Launch Load Resistant Spacecraft Mechanism Bearings Made From Ni-Ti Superelastic Intermetallic Materials

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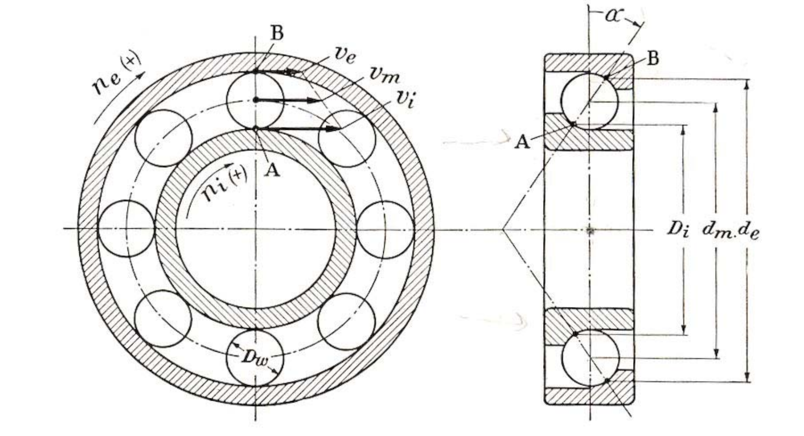
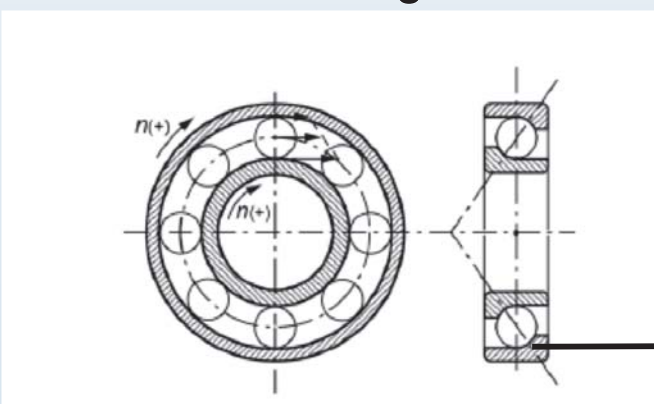
Motivation: the ride into space can be rough
(Vibration/loads impact bearings and components)

- Bearing and component materials must be:
  - 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 centripetal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture

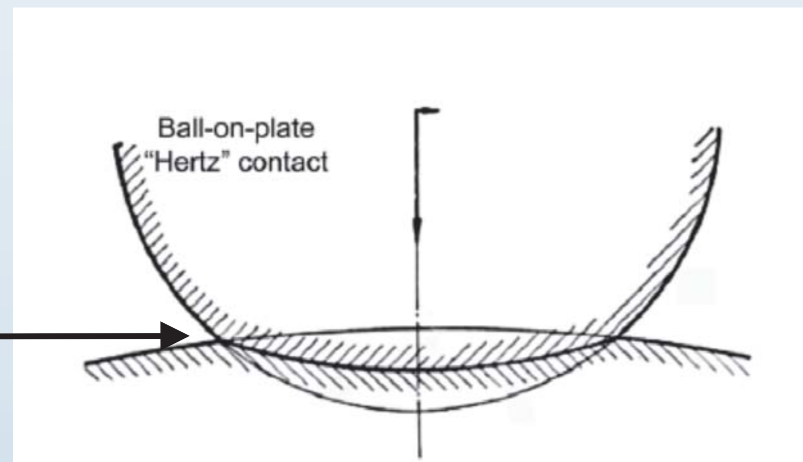


Contact Engineering: Ball-Race

- When hard surfaces contact
  - Forces are transmitted at small, concentrated contact points (Hertz).
  - Resulting stresses cause deformations that help “spread the load”.
  - Contact area is a function of the geometry, material stiffness and load.
  - High stiffness (modulus) inhibits deformations leading to small contact area and high stresses (contrast with a tire contacting the ground).



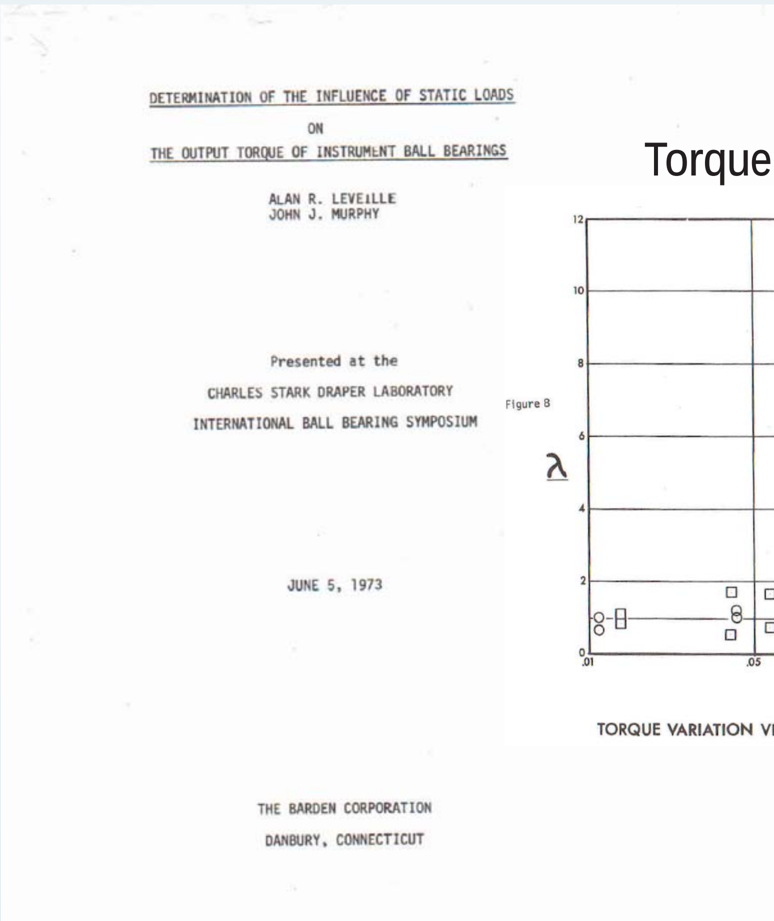
Ball-raceway contacts



- *Hard surfaces can dent*
  - *Even modest loads can exceed stress capability limits.*
  - *Bearing raceways are particularly prone to Brinell dent damage.*

Ball-Race Static Load Capacity: Leveille & Murphy (Dent depth vs. running torque noise)

- Classic 1973 paper on dent depth/ball diameter (dp/D) effects
  - Showed that dp/D~0.0001 criterion too aggressive for precision bearings with respect to torque ripple. Proposed dp/D~0.00003 to 0.00005



DETERMINATION OF THE INFLUENCE OF STATIC LOADS

ON

THE OUTPUT TORQUE OF INSTRUMENT BALL BEARINGS

ALAN R. LEVEILLE
JOHN J. MURPHY

Presented at the

CHARLES STARK DRAPER LABORATORY

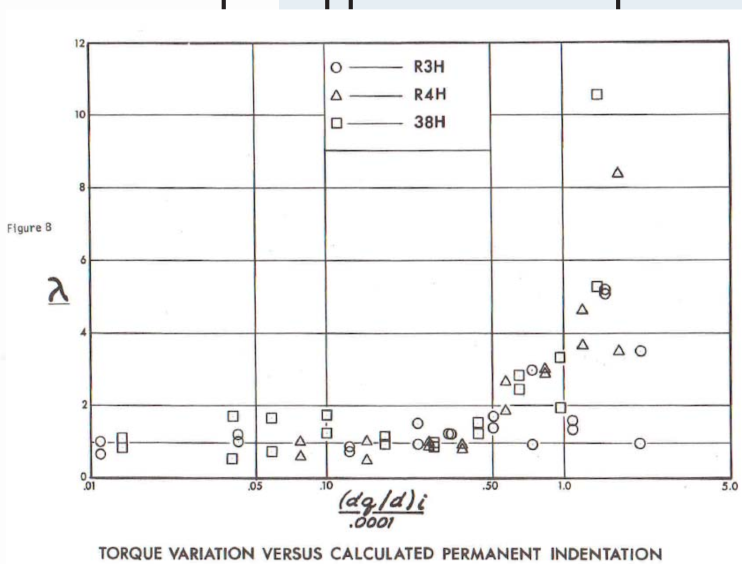
INTERNATIONAL BALL BEARING SYMPOSIUM

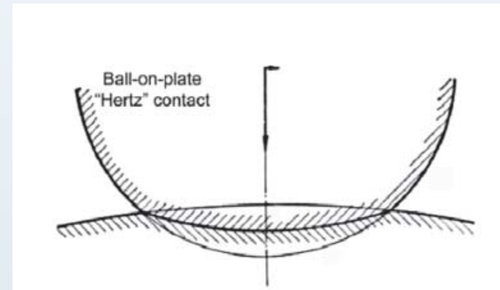
JUNE 5, 1973

THE BARDEN CORPORATION

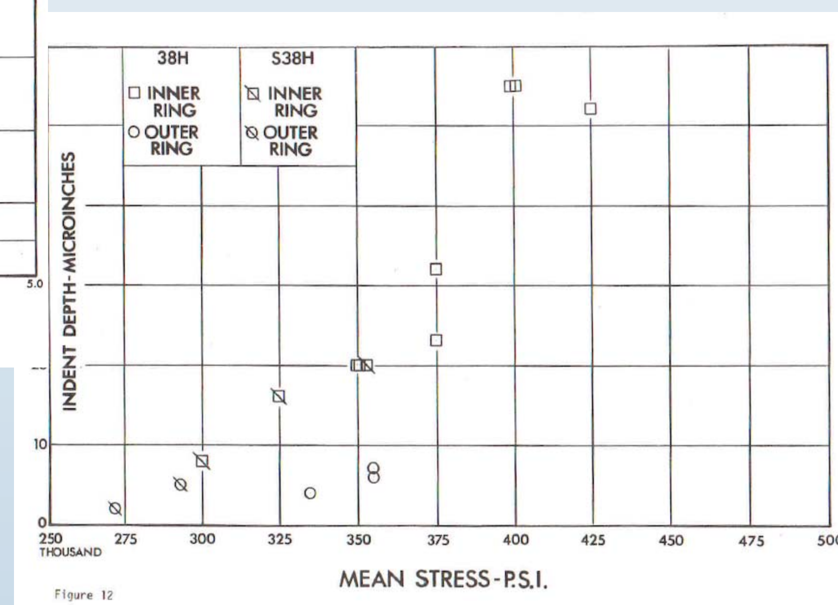
DANBURY, CONNECTICUT

Torque Ripple vs. dent depth



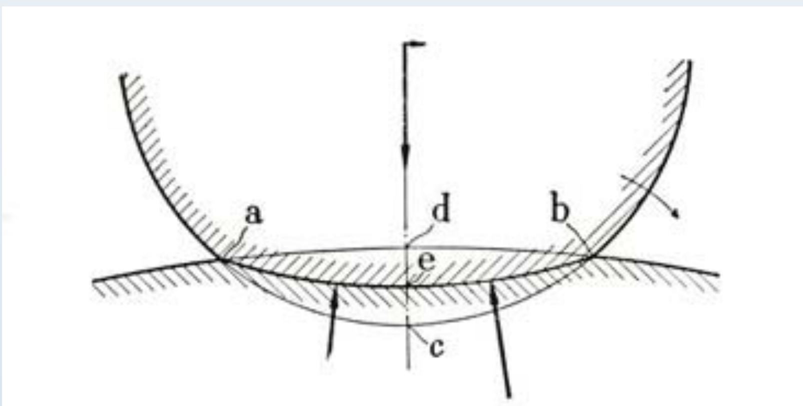


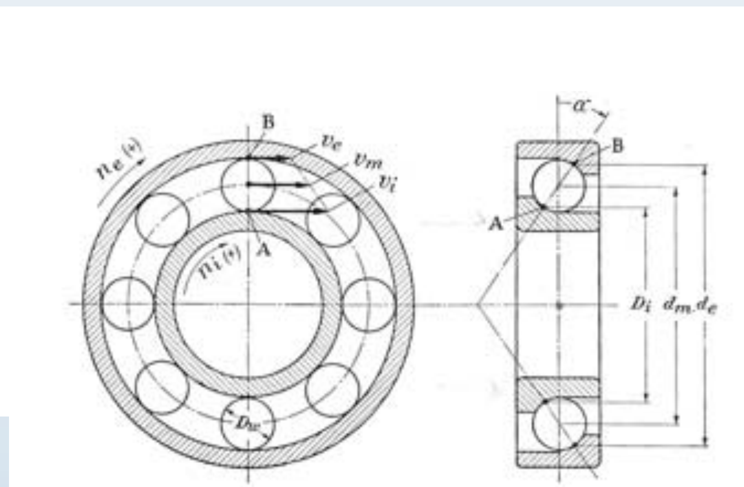
Dent depth vs. hertz stress



Contact Engineering: Geometry, Loads and Materials

- Engineering Mitigations
  - Reduce loads through vibration isolation.
  - Reduce the stresses through margin additions such as increased bearing size and increased ball-race conformity.
  - Use harder materials less prone to denting.





- *Implications*
  - *Load reduction and vibration isolation can add mass.*
  - *Bearing design and material changes introduce other complications.*

Bearing Material: State-of-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.

Technical Opportunity:

60NiTi (a.k.a. NiTiNOL 60)

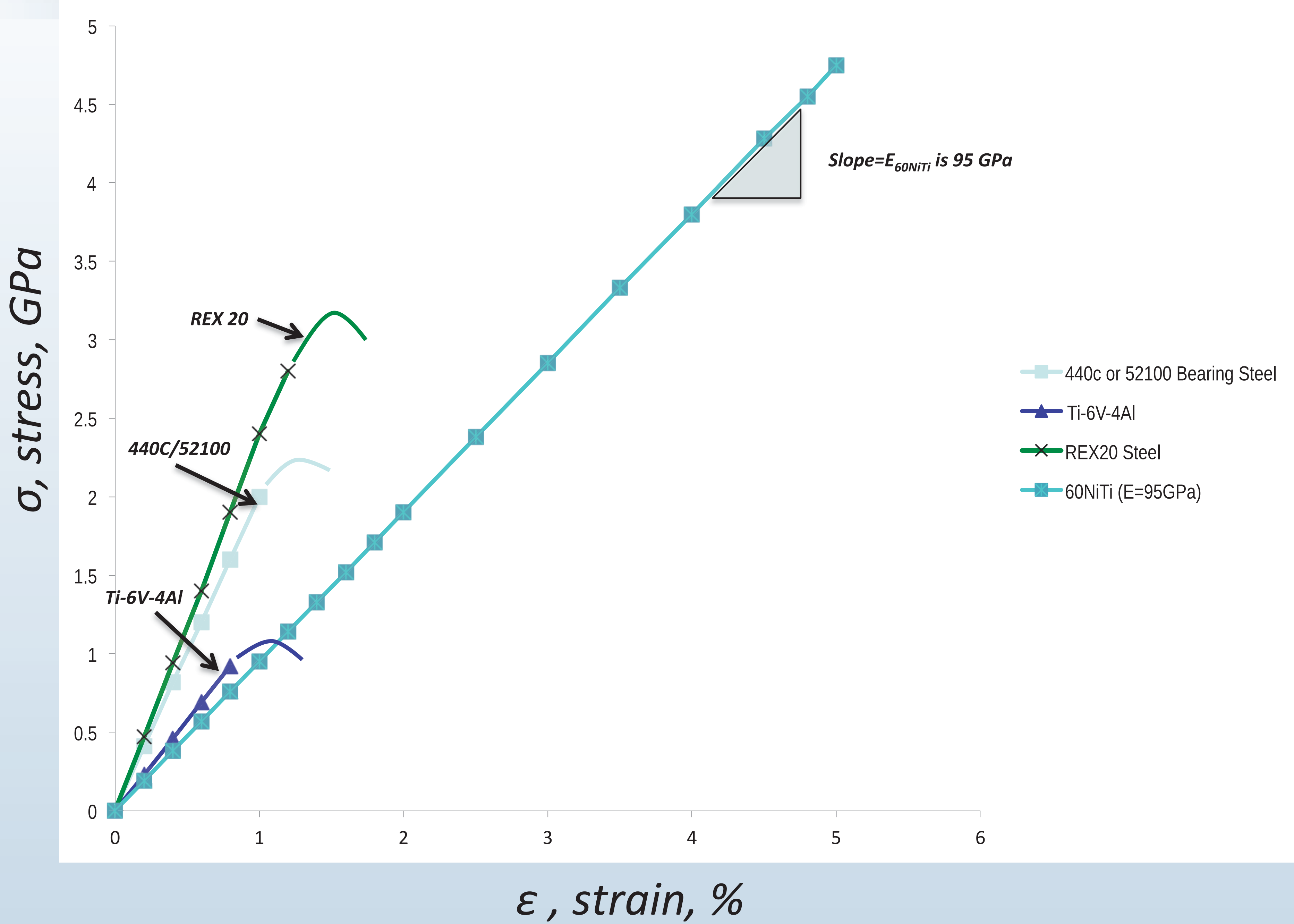
- 60NiTi Basics:
  - Invented by W.J. Buehler (late 1950's) at the Naval Ordinance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordinance Lab).
  - Contains 60 wt% Nickel and 40 wt% Titanium
  - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
  - A member of the super-elastic family. It is dimensionally stable.
  - 60NiTi can be hardened to Rc 60+.
  - Its cousin (55NiTi), the widely used shape memory alloy, is soft and dimensionally unstable.
  - 60NiTi recognized by Buehler for bearings but too difficult to manufacture.
  - Modern (ceramic) processing methods now enable 60NiTi bearings with remarkable properties.

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	$\sim 11.2 \times 10^{-6}$/°C	10×10^{-6}/°C	2.6×10^{-6}/°C	$\sim 11 \times 10^{-6}$/°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	$\sim 1.04 \times 10^{-6}$ Ω-m	$\sim 0.60 \times 10^{-6}$ Ω-m	Insulator	$\sim 0.18 \times 10^{-6}$ Ω-m

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

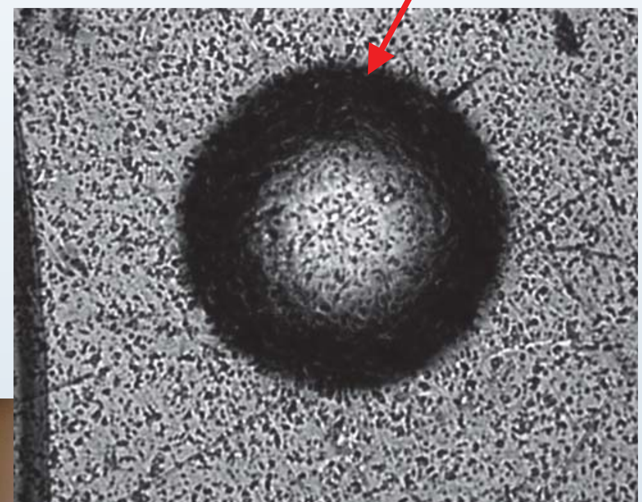
60NiTi: Stress-Strain Behavior

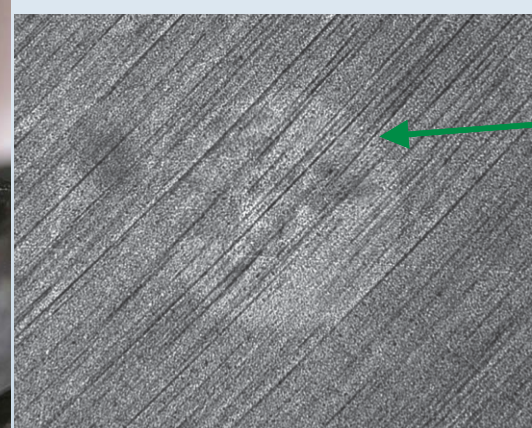


Brinell Test: Elucidates static load capacity

- How well does 60NiTi resist dents?
  - Brinell number
  - dp/D vs. stress (Leveille)

Deep Brinell dent.

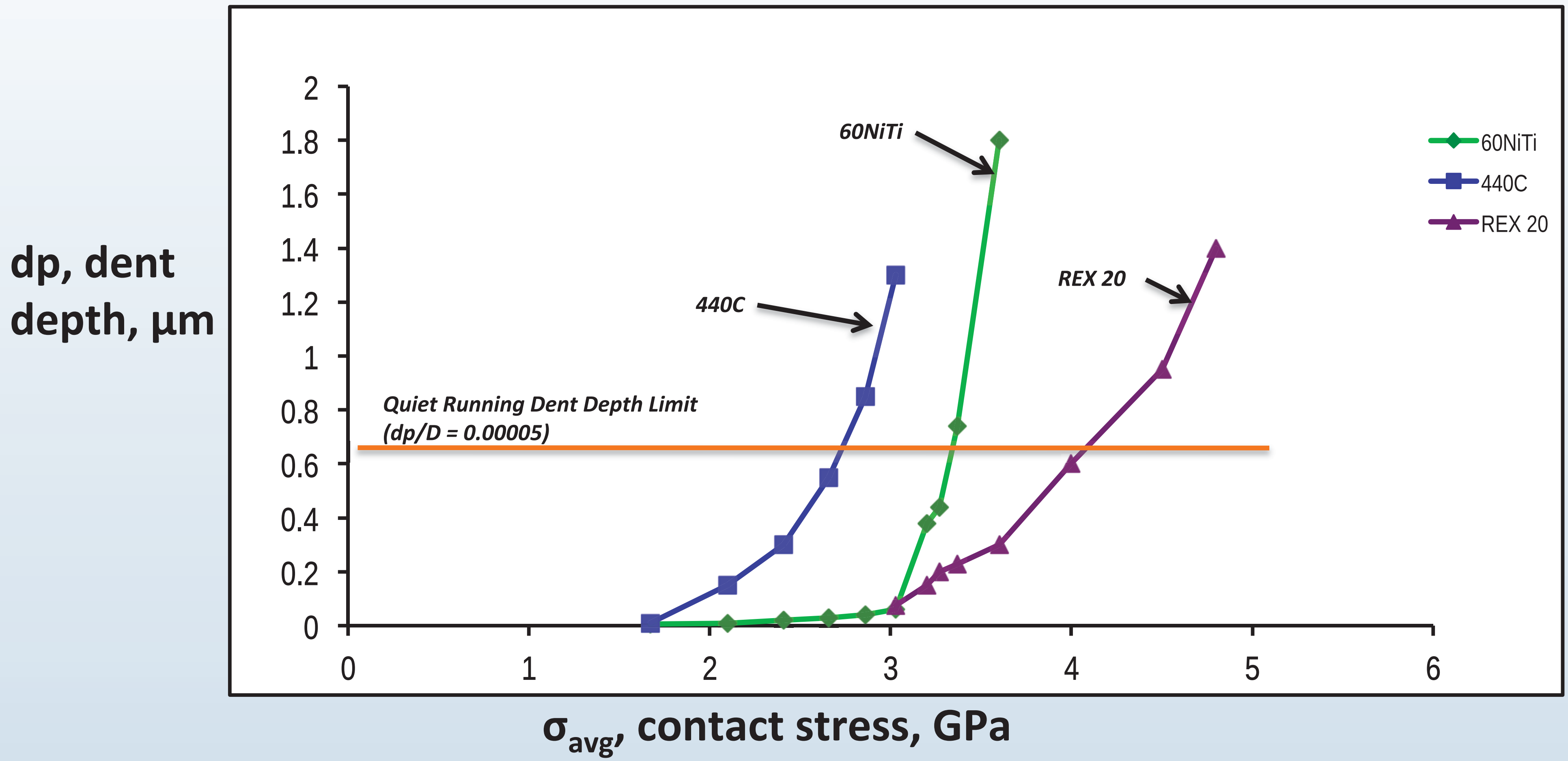




Threshold load visible dent.

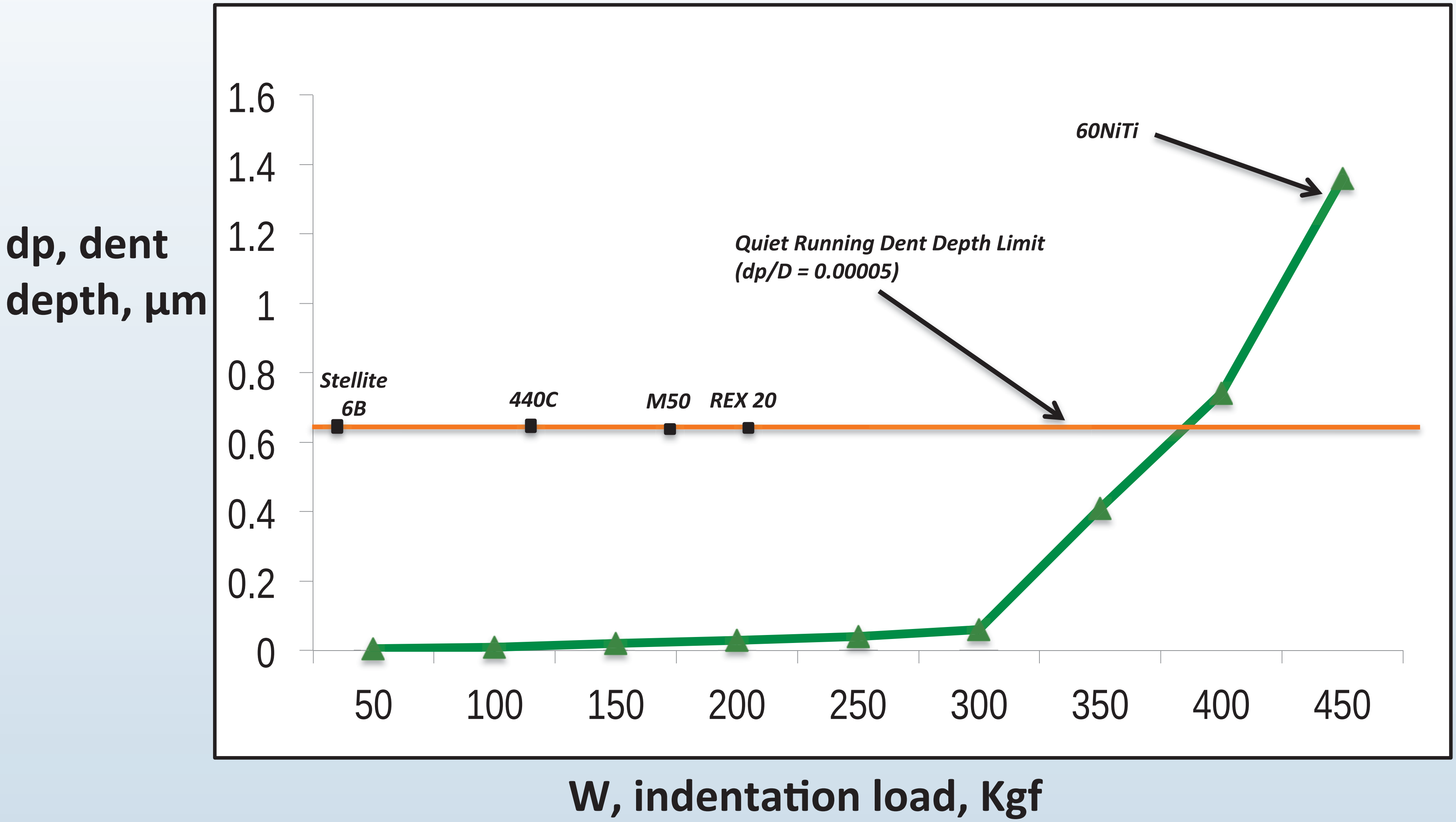
Dent Depth vs. Hertz Contact Stress

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



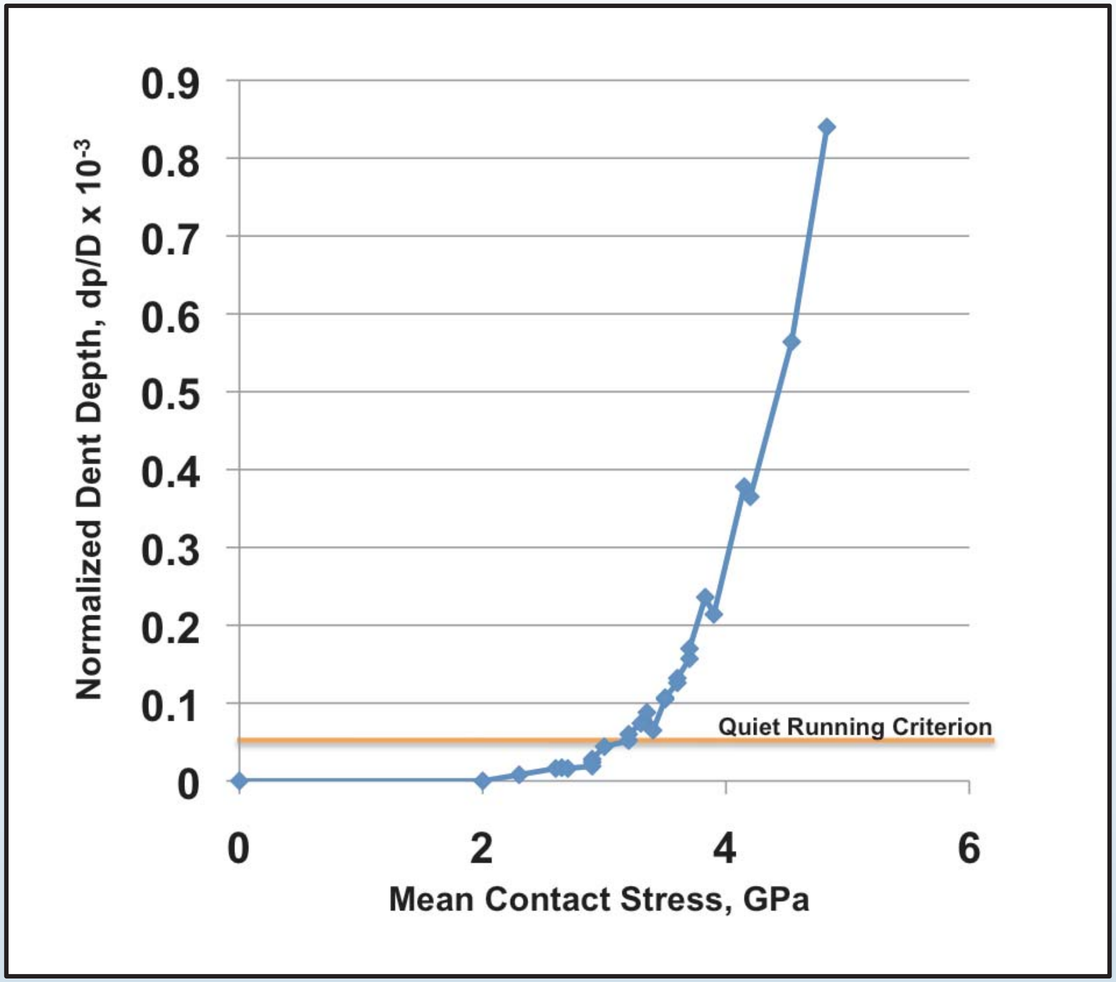
Dent Depth vs. Load

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



Effects of Indenter Diameter

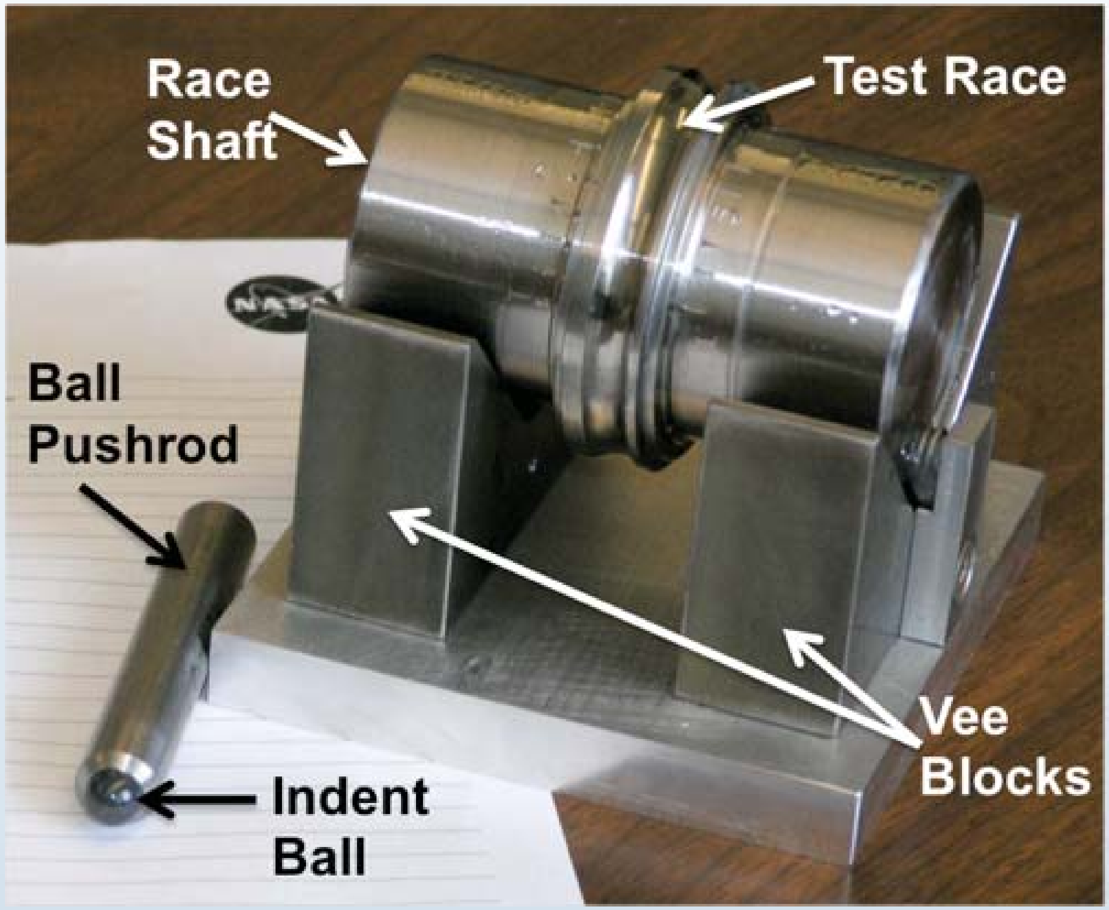
Dent Depth vs. Stress: 6.4 to 12.7mm Si_3N_4 indenter balls



- *Implications*
  - *Hertz stress relations work well for hard balls against flat plates.*

Dent Depth vs. Stress: On bearing races?

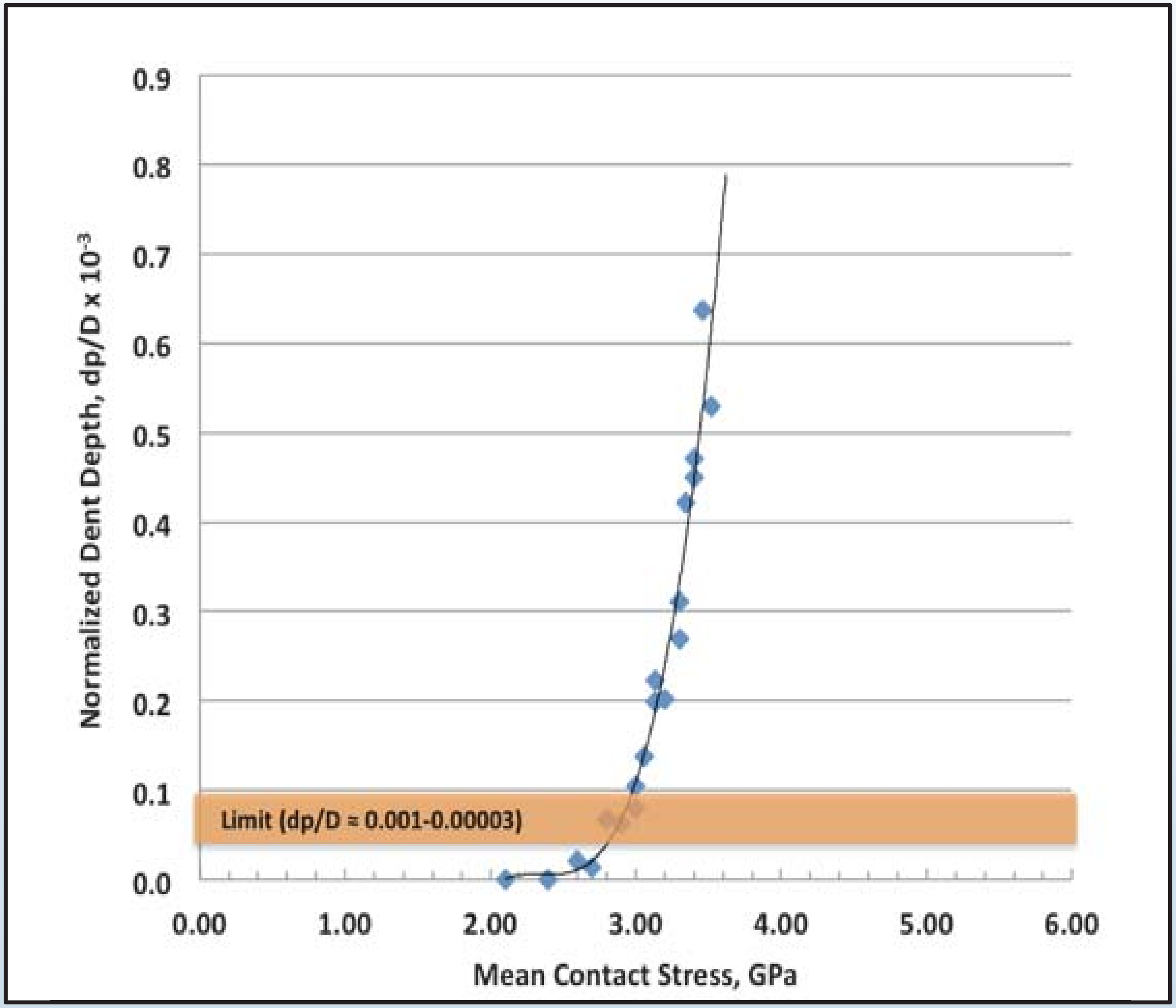
50mm bore 60NiTi-Hybrid Bearing specimens



Full scale (50mm bore) bearing inner race. Dented with 8.74mm Si_3N_4 ball.

Dent Depth vs. Stress: Data Plot

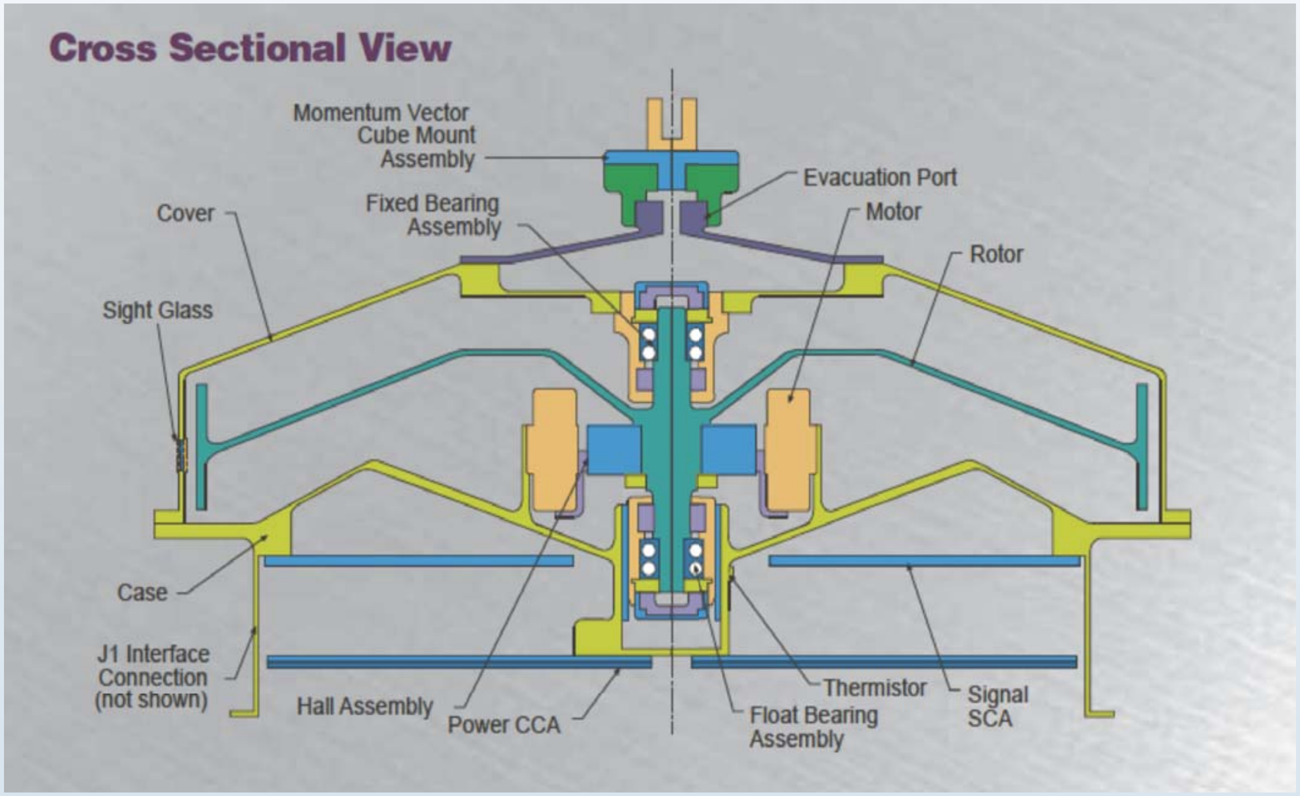
Normalized Dent Depth Versus Mean Hertz Contact Stress



Exemplary dent resistance applies to real bearing races as well as flat plates.

Notional Bearing Application

Typical Reaction Wheel Assembly



-Based on Honeywell Corporation Model HR 0610 design.
-5 kg wheel supported on four R4 ball bearings.

How might NiTi bearings compare to steel w.r.t. static load capacity?

Single Ball on Race Calculations

Reaction Wheel Assembly Bearing Configurations Assessed

[Ball: 8.74 mm dia., Inner Race Curvature Radii: ball-path, 4.25 mm; cross-race, 1.27 mm.]

Configuration no.	Ball material	Race material	Limiting contact Stress,[a] GPa (ksi)	Single ball-race load limit, N (lb)
I	440C	440C	2.5 (350)	196 (44)
II	Si_3N_4	440C	2.5 (350)	138 (31)
III	60NiTi	440C	2.5 (350)	463 (104)
IV	60NiTi	60NiTi	2.5 (350)	846 (190)
V	Si_3N_4	60NiTi	2.5 (350)	374 (84)
VI	60NiTi	60NiTi	3.1 (450)	1780 (400)[c]
VII	Si_3N_4	60NiTi	3.1 (450)	801 (180)
VIII	[b]REX20	REX20	3.8 (550)	587 (132)
IX	Si_3N_4	REX20	3.8 (550)	467 (105)

[a]*Mean Hertz contact stress.*

[b]*REX20 properties: Young's Modulus (E): 234 GPa; Poisson's Ratio (ν): 0.30.*

[c]*Hertz calculations may be invalid due to excessively deformed geometry.*

Calculated Shaft Load Capacity[b]

Reaction Wheel Assembly Bearing Configurations Assessed

[Ball: 8.74 mm dia., Inner Race Curvature Radii: ball-path, 4.25 mm; cross-race, 1.27 mm.]

Configuration Case	Ball material	Race material	Shaft load capacity, kN (lb)	RWA load capacity, g
I	440C	440C	1.4 (316)	28.6
II	Si_3N_4	440C	1.0 (223)	20.2
III	60NiTi	440C	3.3 (748)	67.9
VI	60NiTi	60NiTi	[a]12.8 (2880)	[a]261.2
VII	Si_3N_4	60NiTi	5.8 (1296)	118
VIII	REX20	REX20	4.2 (950)	86.2
IX	Si_3N_4	REX20	3.4 (756)	68.5

[a]Hertz calculations may be invalid due to excessively deformed geometry

[b]Shaft supported by four R4 bearings. Bearing radial load capacity estimated using Derner & Pfaffenburger (9/5) load sharing distribution model.

-Si_3N_4 ball-60NiTi race offers 2x (vs. Rex20) to 5x (440C) improvement.

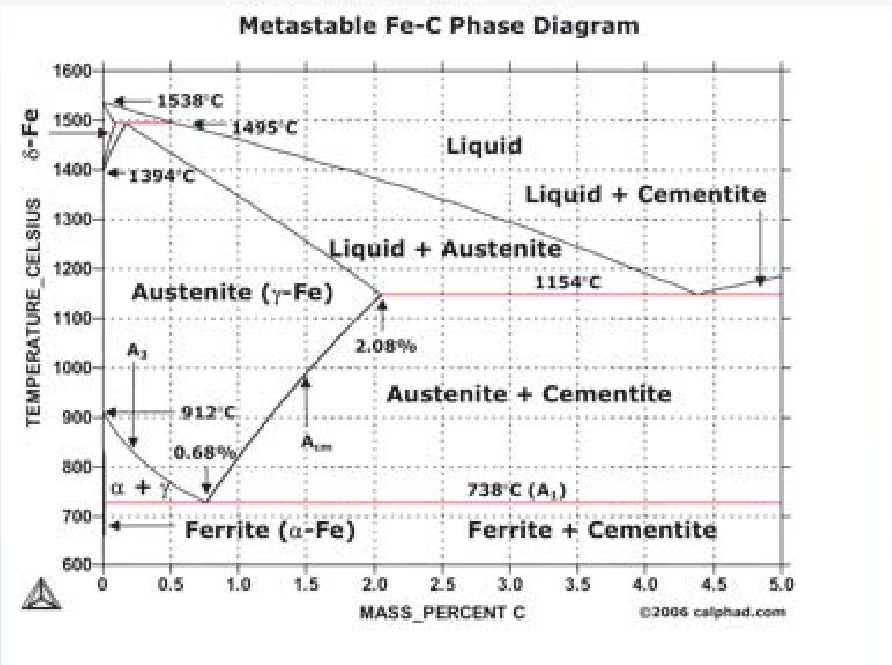
-60NiTi ball-60NiTi race amplifies load capacity effect.

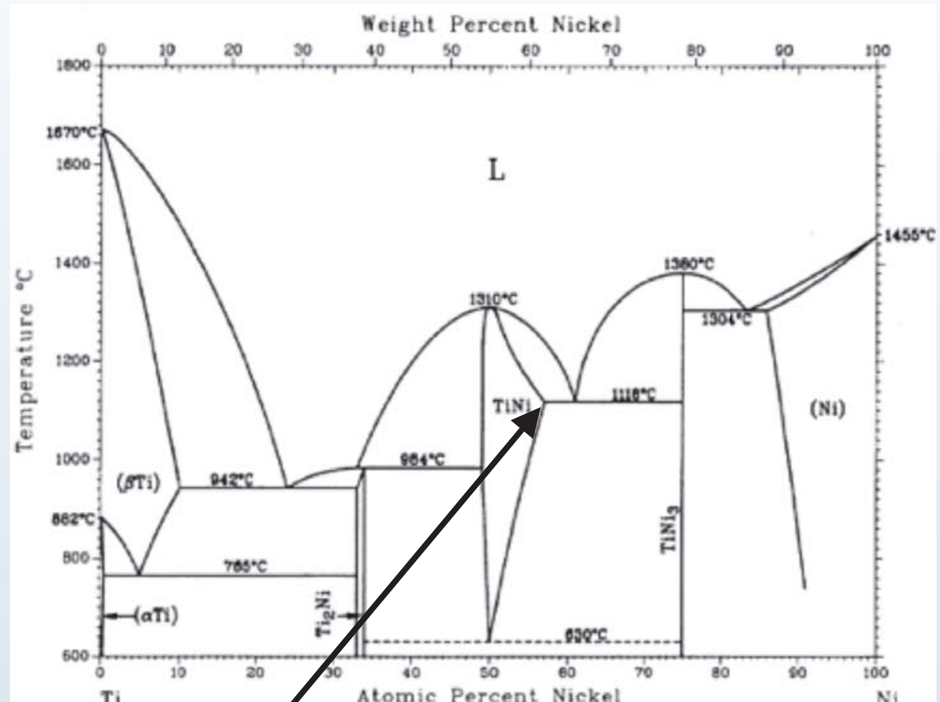
-Additional load capacity may other designs such as smaller or fewer bearings.

Status and Summary Remarks

- 60NiTi has been successfully fabricated into precision bearing balls and races.
- 60NiTi is hard yet has a low elastic modulus and large elastic deformation range enabling high static load capacity.
- Combination of aqueous corrosion immunity, non-magnetic and electrical conductivity not found in any other hard bearing material.
- Low modulus and high elasticity of superelastic gives it more load capacity than that inferred from hardness alone.
- Under load, the reduced modulus may allow better load sharing amongst rolling elements, further reducing local stresses thereby increasing bearing load capacity.
- As the technology matures, more improvements and applications will emerge.

Closing Thoughts: 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 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.

Thank You!