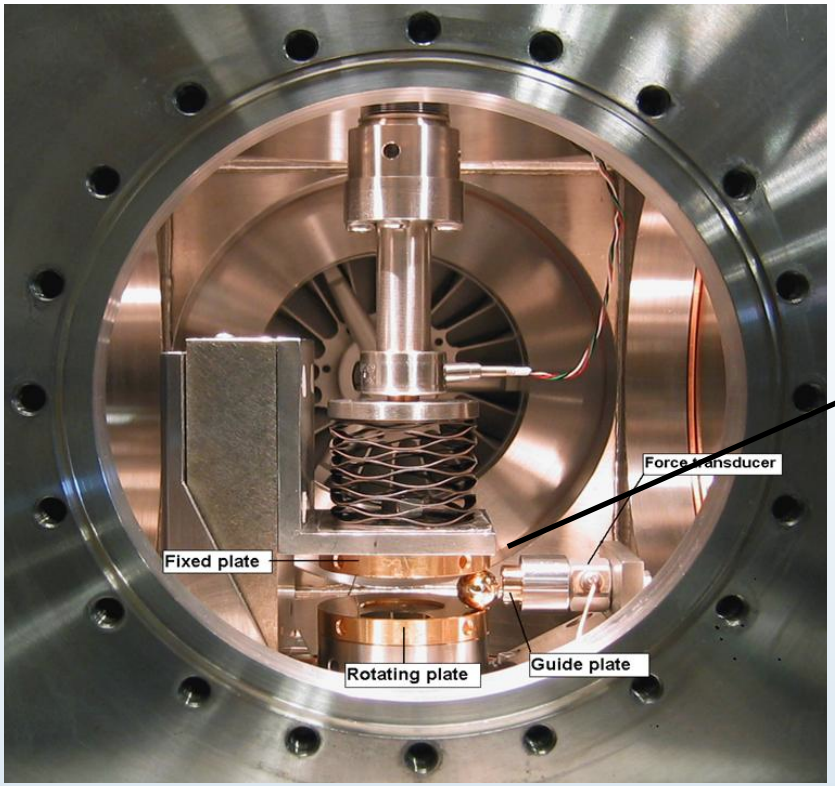
Technical Properties Comparison:

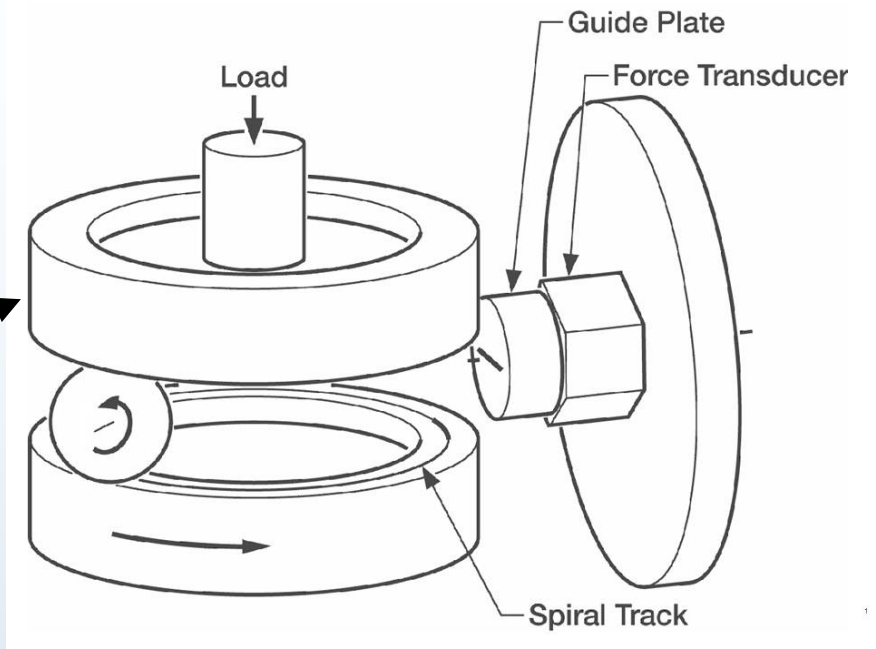
60NiTi Properties Comparison				
Property	60NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56-62 HRC	58-62 HRC	1300-1500Hv	60-65 HRC
Indent Stress Limit, GPa*	3.0	2.3	Not applicable	2.5
Thermal Conductivity W/m-°K	18	24	33	~36
Thermal Expansion	~$12.4x10^{-6}$/°C	$10x10^{-6}$/°C	$2.6x10^{-6}$	~11 10^{-6}/°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion Resistance	Excellent	Marginal	Excellent	Poor
Tensile/Flexural Strength	~1000MPa	1900 MPa	600-1200MPa (Bend Strength)	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's Ratio	~0.34	.3	.27	.30
Fracture Toughness	~15 MPa/√m	22 MPa/√m	5-7 MPa/√m	20-23 MPa/√m
Maximum Use Temp	~500° C	~400° C	~1100° C	~400° C
Electrical Resistivity	~$80x10^{-6}$ Ω-cm	~$36x10^{-6}$ Ω-cm	Insulator	~$60x10^{-6}$ Ω-cm

Nitinol 60: Attribute Peculiarities

- Unexpected attributes and behavior:
  - Readily lubricated.
  - High resilience.
  - High Hardness.
- Questions:
  - Tribology: Titanium (and Nickel) alloys are notoriously difficult to lubricate. They gall, even with lubrication. Why does is it lubricate "able"?
  - Resilience: NiTi is no harder than 440C. Why does it display superior dent resistance?
  - Hardness: NiTi has no carbide or other ceramic forming elements. Why is it hard?

Tribology Evaluation: Spiral Orbit Tribometer (SOT)

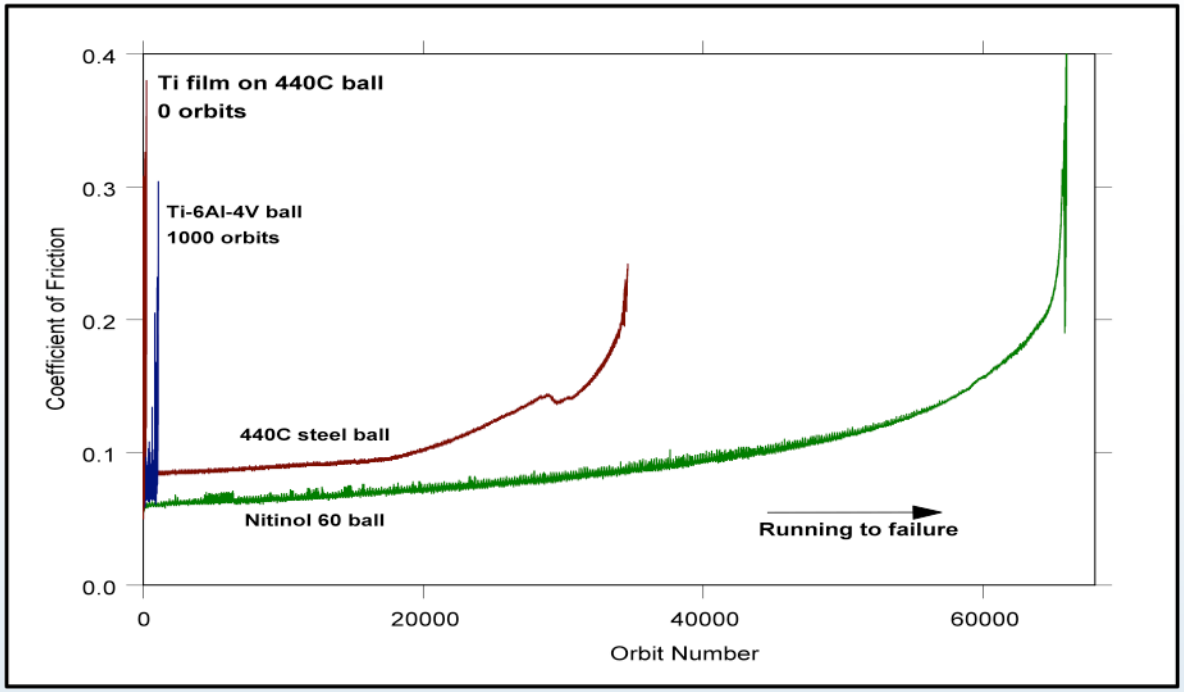




Specimen configuration

SOT is a rolling tribology test with minimal lubricant that experiences a slight scrub against guide plate once per revolution. SOT mimics instrument ball bearings very well and is used to evaluate materials and lubricants. Tests typically run in vacuum to simulate space environment under boundary lubrication.

60NiTi: Friction and lubricant life testing



- Test confirms that that pure titanium and conventional alloys (Ti-6Al-4V) are poor tribological materials.
- 60NiTi exhibits lower running friction than 440C stainless steel.
- 60NiTi yields consistently longer lubricant life than 440C.
- 60NiTi is also corrosion proof, non-magnetic and electrically conductive.

Tribological Properties: Lubricant Affects

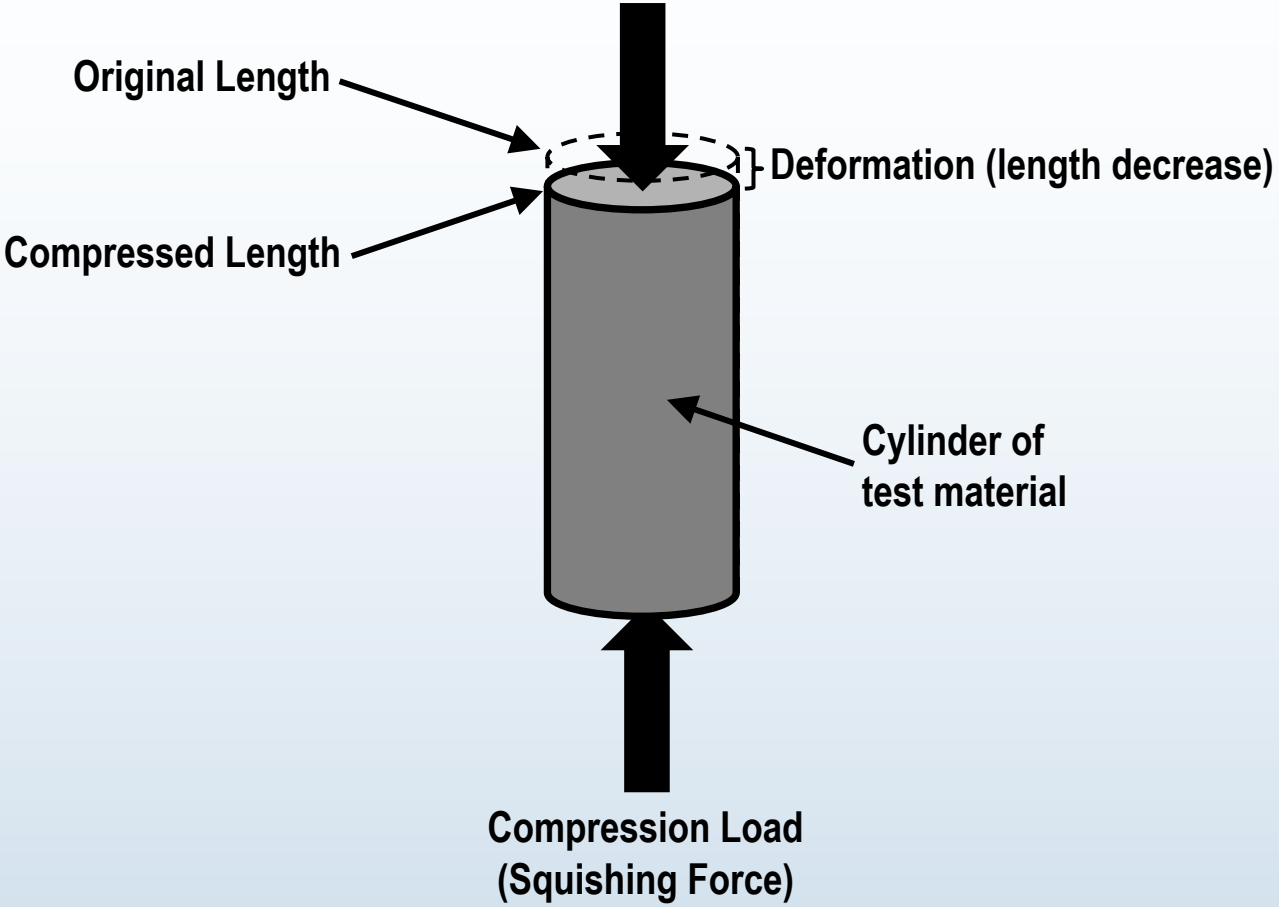
Sliding Friction of 60NiTi*		
Lubricant	Initial Friction, μ	Steady-State Friction, μ
Castor Oil	0.12	0.008
Turbine Oil	0.09	0.2
Seed Oil	0.08	0.034
Paraffin Oil	0.13	0.037
***Data taken from Zeng et. al (2014)**		

The surface of 60NiTi is chemically benign to lubricant molecules but remains sufficiently active to foster boundary lubrication.

Nitinol 60: Material Peculiarities

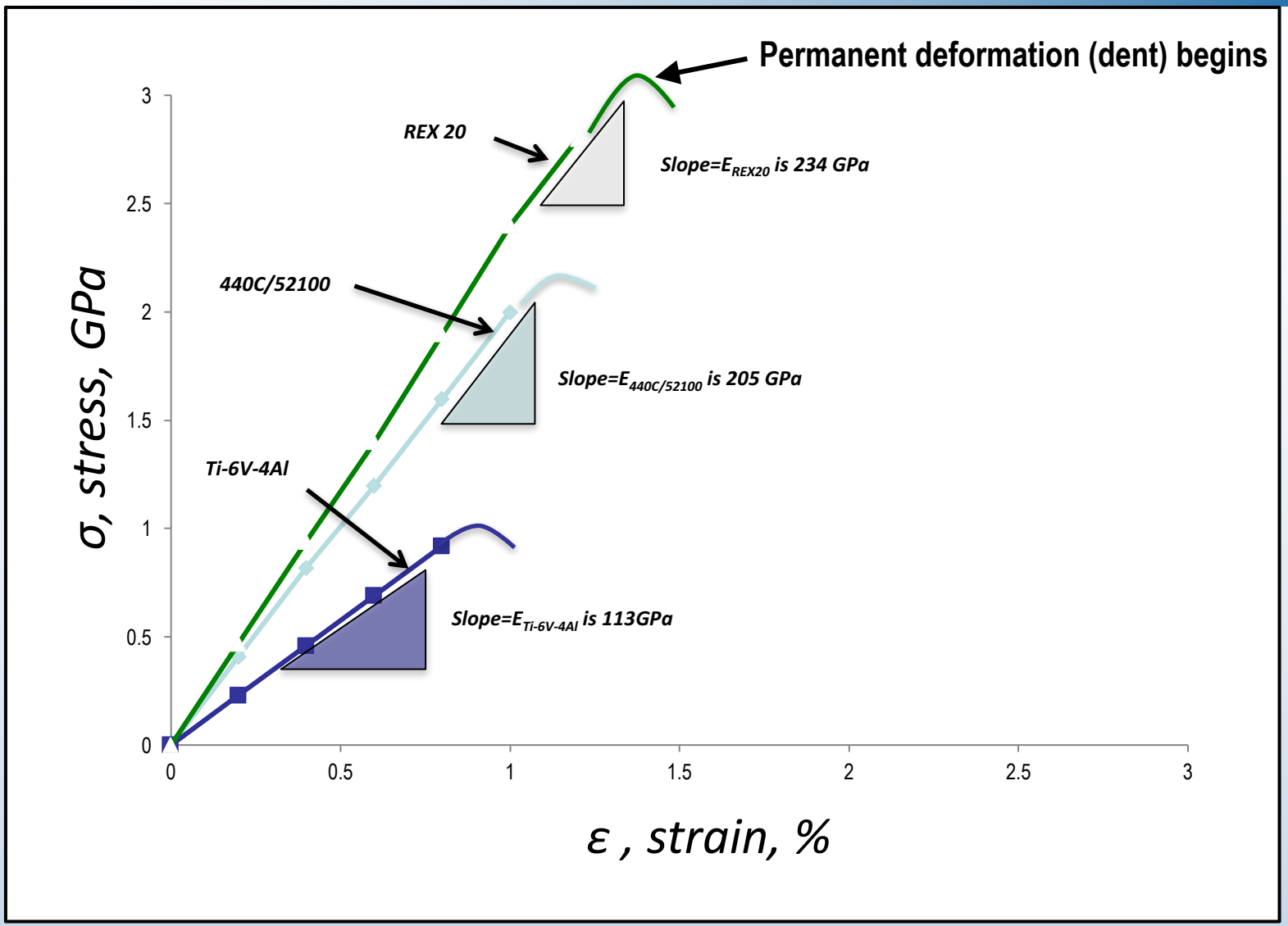
- **Puzzling Mechanical Behavior:**
  - Measured elastic (stress-strain) properties exhibits nearly 10X more deflection than steel.
  - Conventional wisdom: hard and stiff go together yet despite its high hardness, 60NiTi is highly elastic (not so stiff).
- **Question:**
  - What are the reasons behind 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

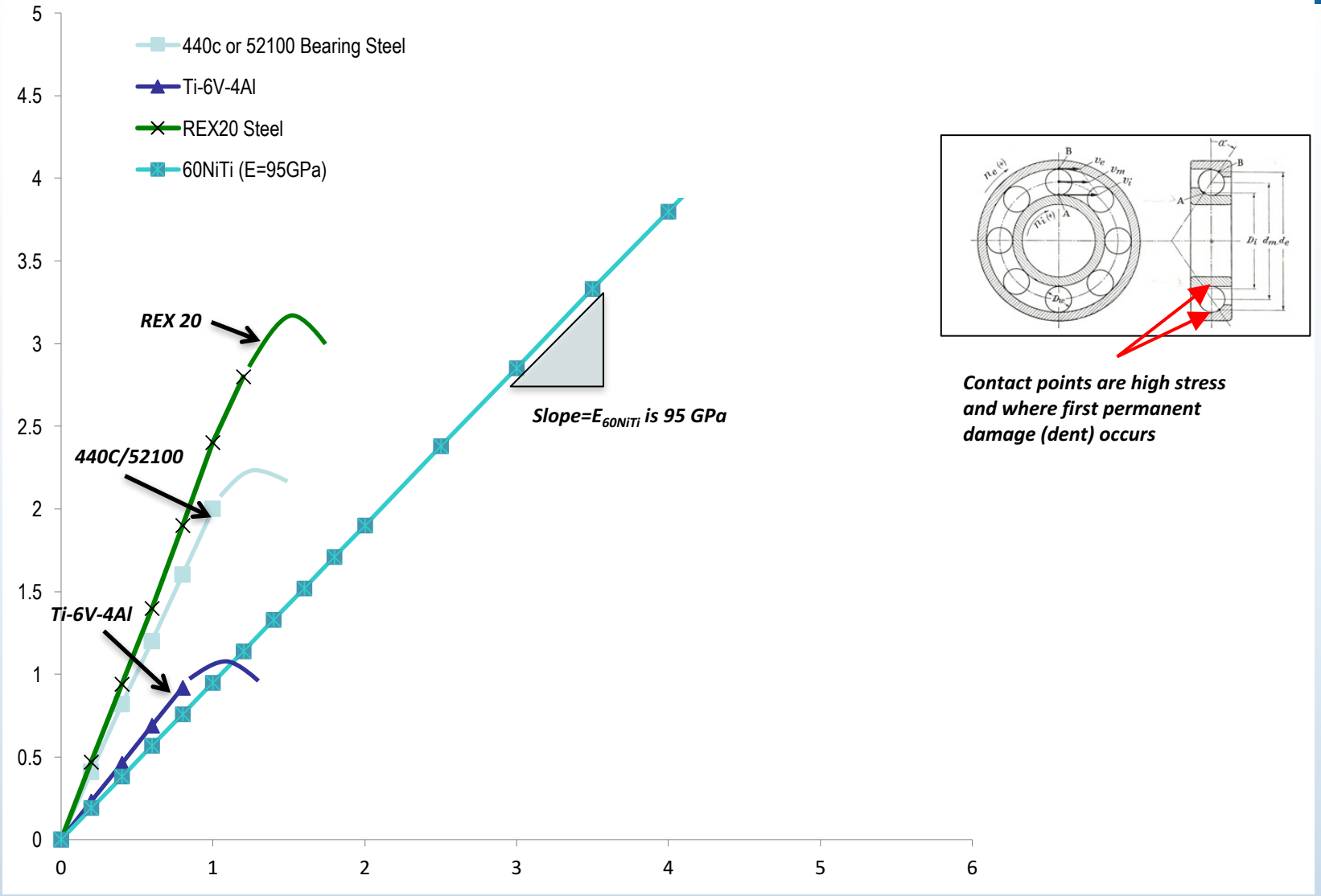


- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior



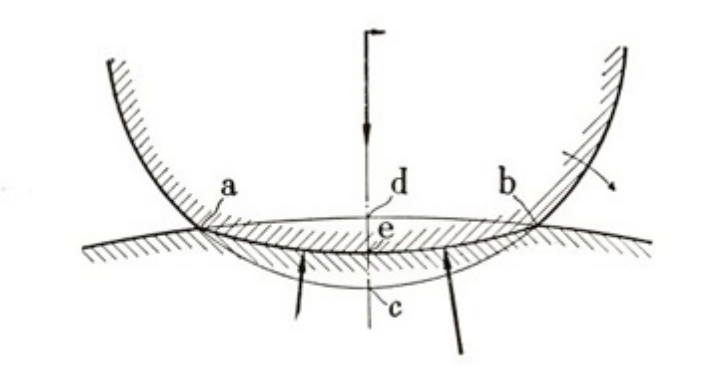
60NiTi: Stress-Strain Behavior



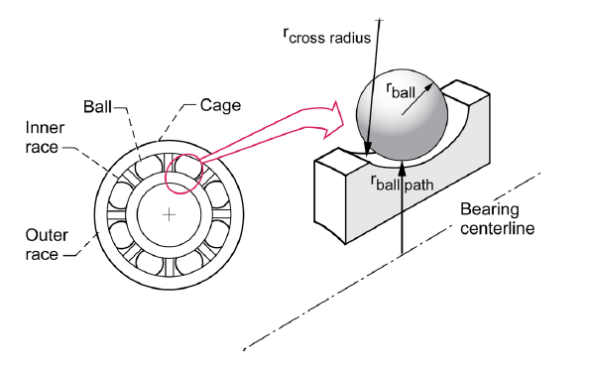
Contact points are high stress and where first permanent damage (dent) occurs

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



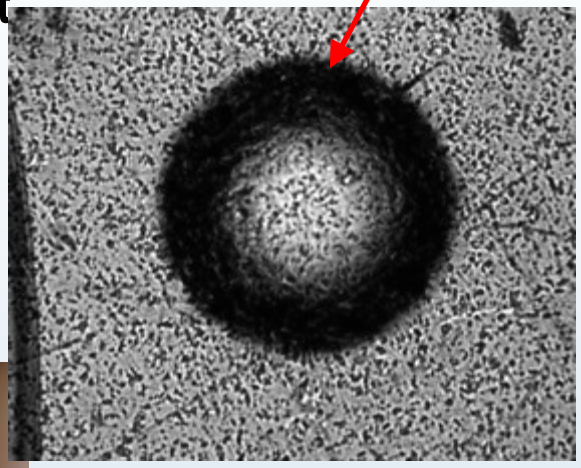
Dents on race surface cause rough running and premature failure

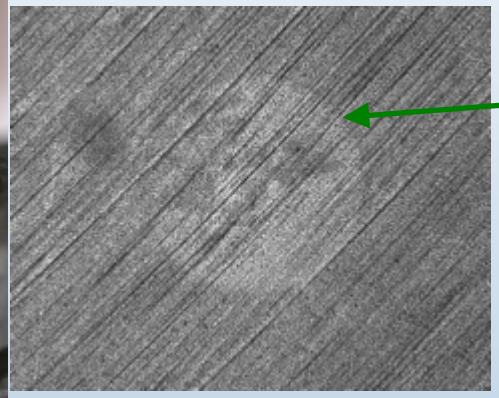
Resilience: Can 60NiTi withstand high dent loads?

(Static denting behavior)

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

Deep Brinell dent.



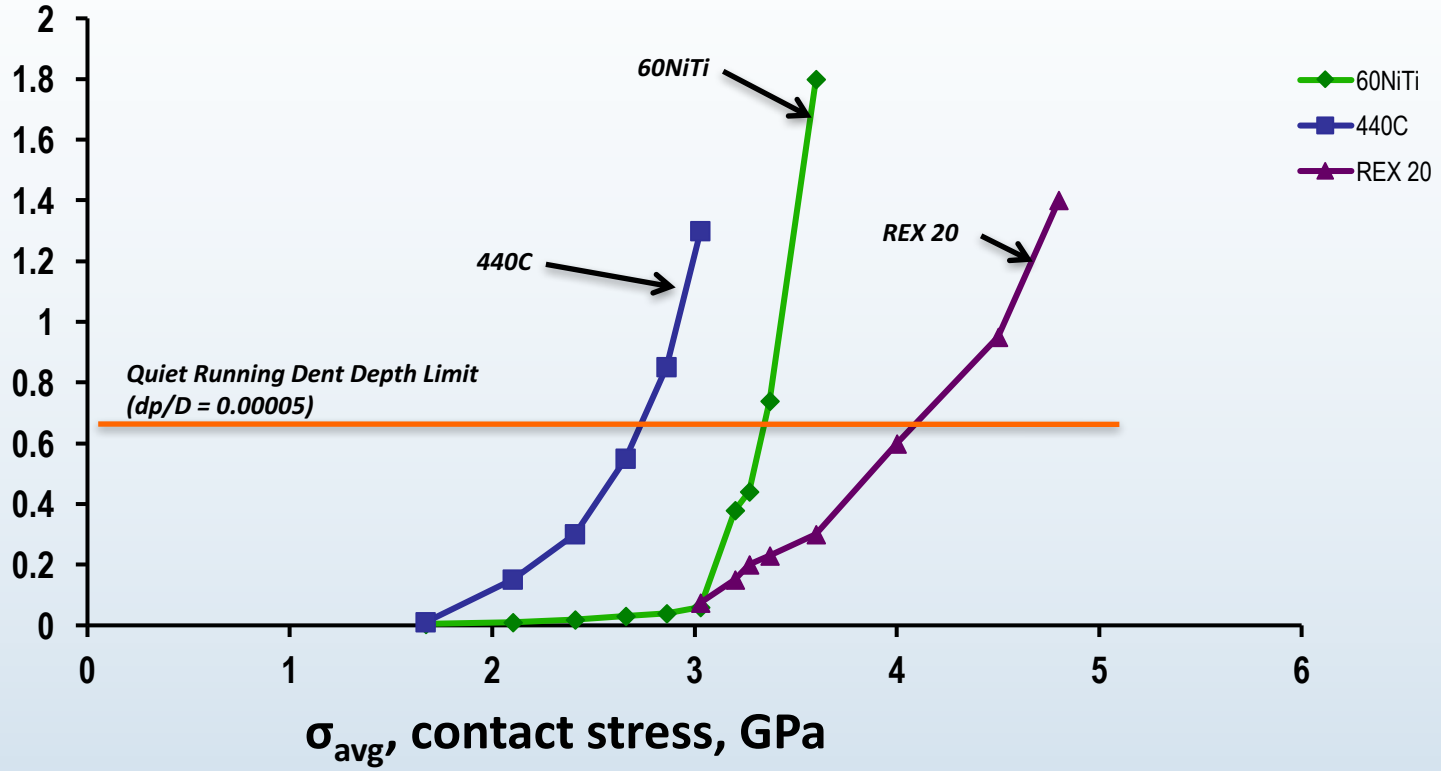


Threshold load visible dent.

Dent Depth vs. Hertz Contact Stress

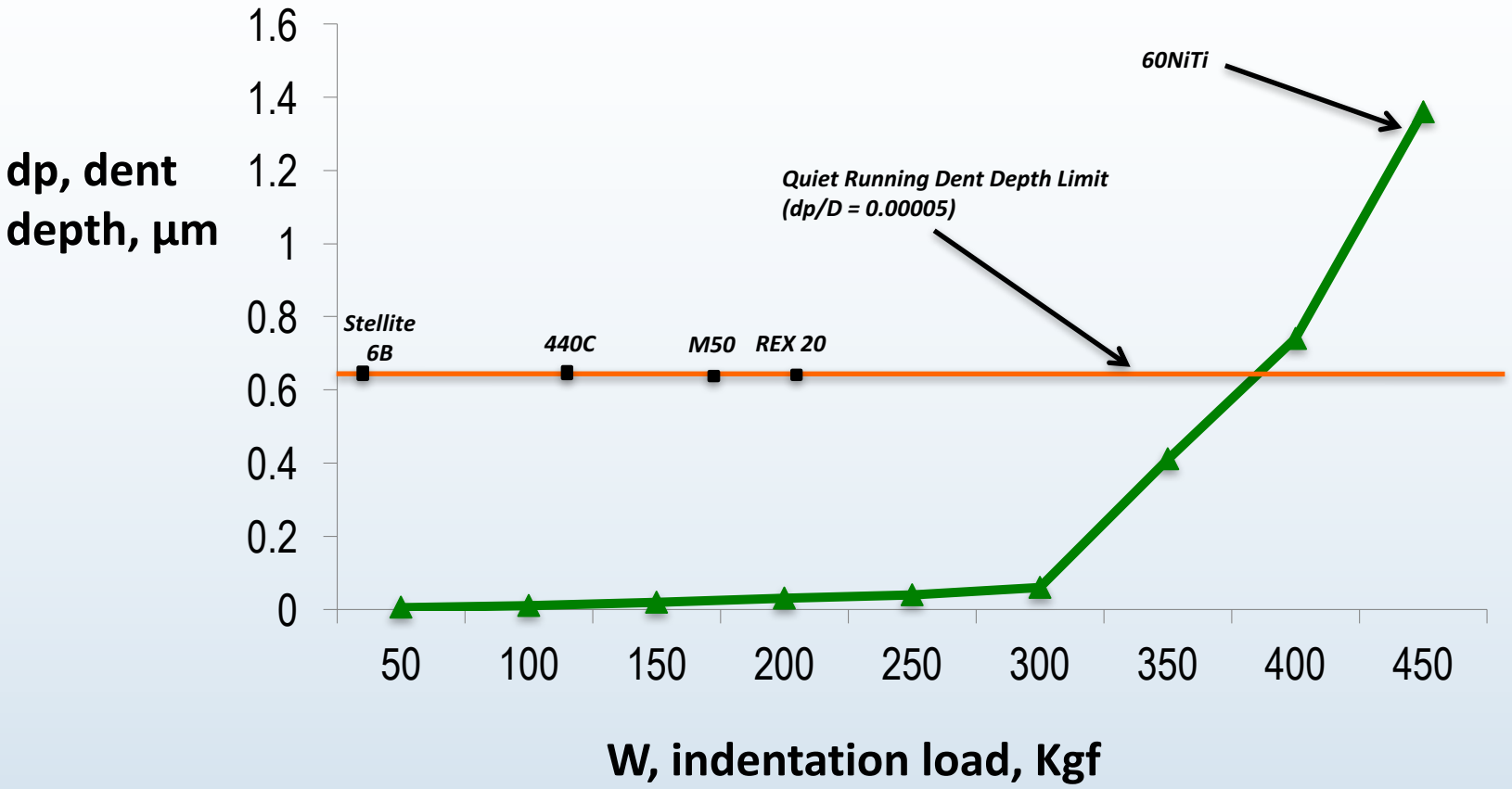
(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)

dp, dent depth, µm



Dent Depth vs. Load

(Si_3N_4 ceramic ball pressed against 60NiTi plate)



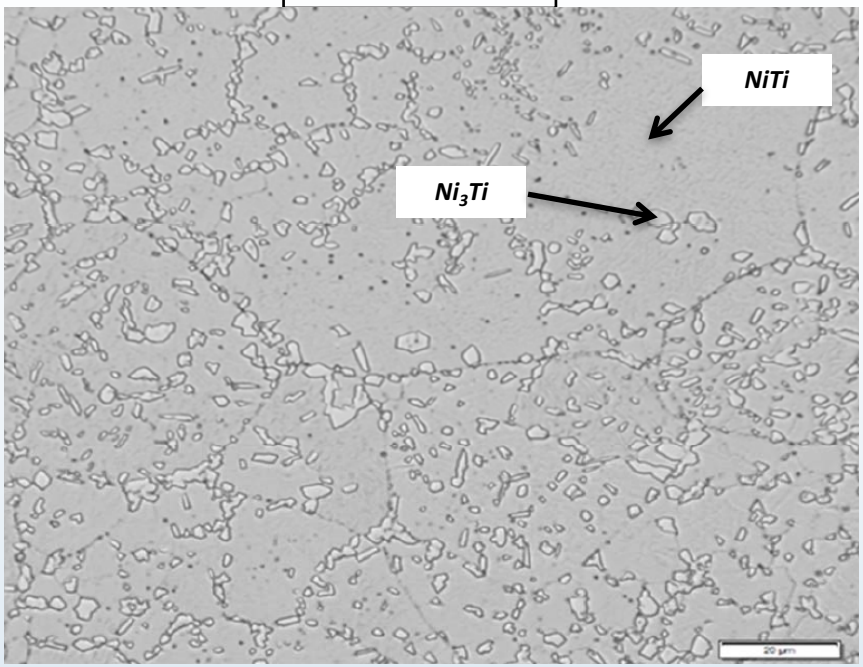
60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!

Nitinol 60: Material Peculiarities

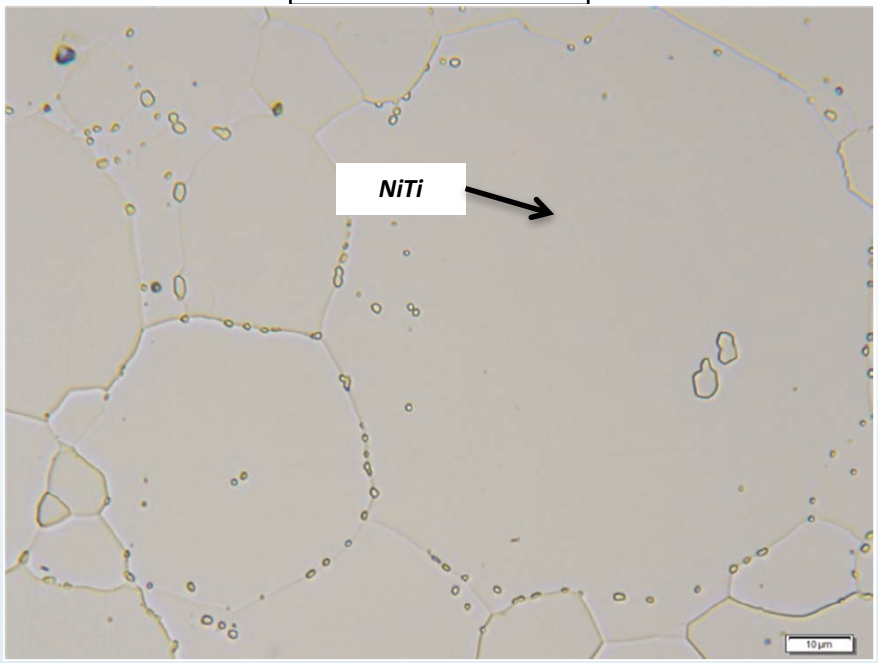
- Puzzling Mechanical Behavior:
  - Measured elastic (stress-strain) properties exhibits nearly 10X more deflection than steel.
  - Conventional wisdom: hard and stiff go together yet despite its high hardness, 60NiTi is highly elastic (not so stiff).
- **Question:**
  - **What are the reasons behind 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?

Nitinol 60: Microstructures-Optical Views

60NiTi Annealed



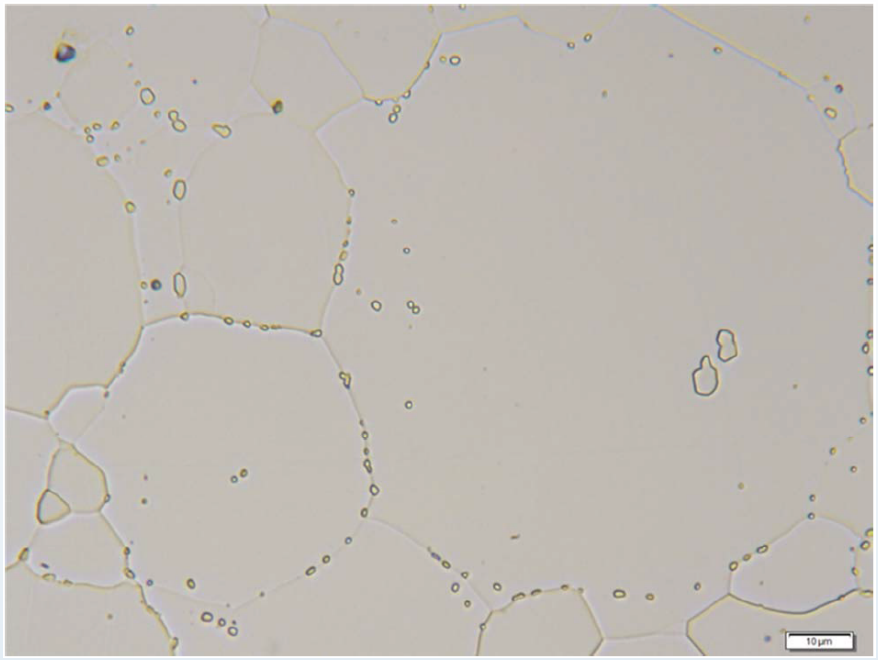
60NiTi-Hardened



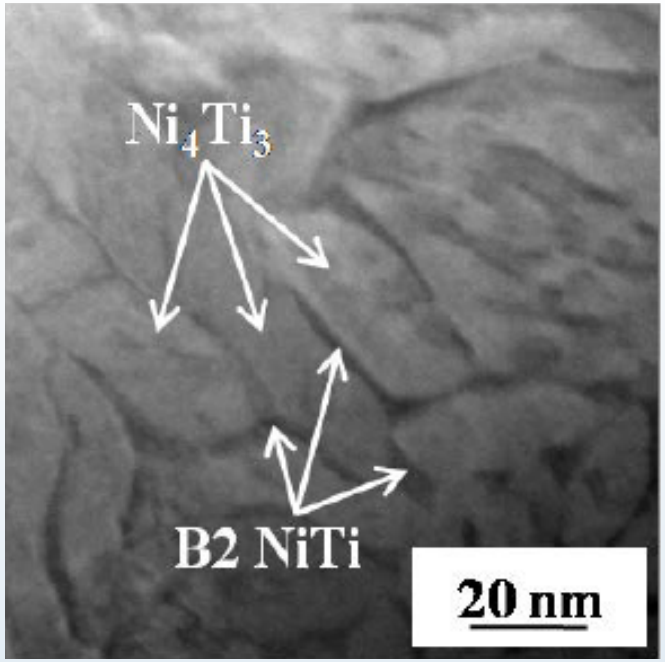
Heat treatment: 1000C + Water Quench

- **Microstructural Elements**
  - Annealed 60NiTi is largely NiTi with substantial Ni_3Ti precipitates.
  - Quenched (hardened) 60NiTi appears to be entirely NiTi but X-ray indicates Ni_4Ti_3.

NiTi Alloys: Hardened by naturally formed nanotechnology



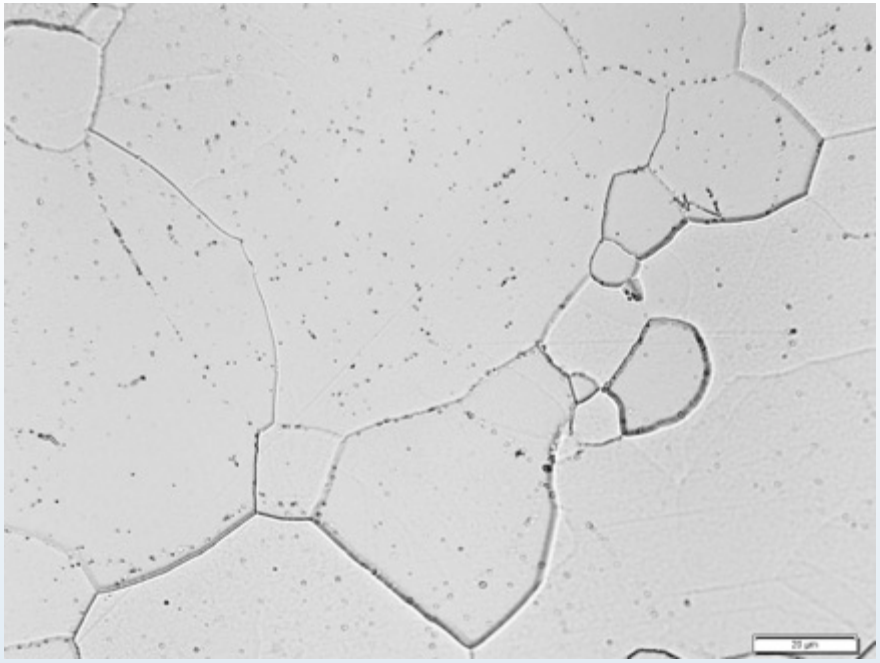
60NiTi. (~500x, optical microscope)



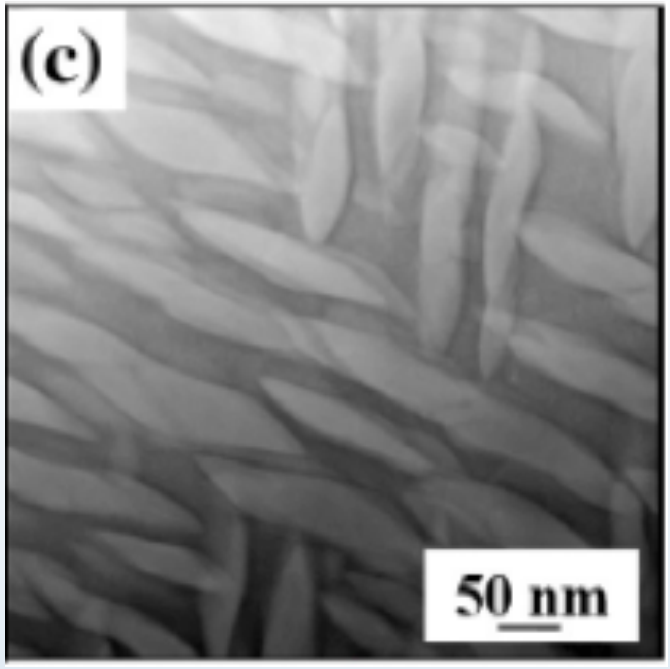
60NiTi (~50,000x, STEM microscope)

- ***Takeaway Points***
  - ***In-situ formation of hard nano-scale Ni_4Ti_3 particles hardens alloy.***
  - ***Revealed by recent HAADF-STEM analyses.***

Recent Advancements: Hf Additions



NiTi-Hf. (~500x, optical microscope)



NiTi-Hf. (~50,000x, STEM microscope)

- ***NiTi-Hf (just 1 atomic %)***
  - ***Same nano-scale Ni_4Ti_3 particles hardens alloy.***
  - ***Hf slows down undesirable Ni_3Ti precipitate formation, eliminates water quench and resulting residual stresses.***

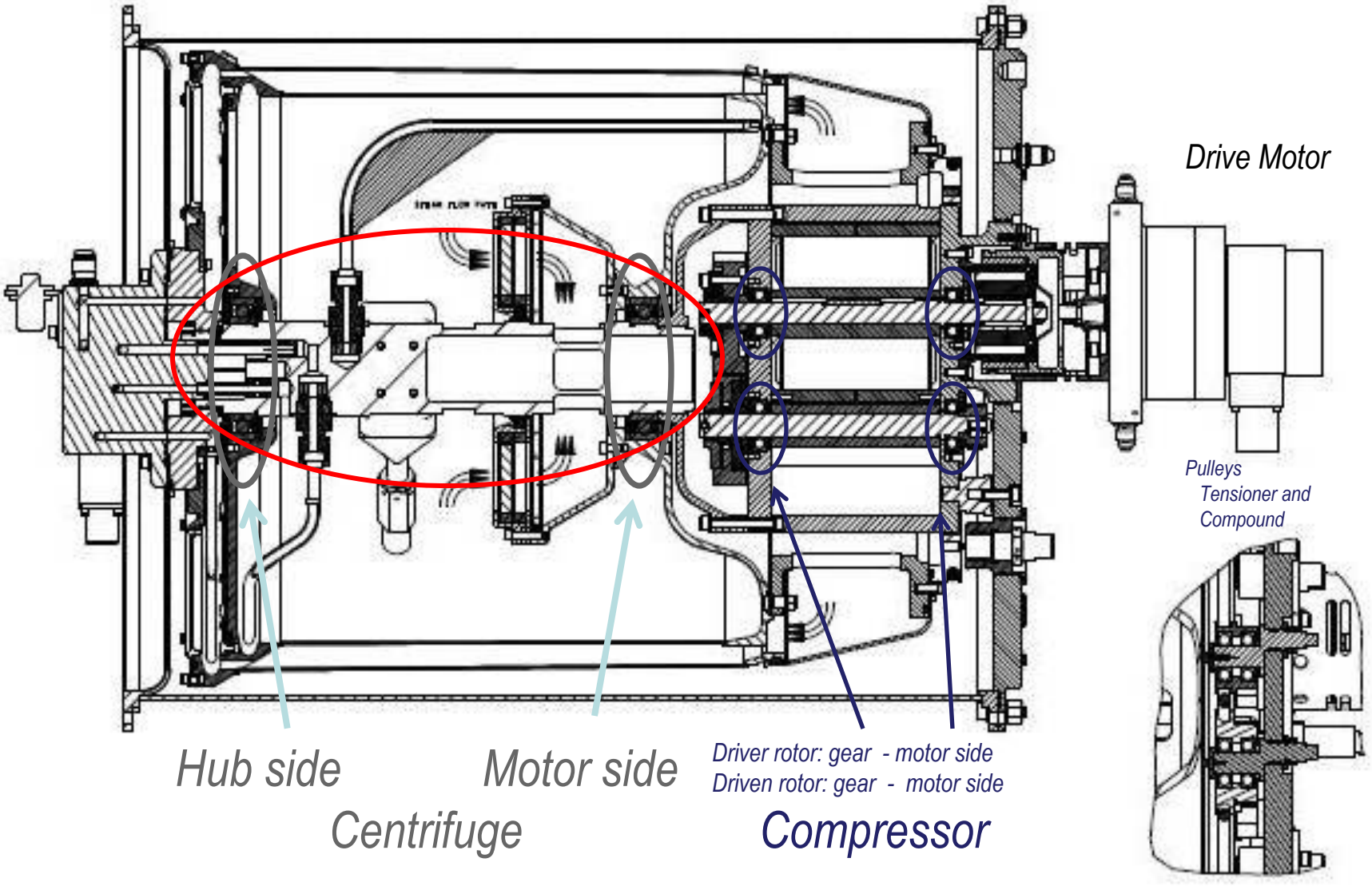
Nitinol 60: Material Peculiarities

- 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?**

Dent and Corrosion Resistant Ball Bearings

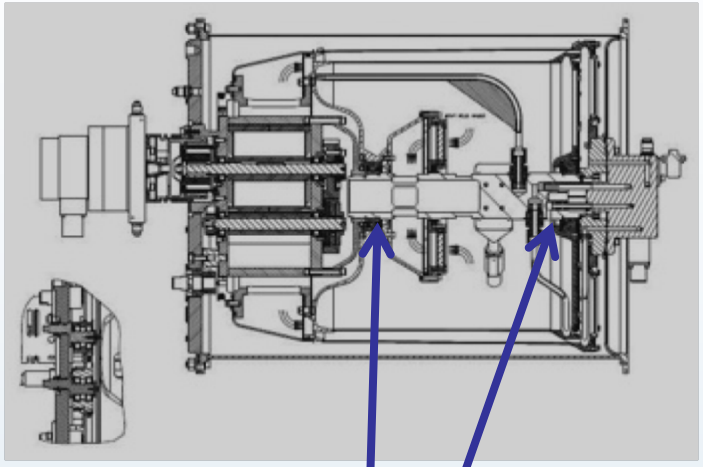
Finished 60NiTi-Hybrid Bearing

ISS DA Centrifuge Bearings: 60NiTi Application

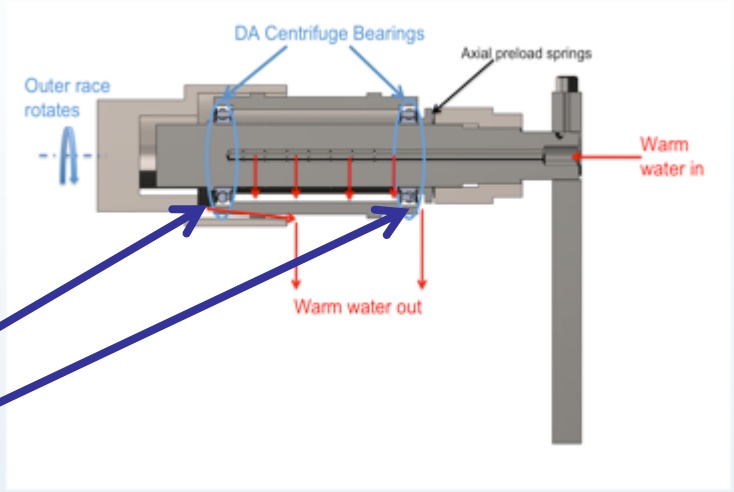


Bearing Testing:
(Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator

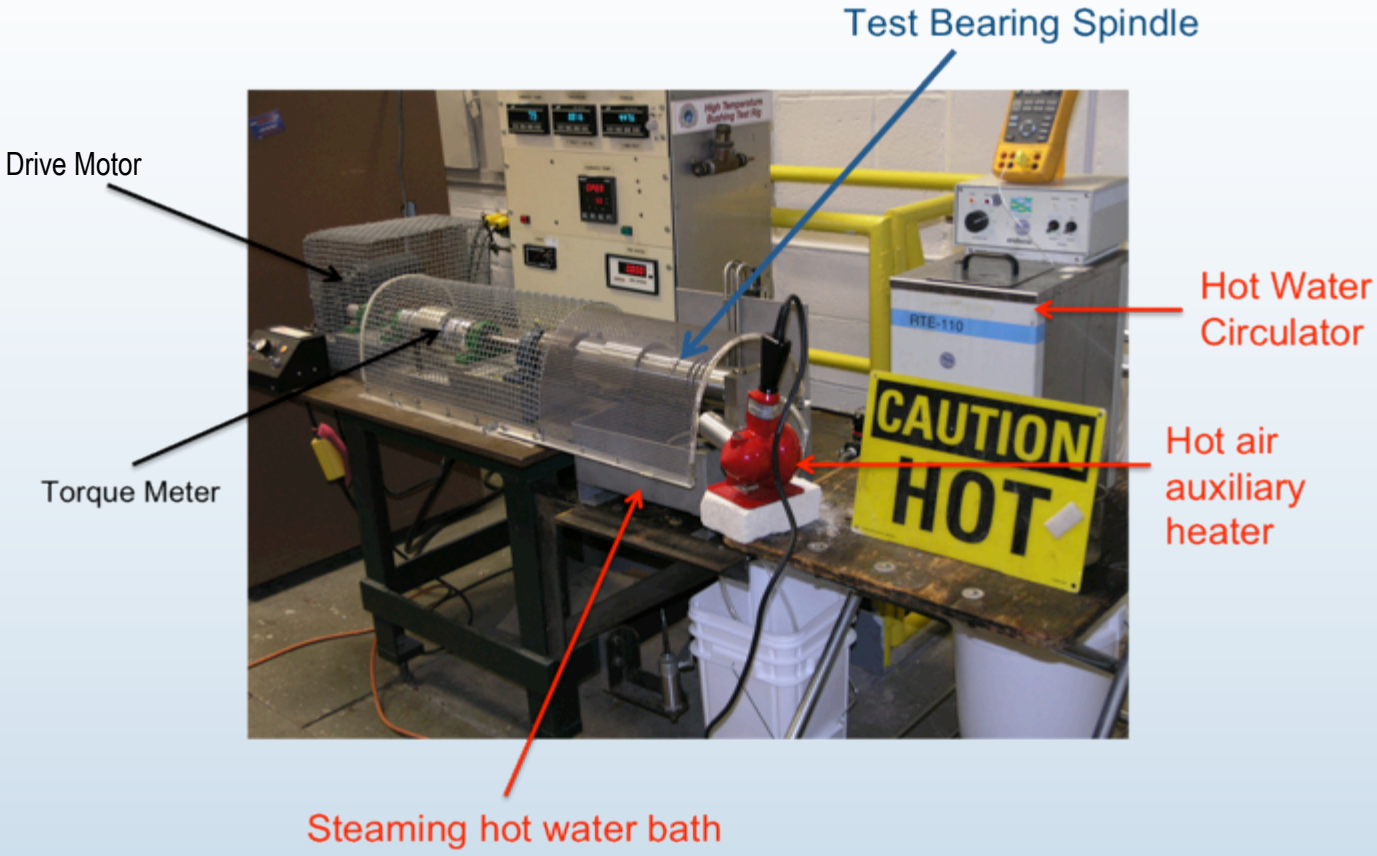


DA Centrifuge Bearing Test Rig
Spindle Components

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.

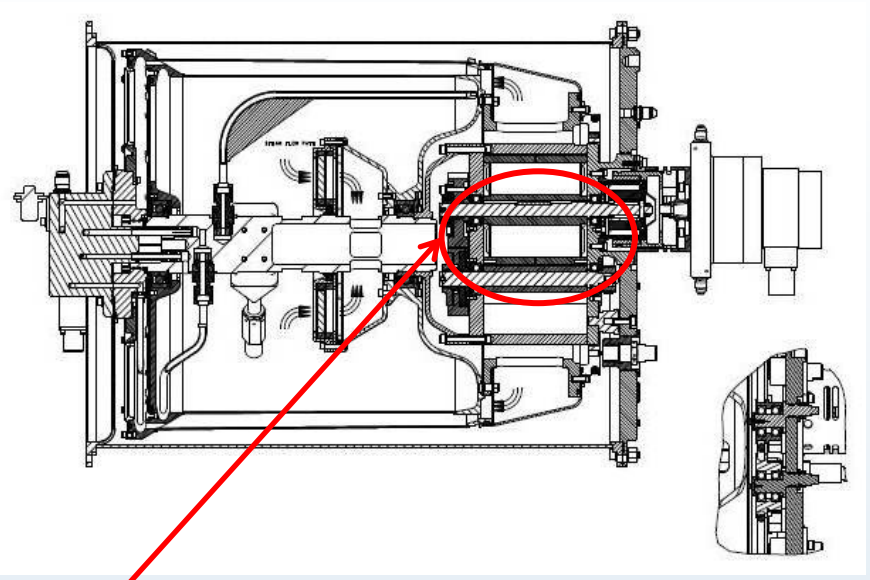
DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid

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

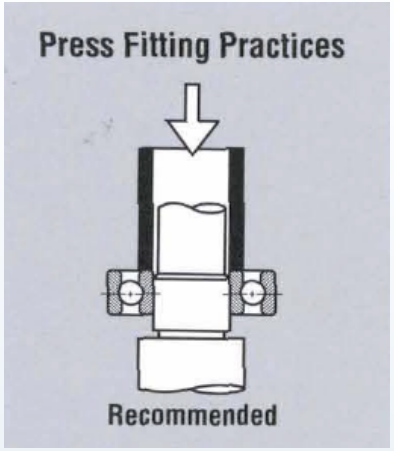
Opportunities: Superelastic Bearings
(ISS Wastewater purifier system offers technology "pull")

- Superelastics 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).
  - Compressor drive gears (dry lubed, damp, low load, high speed).
  - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).

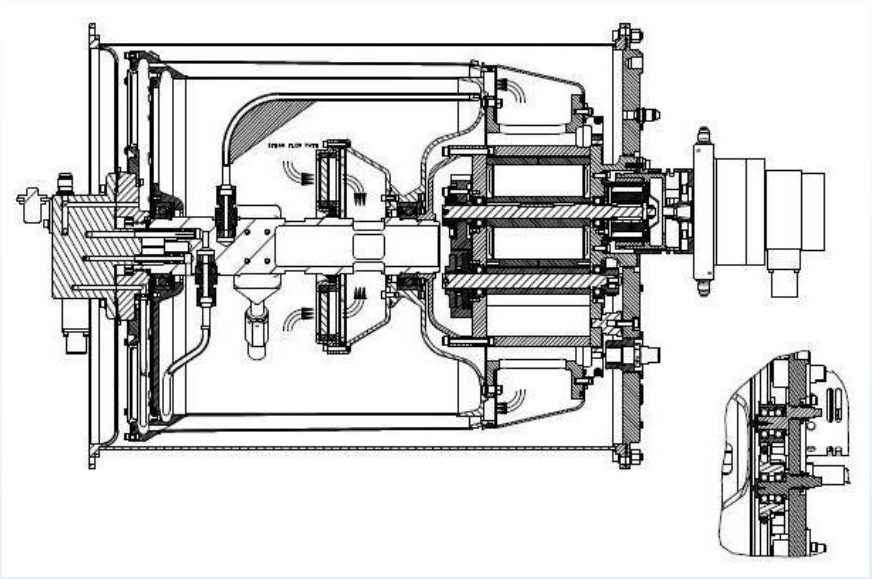


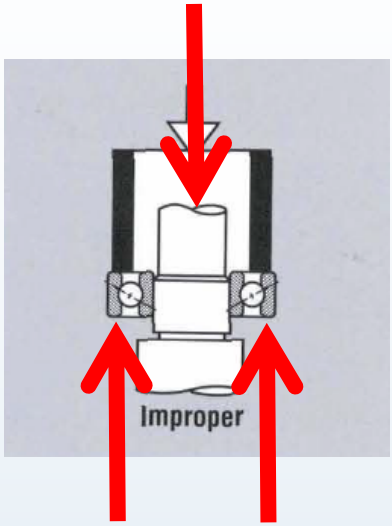
- *Compressor Bearings*
  - *Support roots blower lobes.*
  - *2000 rpm, high precision.*
  - *Moisture exposure.*
  - *Accessible for installation*
  - *Disassembly loads ball-race contact requiring bearing replacement.*

Current Machine Design: Assembly: OK, Removal: Not OK



Acceptable

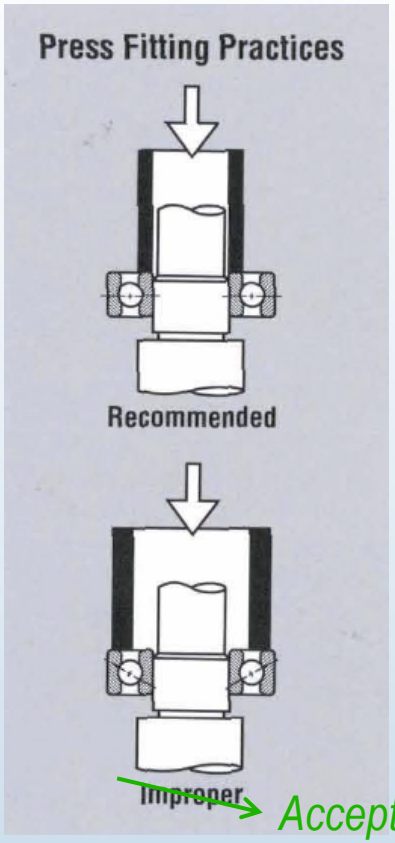


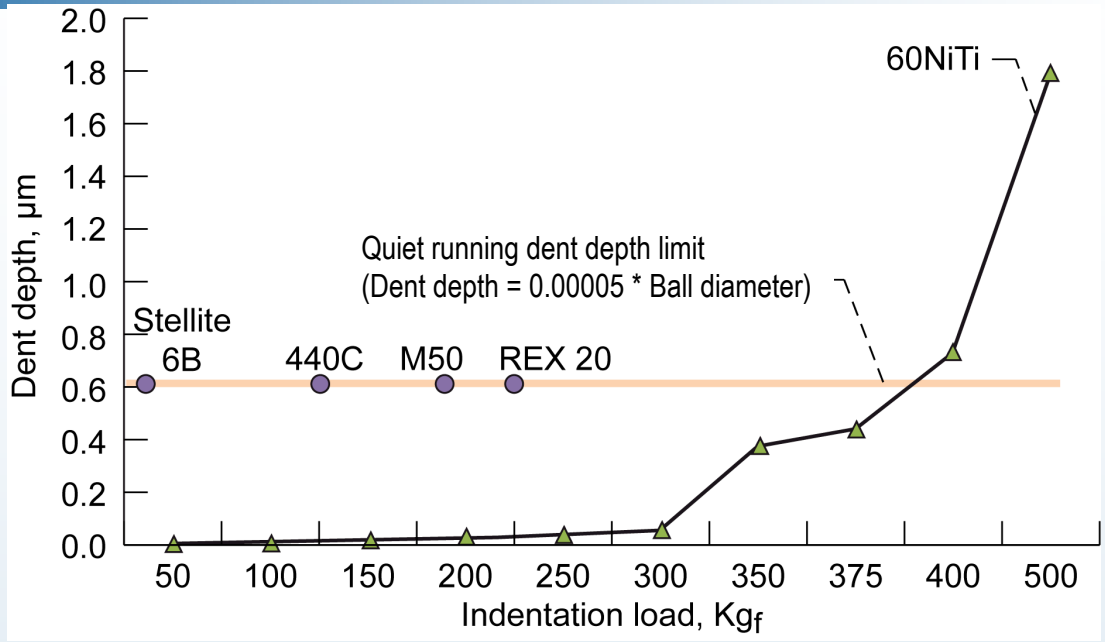


Unacceptable

- *Current Bearing: Deep Groove Instrument Design*
  - *Installation accomplished by pressing on both rings against tight fits.*
  - *Disassembly achieved by pulling on housings resulting in scrapped bearings.*

Superelastic Bearing: Taking Advantage of NiTi Characteristics.



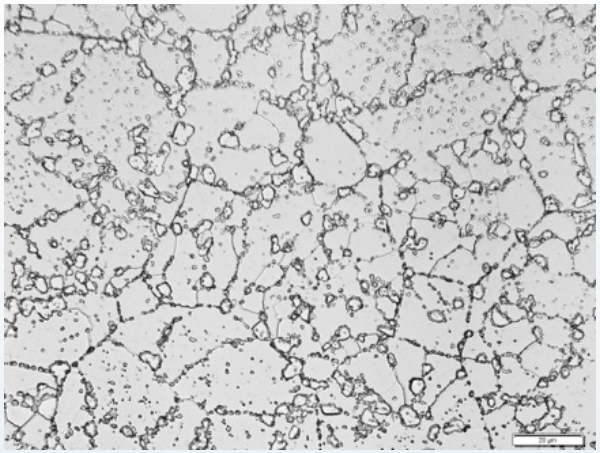


- **60NiTi has more load capability for given geometry:**
  - **Calculations, computer modeling and subsequent experiments led to a 60NiTi-hybrid bearing that withstands removal forces.**
  - **Does the bearing perform (life)?**

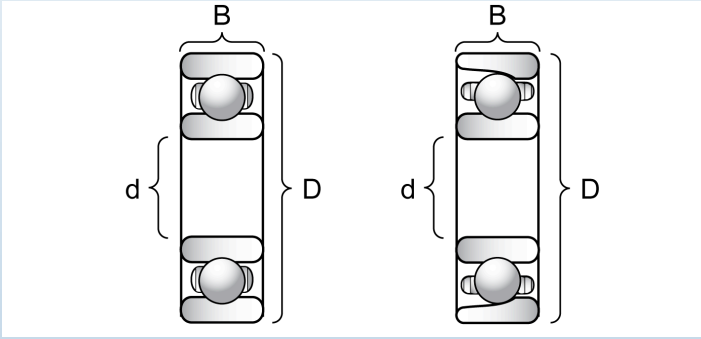
Design Approach: Reusable NiTi R8 Compressor Bearing
(Leverage geometry and materials)

- **Materials**
  - 60NiTi has static stress limit of 3.1GPa. ~3x the static load capacity of steel.
  - Si_3N_4 balls match current baseline but reduce load capacity.
- **Operating Conditions**
  - Moderate speed (2000 rpm), low operating load.
  - Moisture exposure, 5000 hour life requirement.
  - 1.5-2.2kN installation/removal axial load.
- **Bearing Geometry**
  - Baseline bearing is deep groove ball bearing with conventional internal geometry.

60NiTi-Microstructure
(etched to reveal grains)

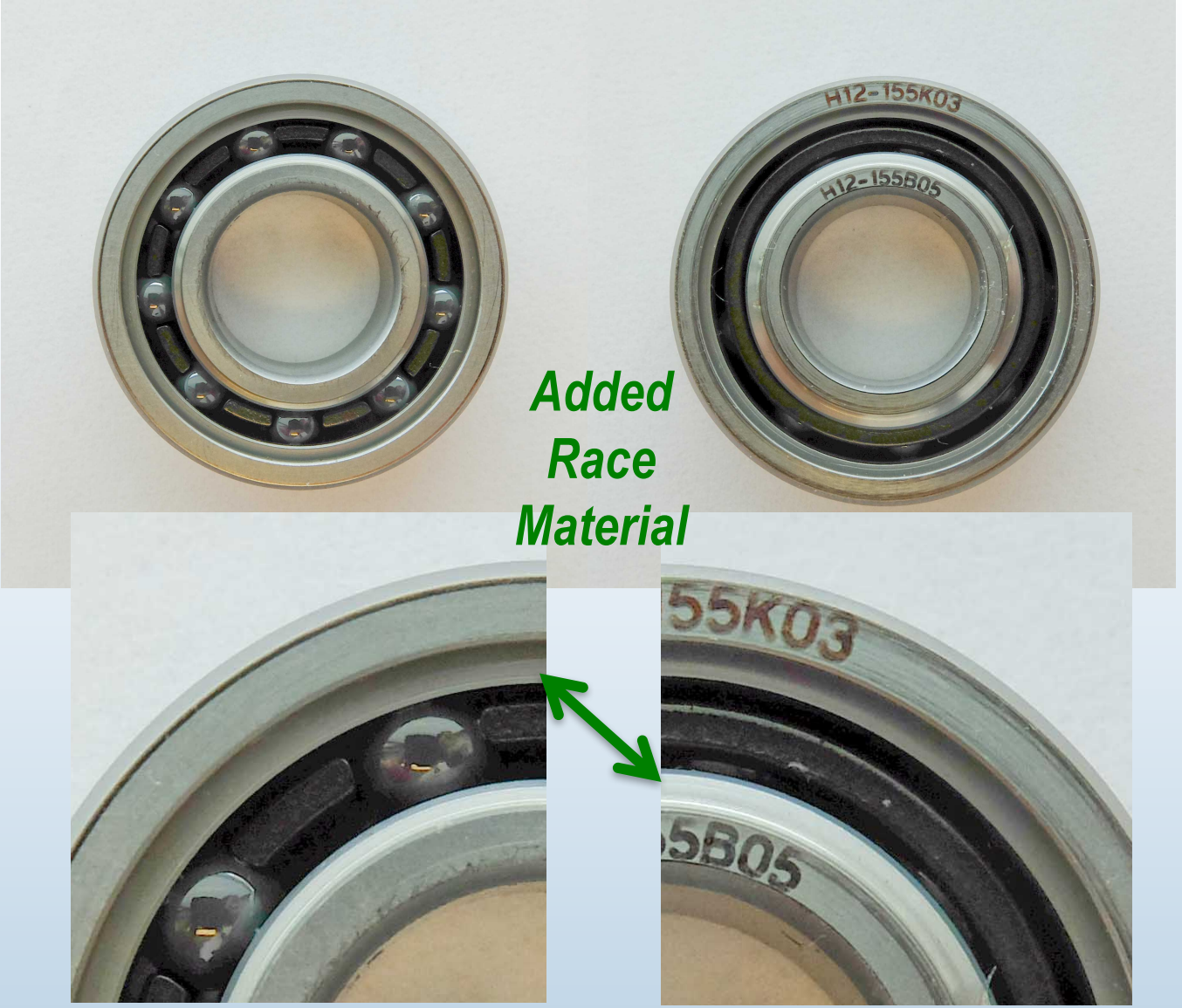


Ball-Race Contact Engineering

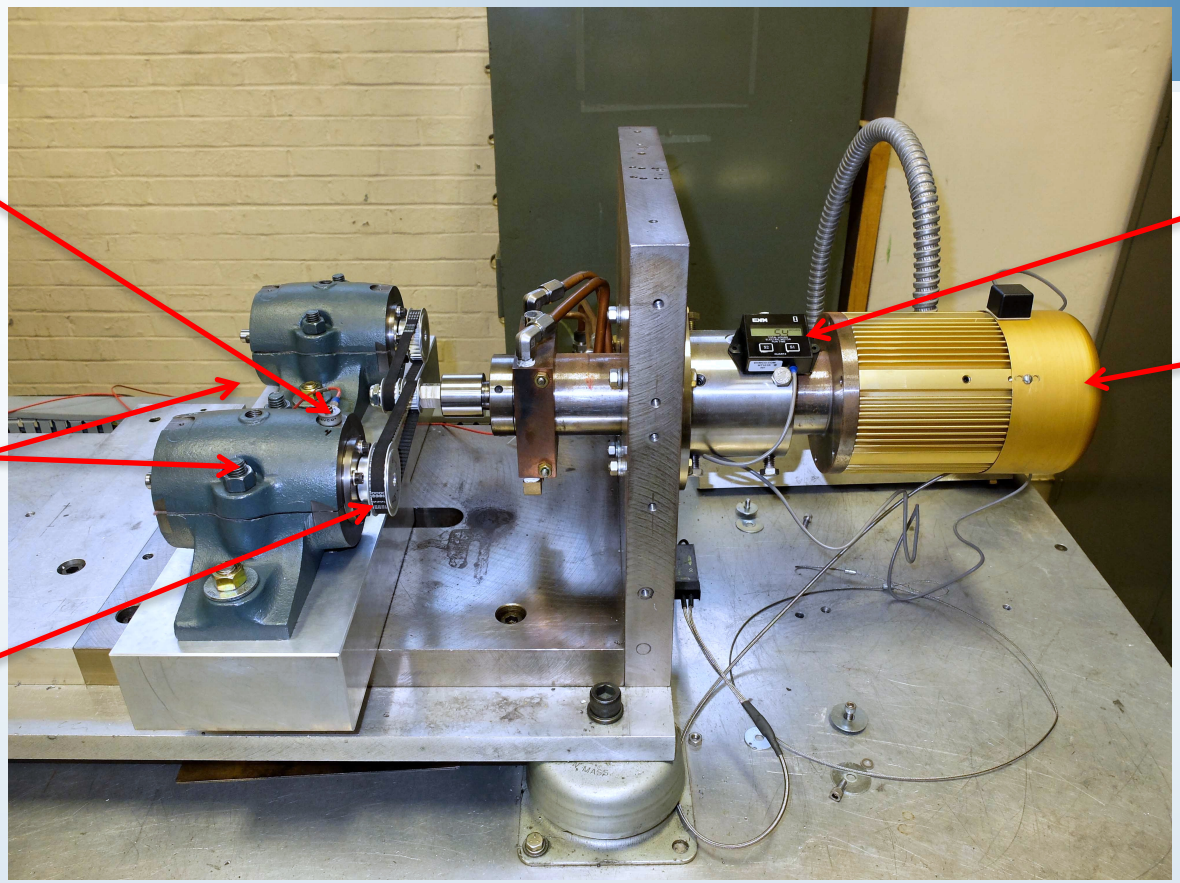


Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

- The resulting modified bearing was manufactured by combination of in-house and specialty bearing firm.



Compressor Bearing Rig

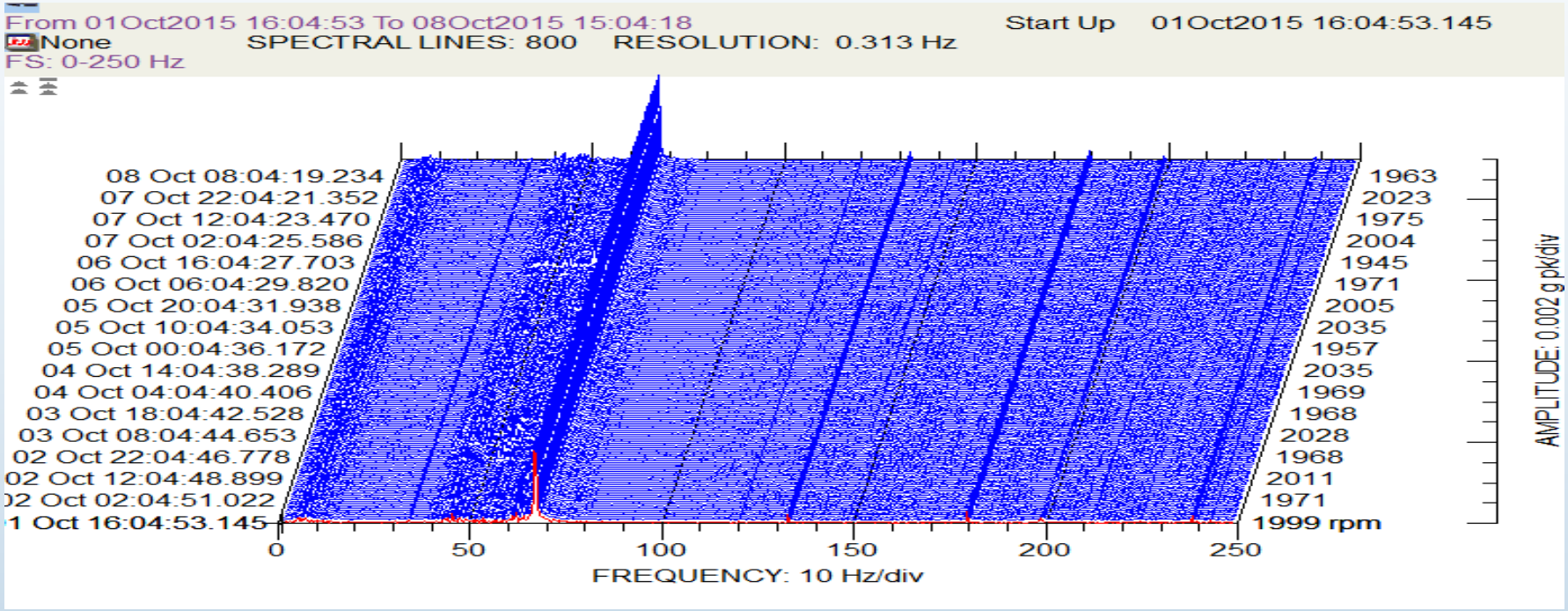


- ***Rig accurately duplicates materials, fits, loads, speed, and drive mechanism of flight compressor.***
- ***Accelerometers on housings to capture vibration signatures for health monitoring.***
- **Rig enables evaluation of load effects, speed effects, bearing performance before/after disassembly and re-installation trials.**
- ***Tests run (24/7) until vibration changes or 10,000 hours reached.***

Removable Superelastic Bearings: Experimental Work

Life Tests:

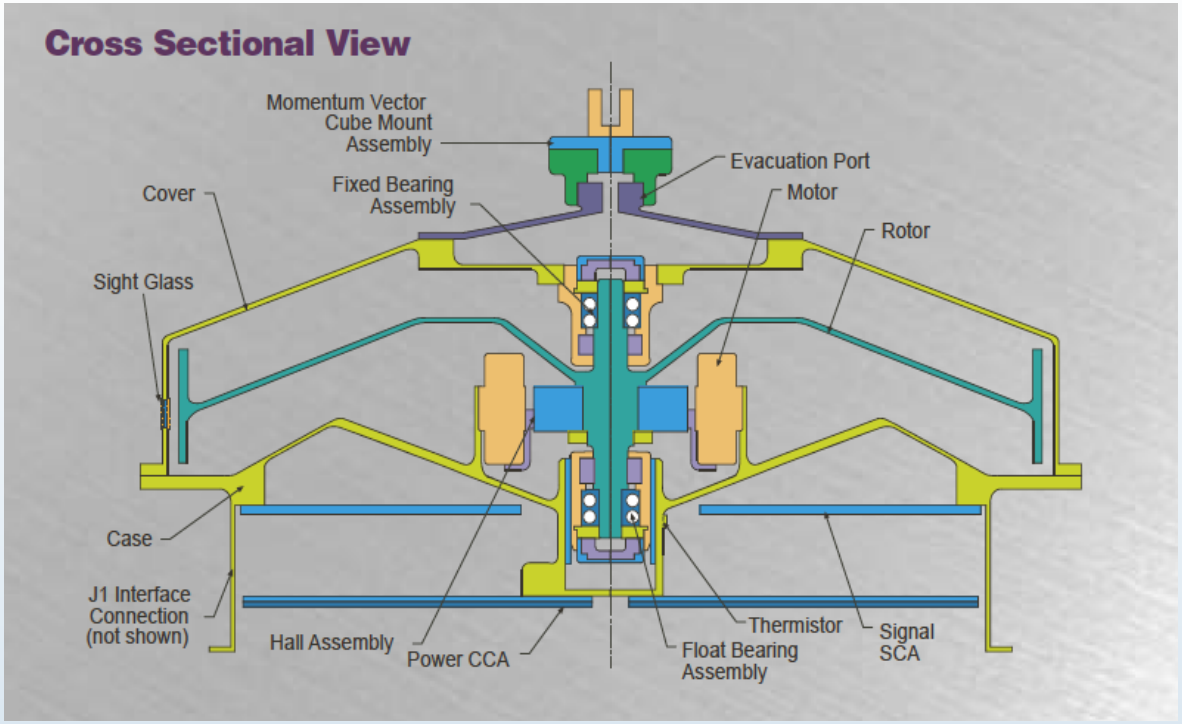
- 4 NiTi bearings underwent 10,000 hour life test.
- 1 700, 5 000 and 10 000 hour tear-down for visual inspection
  - No damage detected by vibration spectrum, by hand, or visual inspection.



10 000 hr: Bearings like new after 1200 M cycles

Space Bearing Application: Game Changer

Typical Reaction Wheel Assembly

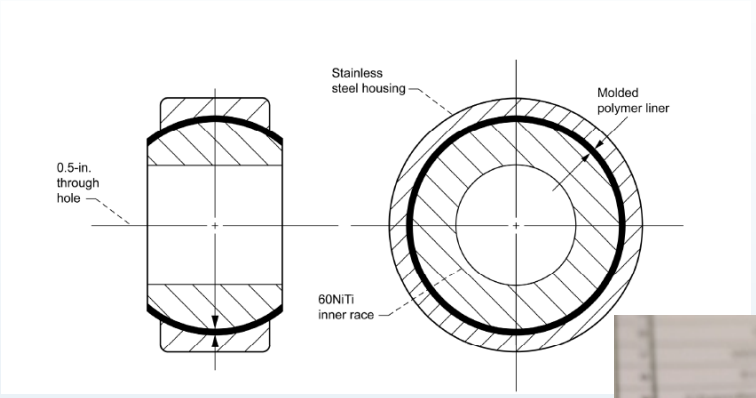


-60NiTi bearing races offer 2x (vs. Rex20) to 5x (440C) improvement.

-Adoption of NiTi bearings enables the elimination of half the ball bearings, reducing friction by half with considerable cost and weight savings.

Spherical Bearings: 60NiTi balls-PTFE Liner

Inner Race (ball) Drawing



Finished inner races

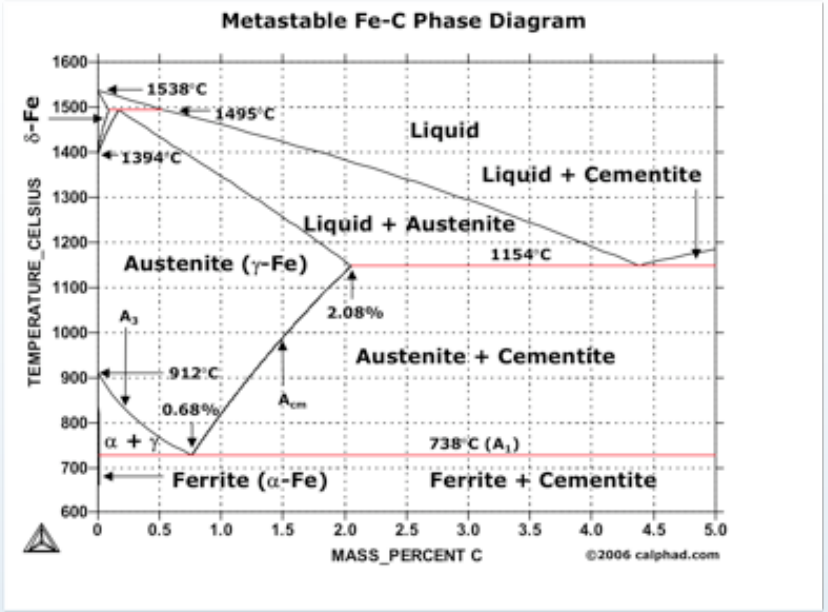
Corrosion-Proof Rod bearings

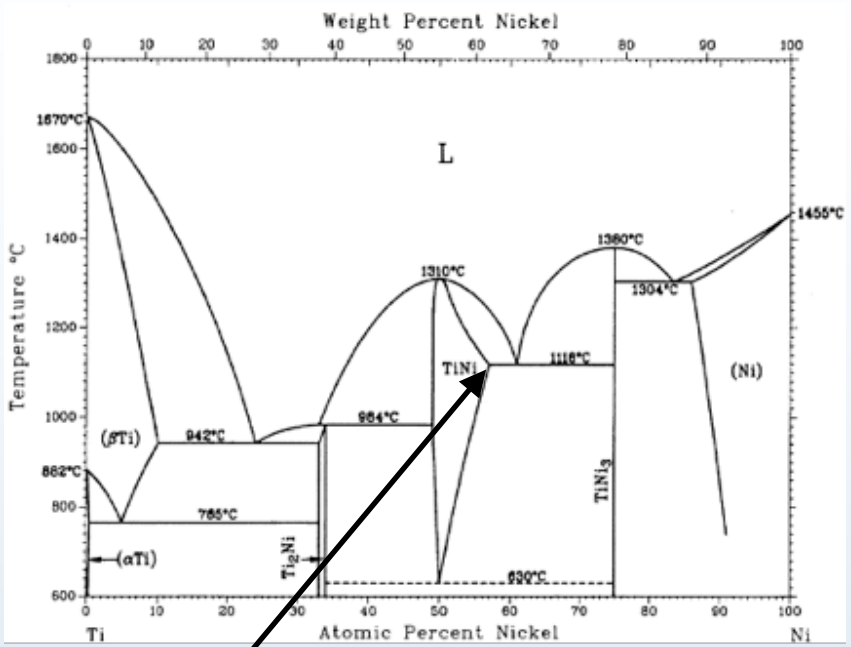
Status: Performance tests confirm equivalence to steel with superior corrosion immunity and lower weight.

Summary: More than a Shape Memory Alloy

- Early NiTi investigations sought a better structural alloy and followed conventional evolutionary path.
- Structural properties of Ni-rich alloys were overshadowed by remarkable shape memory behavior. Buehler was visionary but also pragmatic.
- 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.
- It is expected that structural applications will grow the entire NiTi industry.

Future View: Materials Design Space





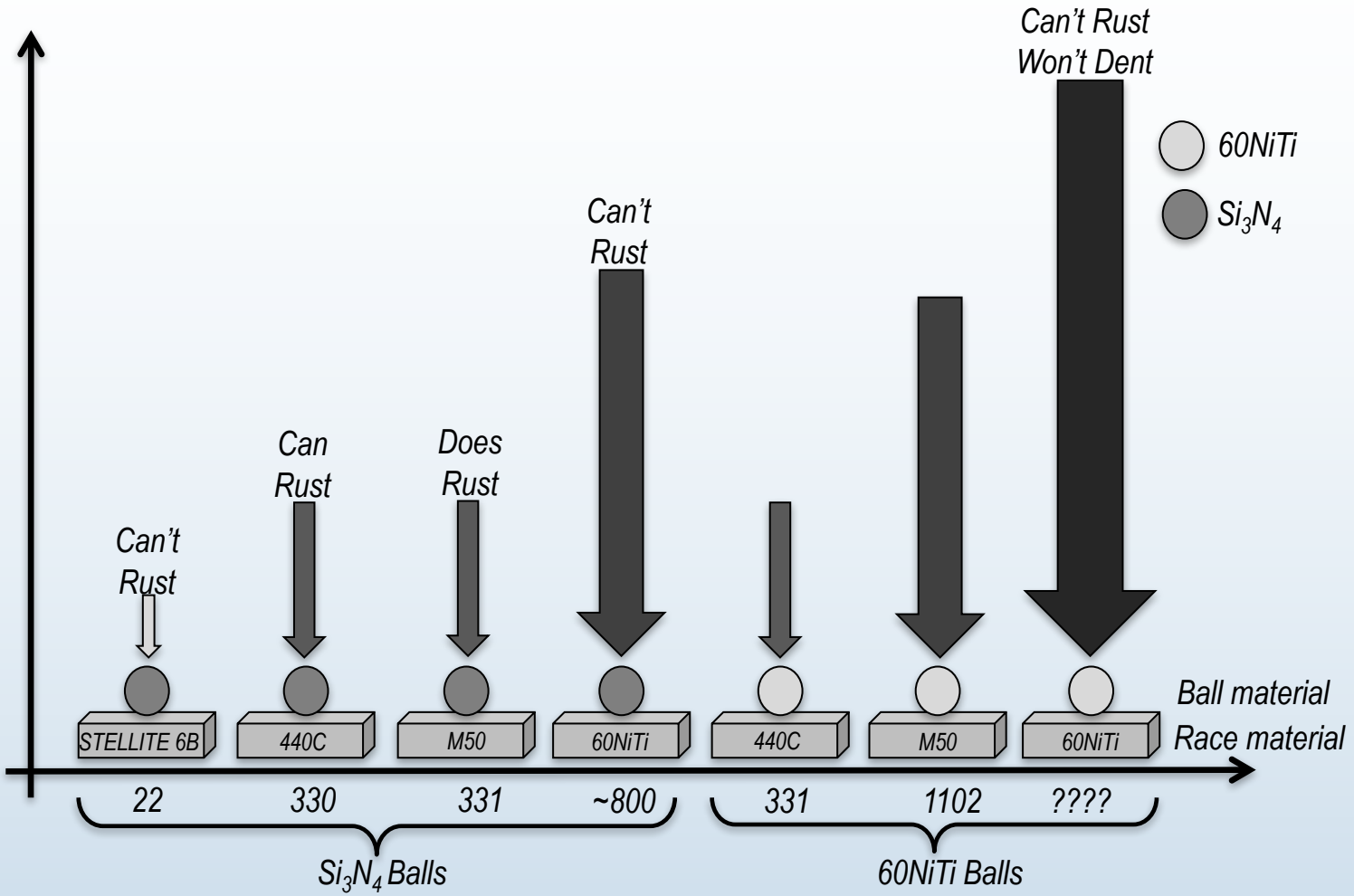
Fe-C system has yielded literally thousands of alloys and variants following centuries of development.

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.

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

Indent test



Low modulus + high hardness +superelasticity = extreme load capacity

Thank You!