Ni-Ti Alloys for Tribological Applications: The Role of In-Situ Nanotechnology

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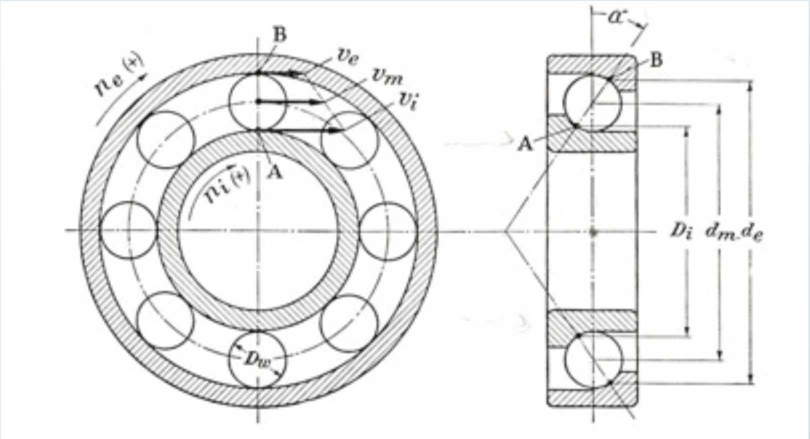
Bearings 101: The what, where, whys and hows

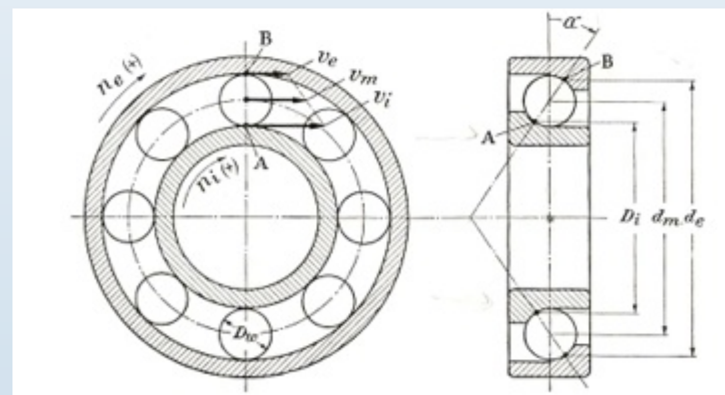
- **Definition: A bearing is a device that allows free movement between two connected machine parts.**
  - Allows one part to turn while the other remains stationary (e.g. wheel vs. car frame, propeller vs. airplane wing).
  - Must operate with low friction and no wear.
  - Be able to withstand severe loads.
  - Ubiquitous (cars, planes, washing machines, spacecraft, pumps, fans, computer disk drives, roller skates and bicycles).
- **Commonly rely on balls rolling between tracks (races).**
- **Bearing materials must be hard.**



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

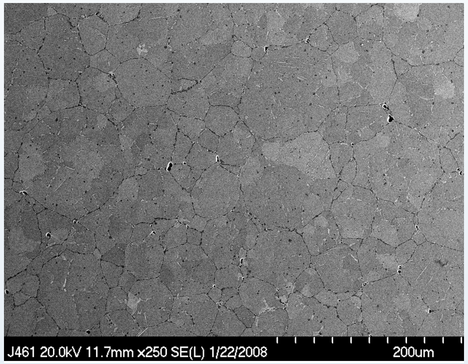


Bearing Material: State-of-the-Art (SOA)
(Current suite of candidates is severely limited)

- 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.



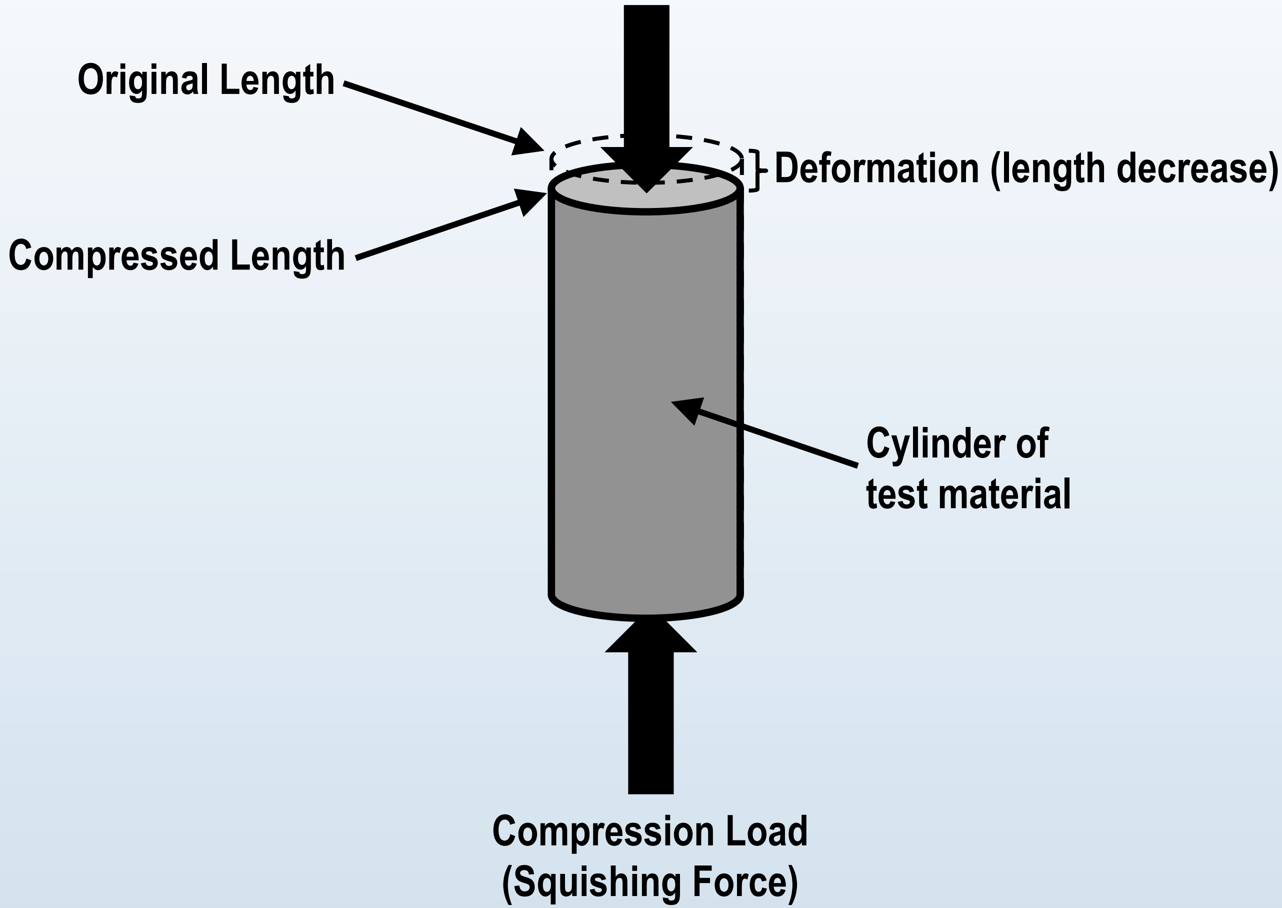
60NiTi microstructure

Highly polished 60NiTi bearing balls

Nitinol 60: Material Peculiarities

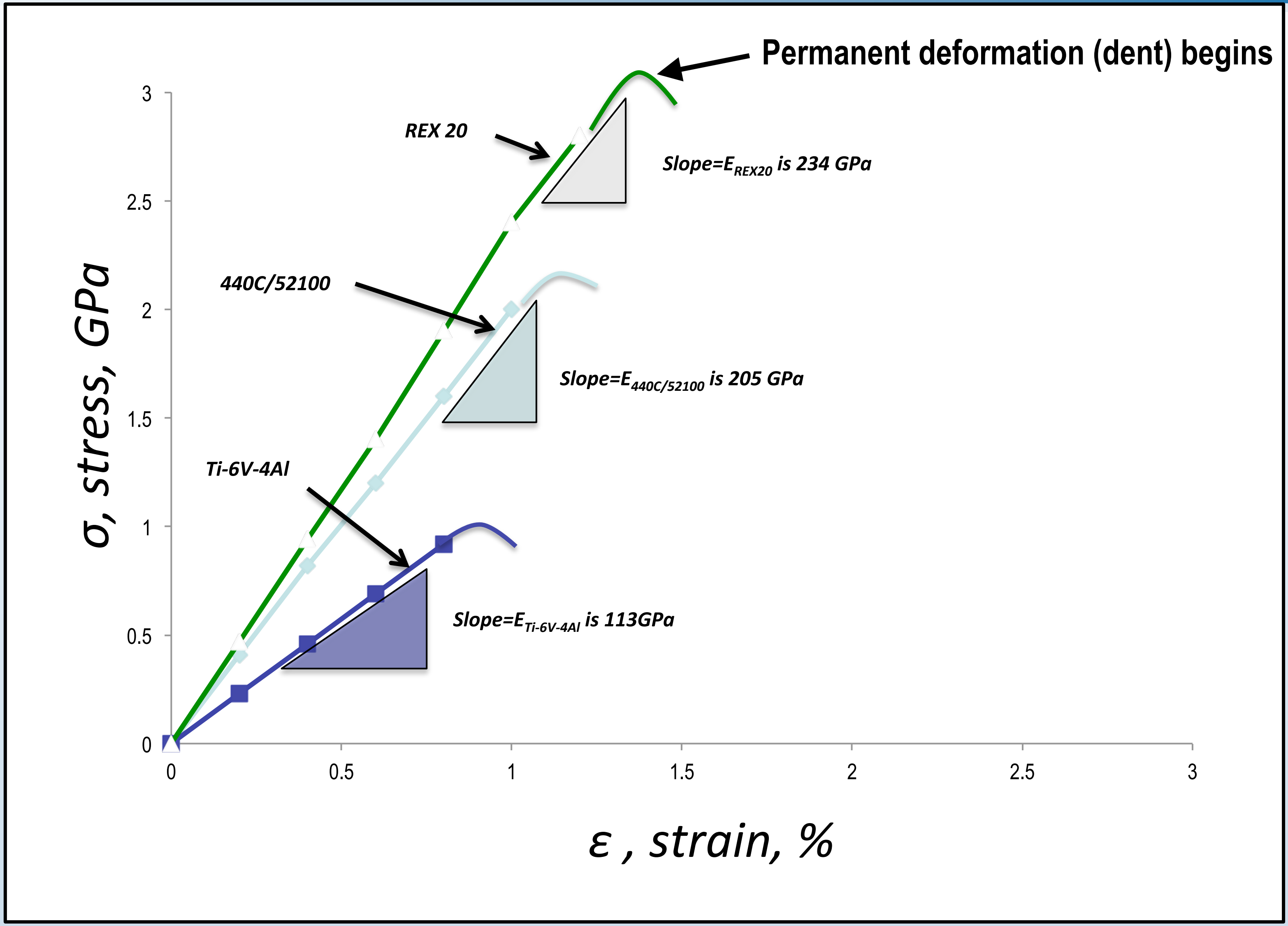
- **Puzzling Mechanical Behavior:**
  - Measured elastic (stress-strain) properties exhibits nearly 10X more deflection than steel.
  - Conventional wisdom: hard and stiff go together yet despite its high hardness, 60NiTi is highly elastic (not so stiff).
- **Question:**
  - What are the reasons behind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

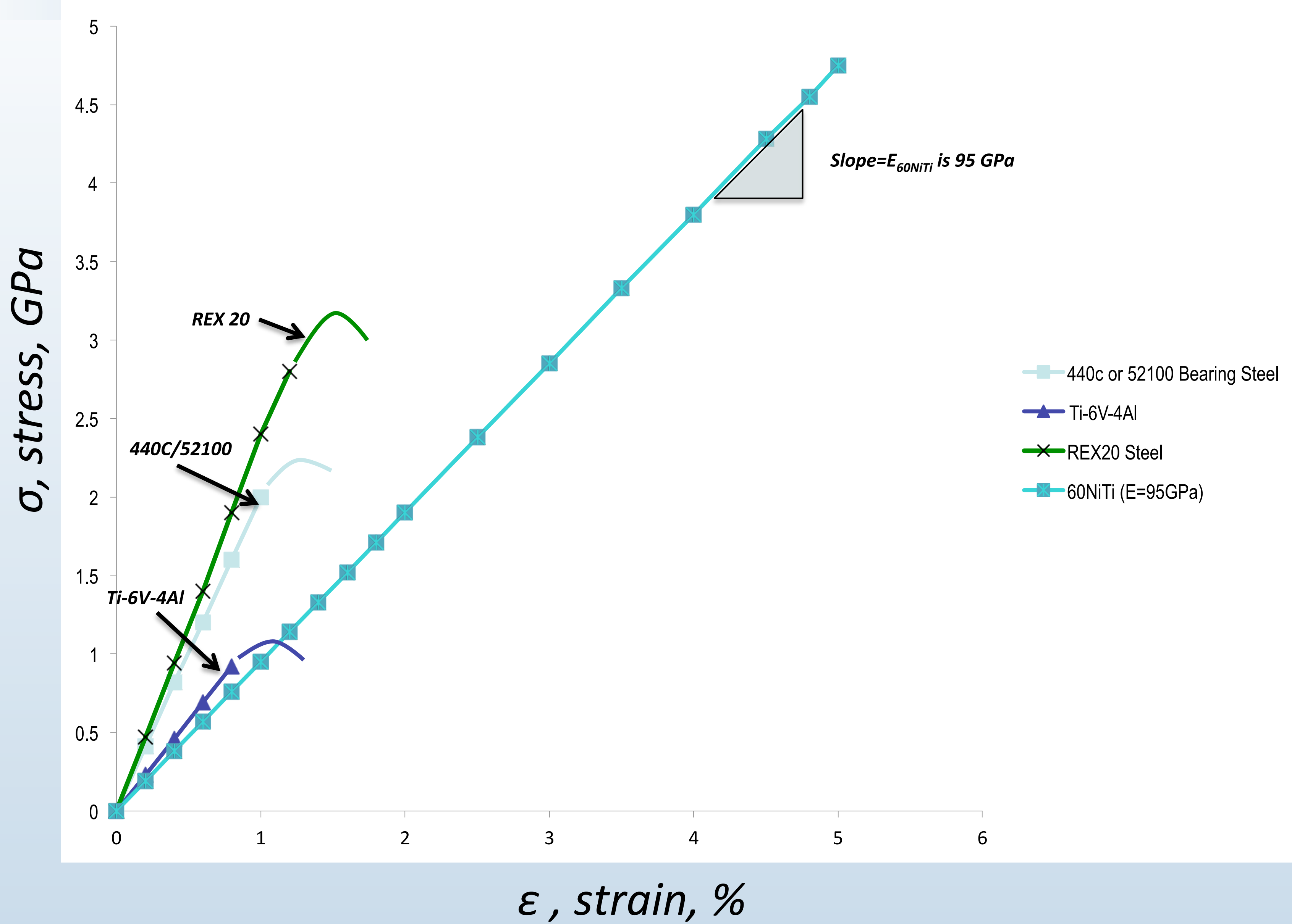


- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior



60NiTi: Stress-Strain Behavior



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

- ***Primary Points***
  - ***Modulus is ½ that of steel, yet hardness is comparable.***
  - ***Tensile strength akin to ceramics.***

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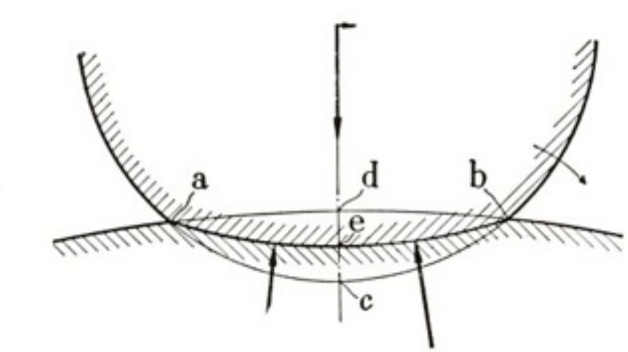
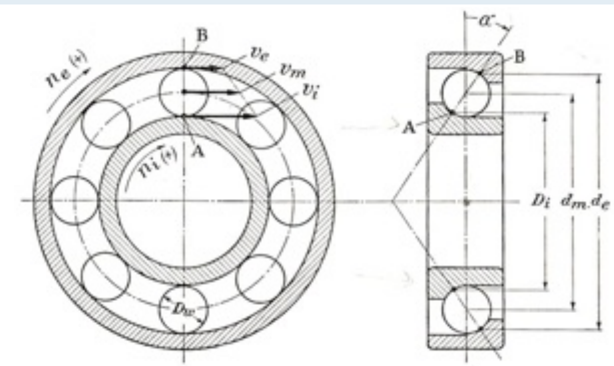
Low Modulus + Hard: A Technical Opportunity

- **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.





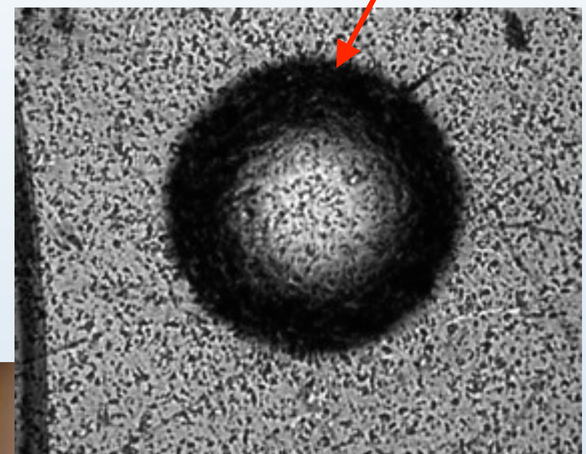
Balls touch races at small points causing race surface dents

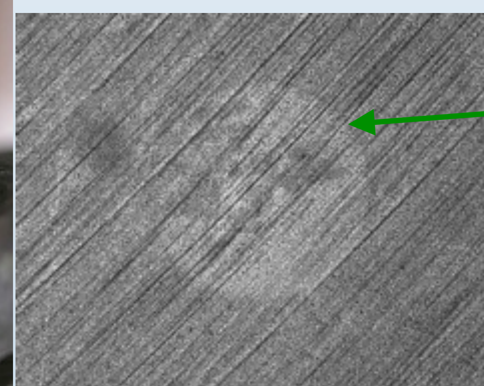
Dents on race surface cause rough running and premature failure

Resilience: Can 60NiTi withstand high dent loads?
(Static denting behavior)

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

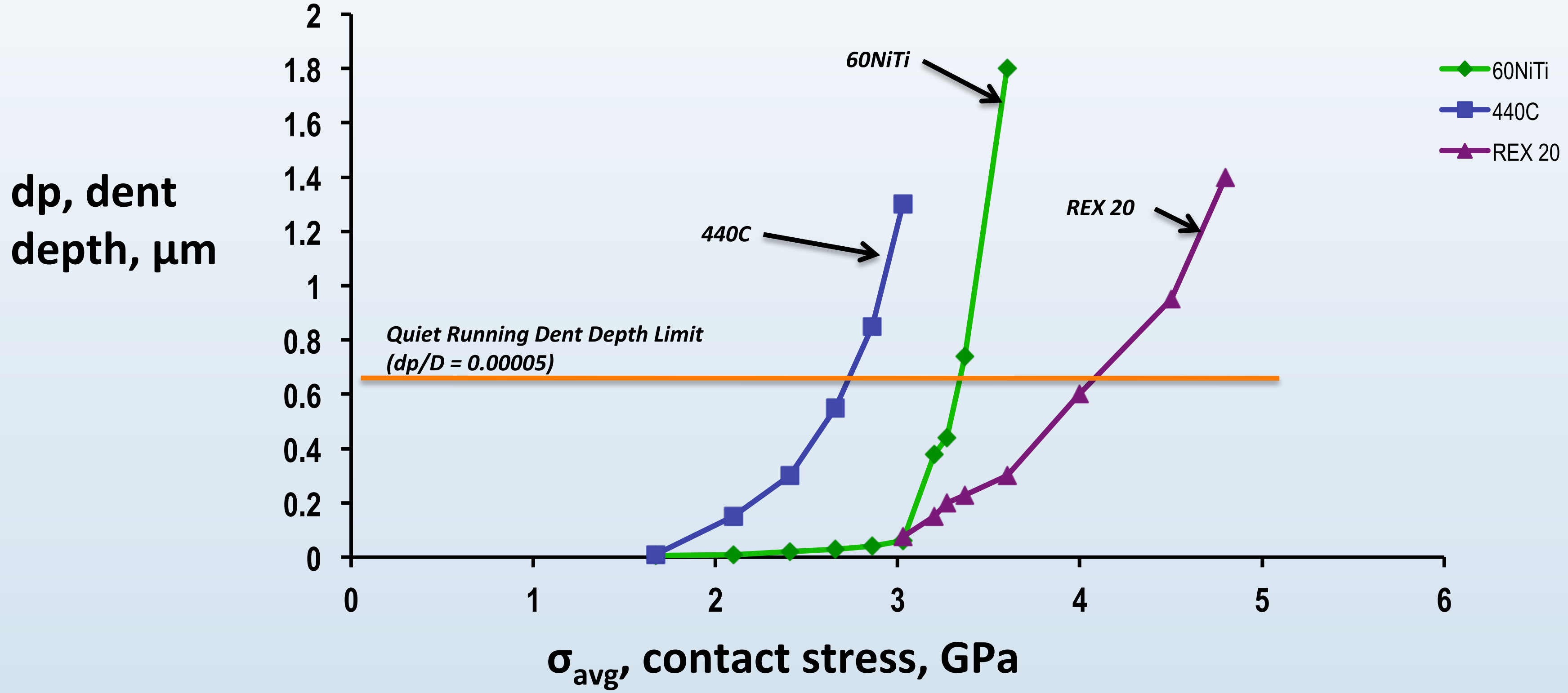

Deep Brinell dent.





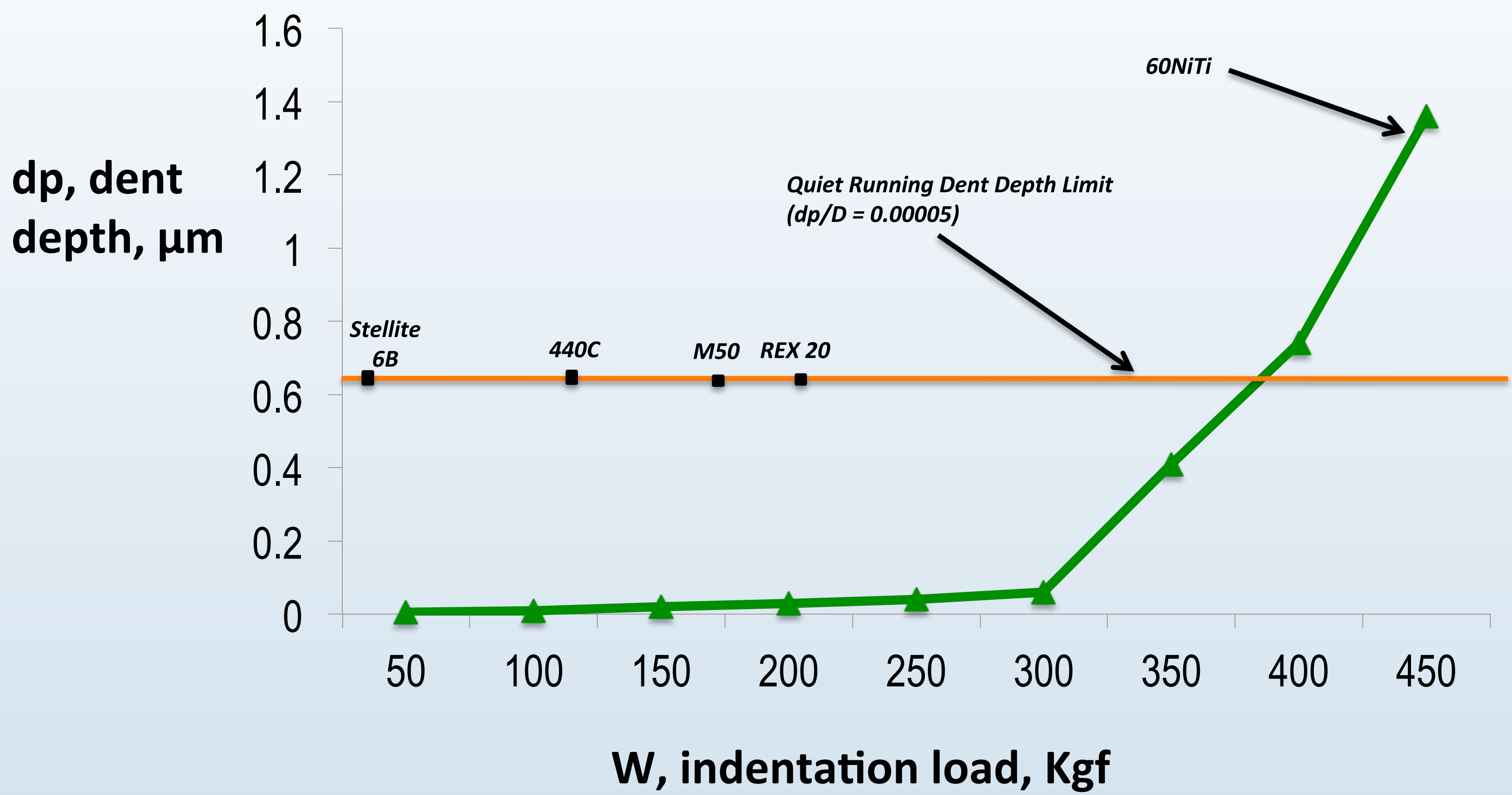
Threshold load visible dent.

Dent Depth vs. Hertz Contact Stress
(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



Dent Depth vs. Load

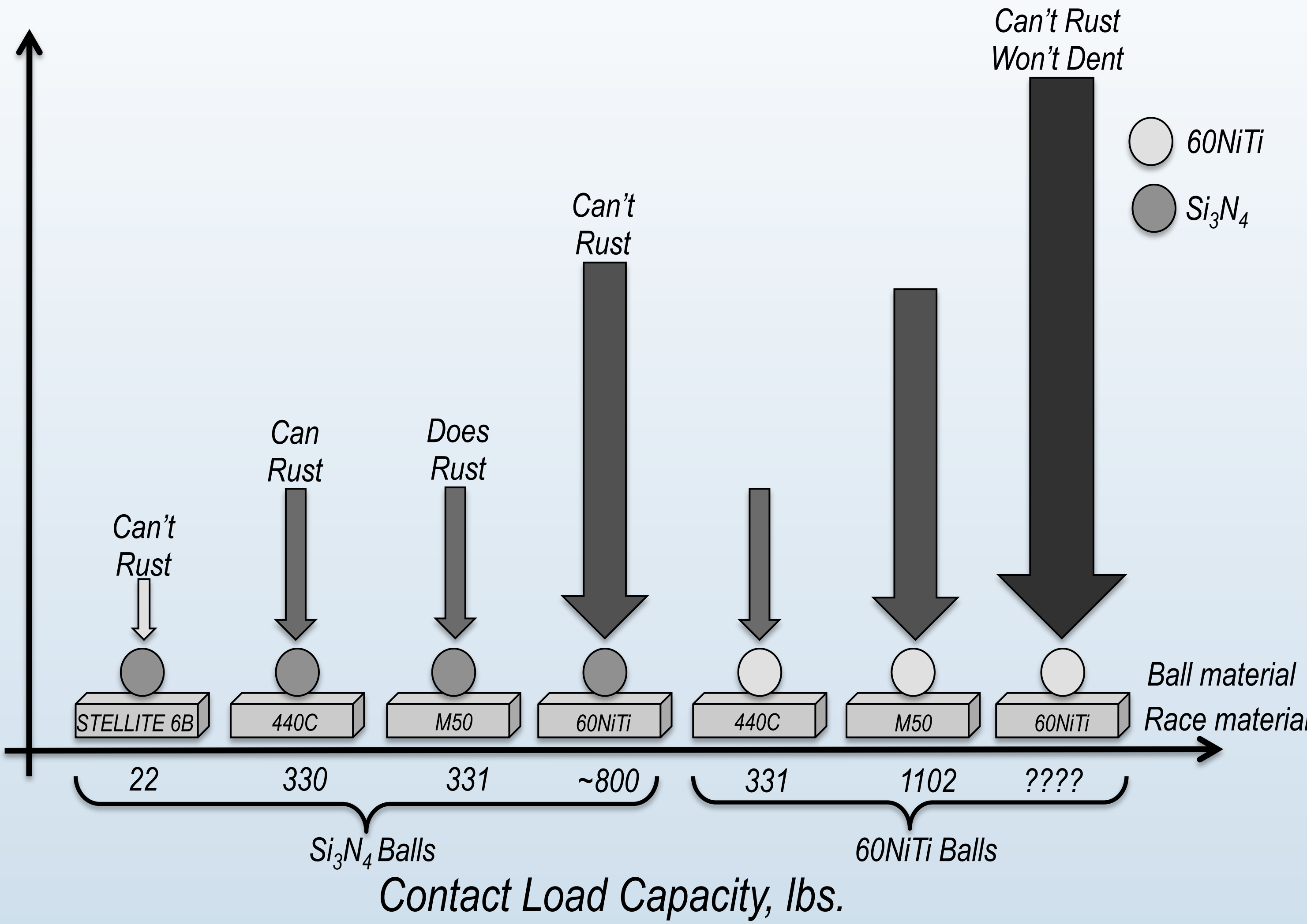
(Si_3N_4 ceramic ball pressed against 60NiTi plate)



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

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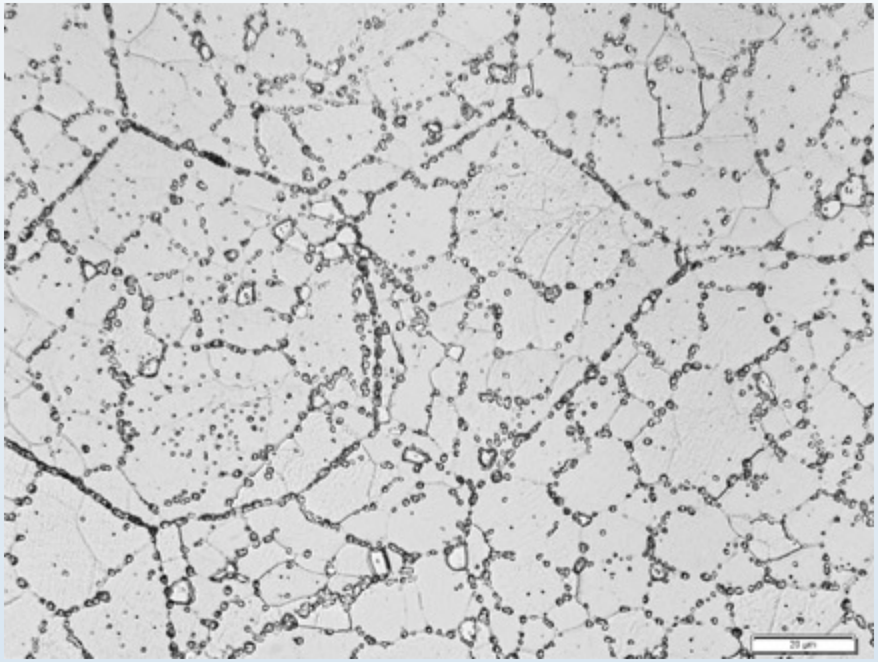
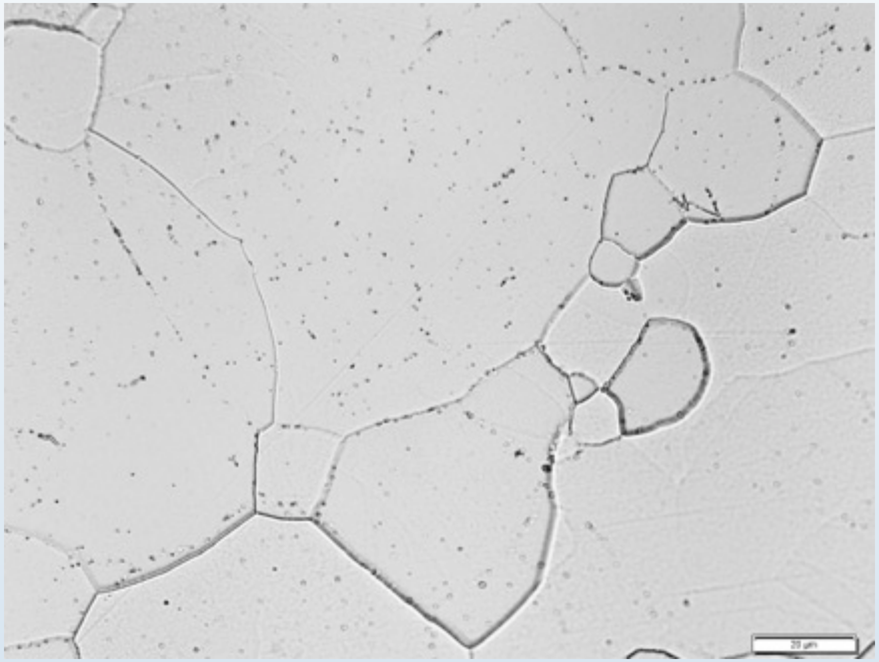
Nitinol 60: Microstructures-Optical View





60NiTi.

NiTi-Hf.

Standard Heat treatment#1: 1000C + Water Quench

Nitinol 60: Microstructures-SEM View

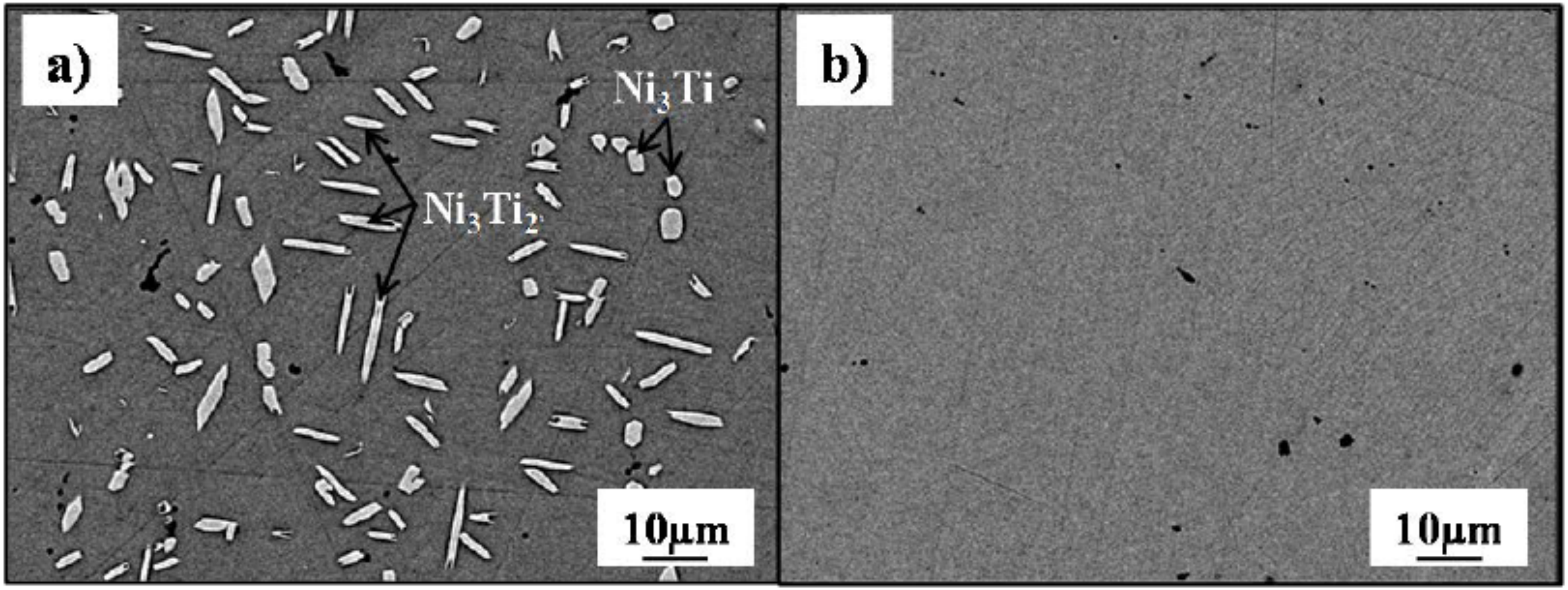


Figure 3:**(a)** BSE SEM micrograph of the 57NiTi solutionized/quenched microstructure revealing coarse Ni_3Ti and Ni_3Ti_2 precipitates, indicated by the arrows, in a B2 matrix. **(b)** BSE SEM micrograph of the 54NiTi solutionized/quenched microstructure where no obvious coarse precipitates were observed at this magnification. The fine scale of the Ni_4Ti_3 precipitates in both alloys precluded their observation by SEM at this magnification.

Conventional SEM Cannot see Hardening Phase

Nitinol 60: Microstructures-TEM View

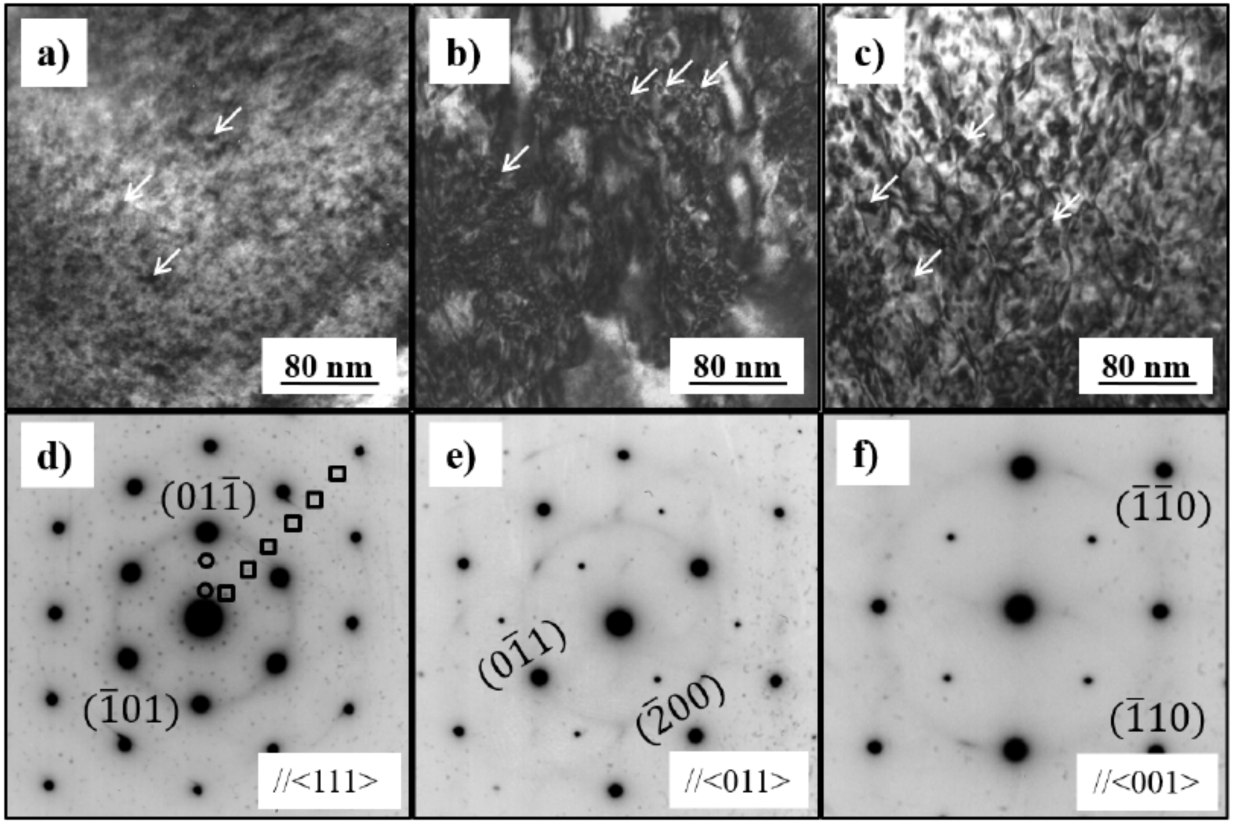


Figure 4: Multiple beam bright field image of the solution annealed condition for **(a)** 53NiTi, **(b)** 56NiTi, and **(c)** 58NiTi. Note the stark difference in strain contrast as Ni content is increased especially from 53NiTi to 56Ni. SAED patterns for the solution annealed condition for the 54NiTi sample from **(d)** the [111] zone axis of B2 matrix phase with squares highlighting the Ni_4Ti_3 reflections and circles highlighting the R-phase, **(e)** the [011] zone axis of B2 matrix phase, and **(f)** the [001] zone axis of B2 matrix phase.

Conventional TEM Hints at a hardening phase but cannot see it

Nitinol 60: Super-TEM View

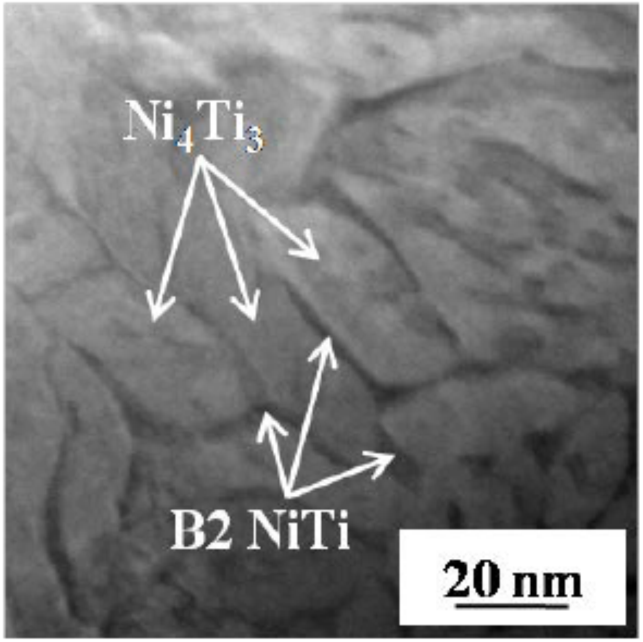


Figure 5: STEM-HAADF image from a 55NiTi alloy to give prospective of Ni_4Ti_3 spacing and narrow B2 NiTi channels between the precipitates. Ni_4Ti_3 volume fraction was ~ 69%.

STEM HAADF Reveals Nano phase

NiTi-Hf Alloy: STEM reveals same nanophase

B.C. Hornbuckle et al. / Journal of Alloys and Compounds 640 (2015) 449–454 451

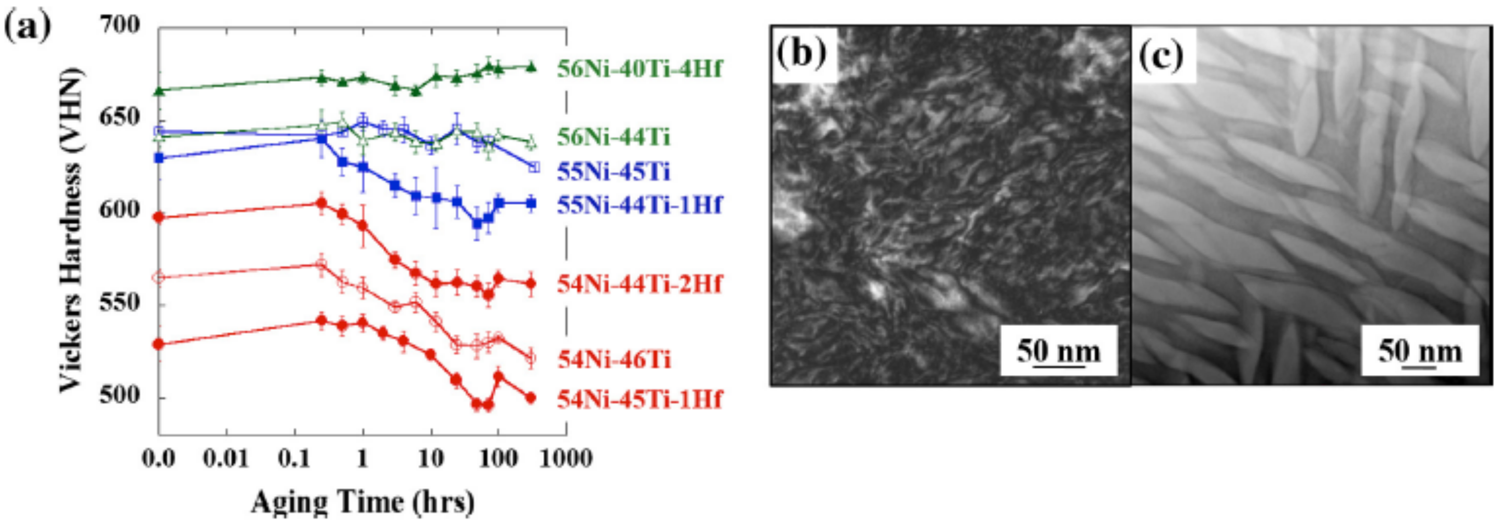
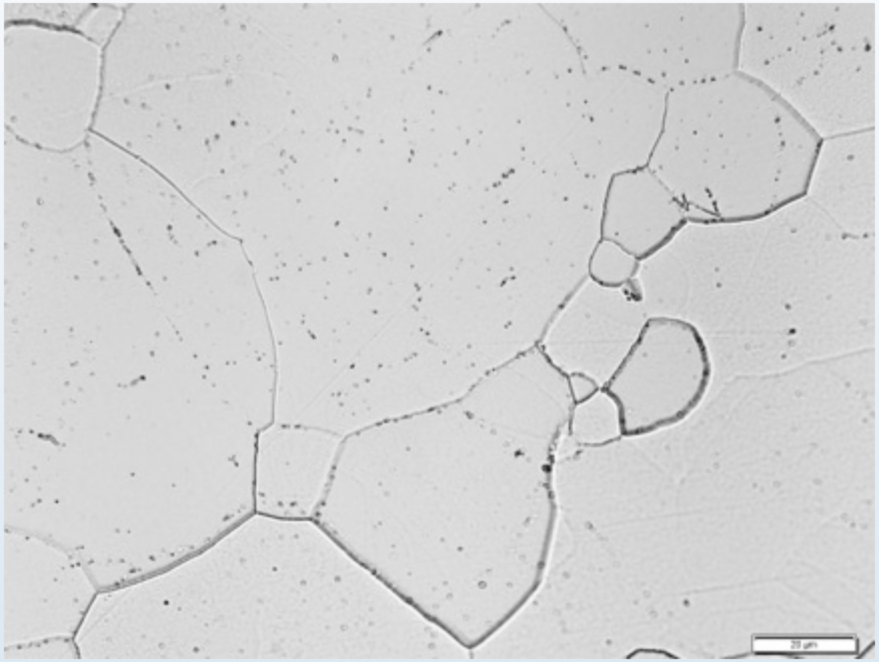


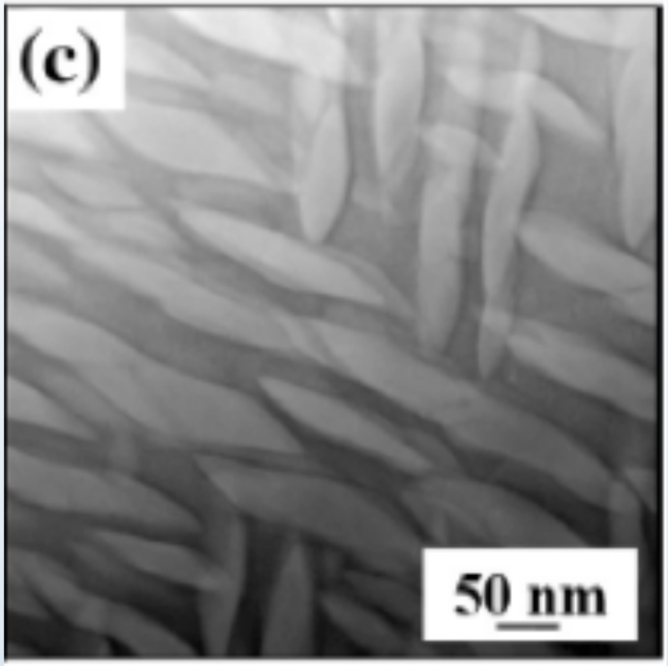
Fig. 1. (a) 400 °C aging curves for various Ni-rich binary and ternary Ni–Ti alloys; note the binary data is from [8]. (b) Bright-field image and (c) STEM-HAADF image of the 54Ni–44Ti–2Hf solutionized/quenched microstructure. Note the significant strain contrast generated from the high volume fraction of Ni_4Ti_3 precipitates in (b) and the nanoscale Ni_4Ti_3 precipitates and narrow B2 matrix channels revealed in (c).

STEM HAADF-NiTi-Hf alloy also shows Ni4Ti3 Phase-refined.

NiTi Alloys: Hardened by naturally formed nanotechnology



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



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

- ***Takeaway Points***
  - ***In-situ formation of hard nano-scale Ni4Ti3 particles hardens alloy.***
  - ***Revealed by exotic and recent microscopy technology.***
  - ***Knowledge aids and guides future development.***

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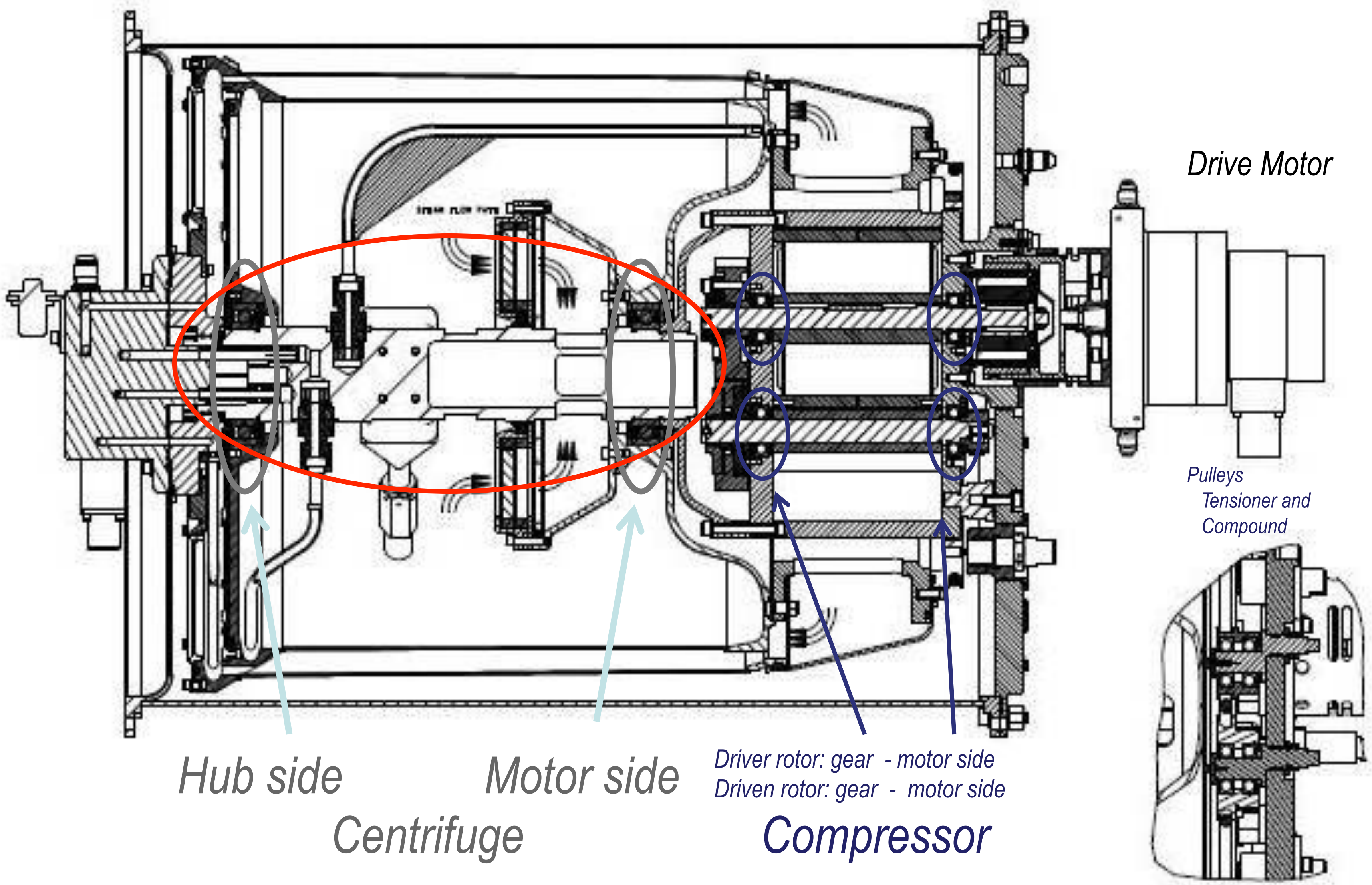
Dent and Corrosion Resistant Ball Bearings

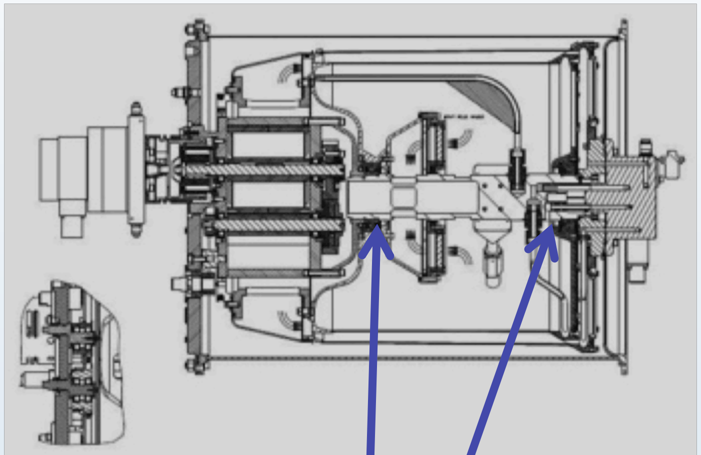
Finished 60NiTi-Hybrid Bearing

ISS DA Centrifuge Bearings: 60NiTi Application

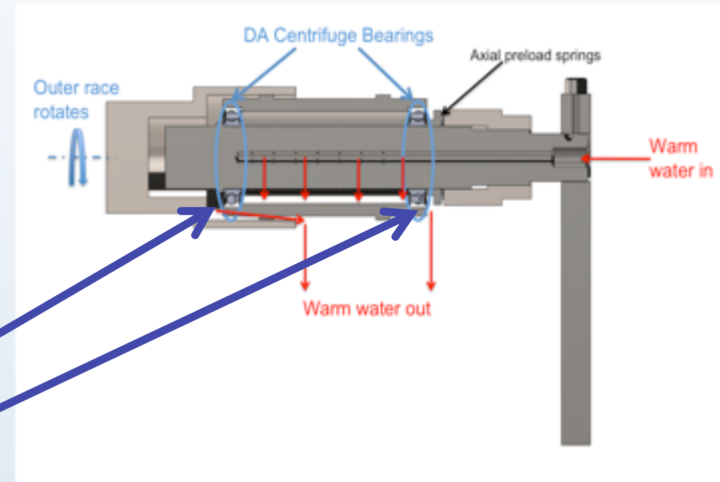


Bearing Testing:
(Warm, wet, slow conditions)

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.

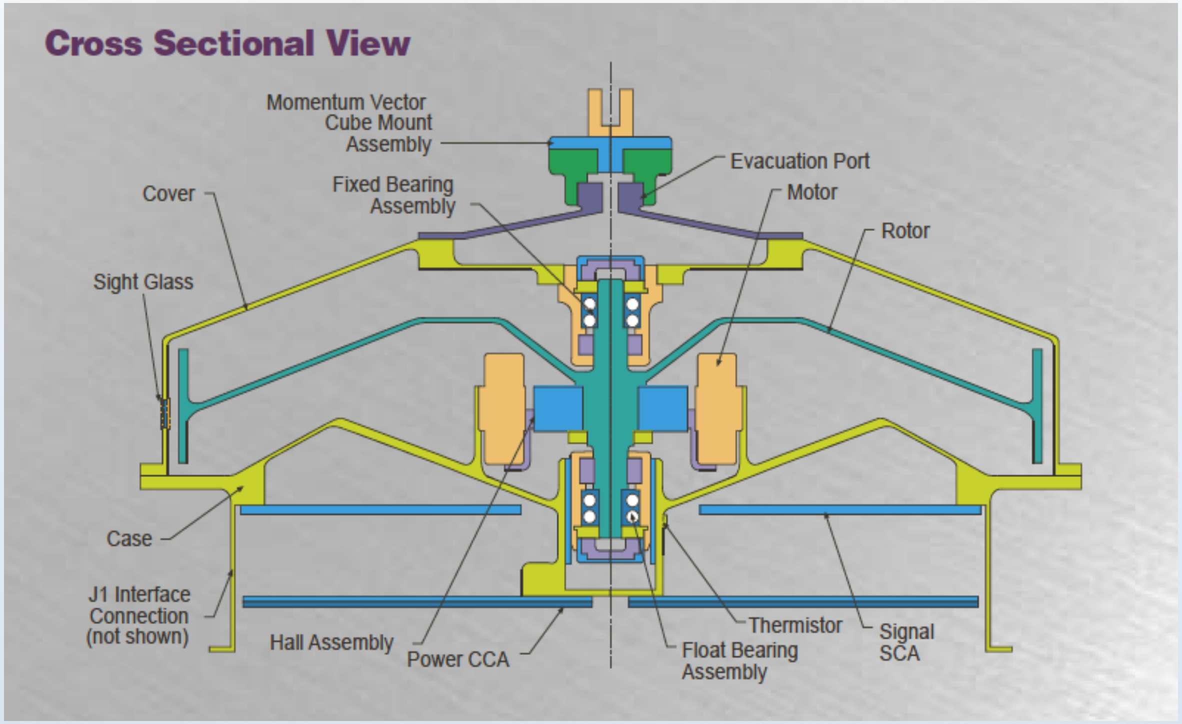
DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid

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

Space Bearing Application: Game Changer

Typical Reaction Wheel Assembly



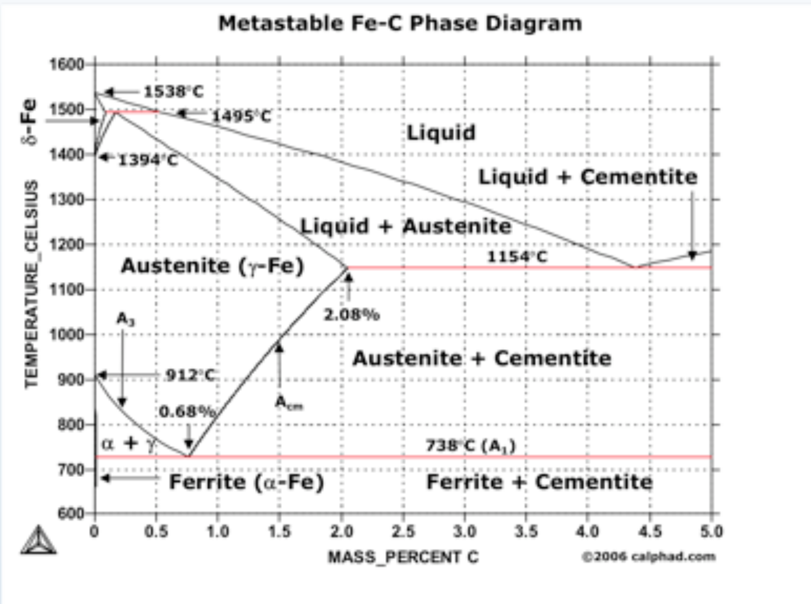
-60NiTi bearing races offer 2x (vs. Rex20) to 5x (440C) improvement.

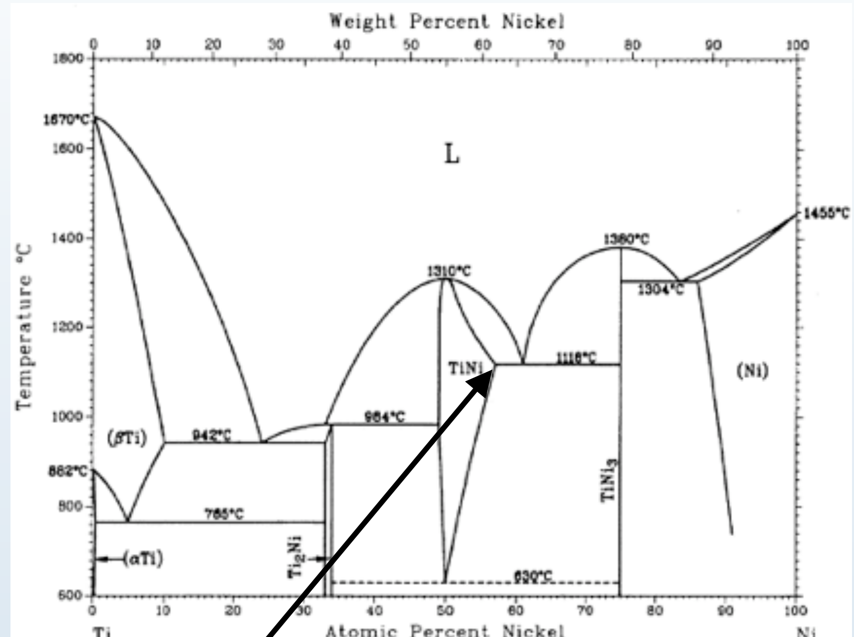
-Adoption of NiTi bearings enables the elimination of half the ball bearings, reducing friction by half with considerable cost and weight savings.

Summary: NiTi is a new nanotechnology!

- NiTi alloy R&D initially followed conventional macro and microscopic maturation path.
- Macro-level properties hinted at something unusual driving behavior at microscopic level.
- Traditional microscopic level tools were unsuccessful in deciphering the mechanisms responsible for behavior (and revealing clues to further improvements).
- High resolution-nontraditional microscopy revealed in-situ formed nanoscale phase drives macroscopic properties.
- With this knowledge we are now positioned to push the technology forward.

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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