The Role of Tribology in the Success and Challenges In Space Telescopes

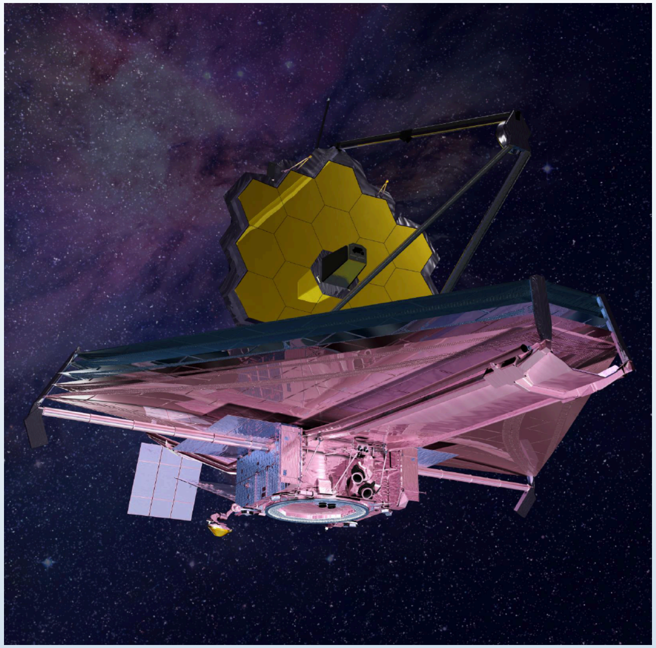
Dr. Christopher DellaCorte

Senior Technologist, Tribology and Rotating Machinery

NASA, Glenn

Cleveland, Ohio

USA



Brunswick Astronomy Club

January 11th, 2018

Background: Tribology?

- Tribology
  - <u>Root</u>: From the Greek “tribos” which means to “rub”.
  - <u>Suffix</u>: “ology” the study of. Tribology is the ”study of rubbing?”
  - <u>Colloquial</u>: The study of friction, wear and lubrication.
  - <u>General Scope</u>: Bearings, gears, lubricants, and wear.

Space Telescopes: NASA Grand Observatories

- Four Programs
  - Hubble: Most well known. Visible Light. Placed by Space Shuttle in 1990.
  - Compton: Gamma Ray Observatory. Placed by Space Shuttle in 1991.
  - Chandra: X-ray Observatory. Placed by Space Shuttle in 1999.
  - Spitzer: Infra-red Observatory. Launched on Delta II rocket in 2003.

Space Telescopes: Track Record

- Hubble: Initially flawed optics. Several in-space repair missions. Continuing service.
- Compton: Gamma Ray Observatory. Placed by Space Shuttle in 1991. De-orbited in 2000 due to a gyroscope failure.
- Chandra: X-ray Observatory. Placed by Space Shuttle in 1999. Still operating.
- Spitzer: Infra-red Observatory. Launched on Delta II rocket in 2003. Coolant depleted in 2009 but still operating at a diminished level.

Other Notables: Probes & Telescopes

- Past, present and future:
  - Galileo: Jupiter probe. Digital images taken of the earth and moon. Antennae problems limited probe to 70% of planned mission.
  - Kepler: Earth-like planet hunter. Met objectives but facing aging problems.
  - James Webb: Next generation far-seeing telescope that will rely on segmented optics and complex mechanisms.

Tribology Challenge: Impact Telescopes

- **Common Space Telescope Problems:**
  - **Power & Electronics: Batteries, solar cells, circuits easily damaged by space debris and radiation, thermal extremes**
  - **Cooling & Propulsion: Propellants and cryogenic fluids leak and deplete over time.**
  - **Mechanisms: Moving parts (reaction wheels, pointing gimbals, deployment mechanisms) bind, stick, wear out. Lubricants degrade.**

Tribology Challenge: Impact Telescopes

- Common Space Telescope Problems:
  - Power & Electronics: Batteries, solar cells, circuits easily damaged by space debris and radiation, thermal extremes
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Space Mechanisms: Telescopes

- Common Space Mechanisms:
  - Deployment: Solar panel array mechanisms, latches, optical covers, etc.
  - Attitude Control: Reaction wheels, comtrol moment gyros, etc.
  - Optical Mechanisms: Rotating filter wheels, gearbox driven linear positioning actuators, etc.

Space Mechanisms: Challenges

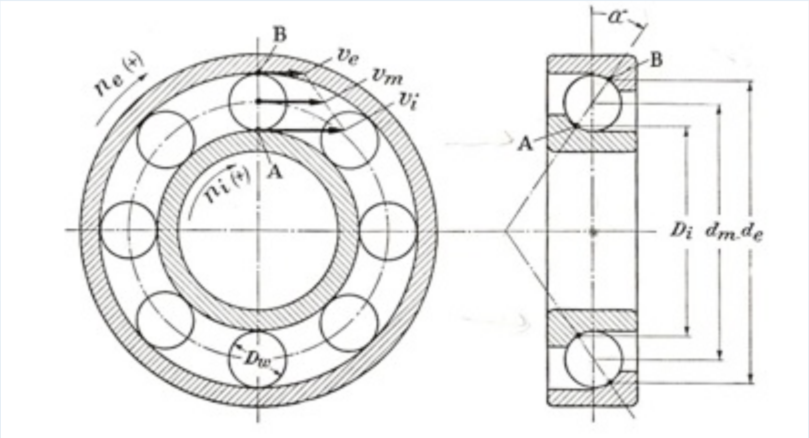
- Common Space Mechanism Problems:
  - Latches: Jam and stick, don't fully open.
  - Bearings: Uneven friction leads to vibrations.
  - Lubricants: Oil and grease "dry out" over time and cause bearings to seize.
  - Gears: Wear leads to debris particles that can float around telescope and hinder optics.

Space Environment: Tribology Impact

- Space environment
  - Vacuum: Causes evaporation of most oils and greases. Heavy reliance on vacuum compatible grease and solid film lubricants.
  - Radiation: Can damage lubricants.
  - Extreme Temperatures: Hot and cold, lead to the use of “thin” oils with limited lubricity.
  - Launch: Vibe induced shock loads can damage delicate instruments, bearings and mechanisms.

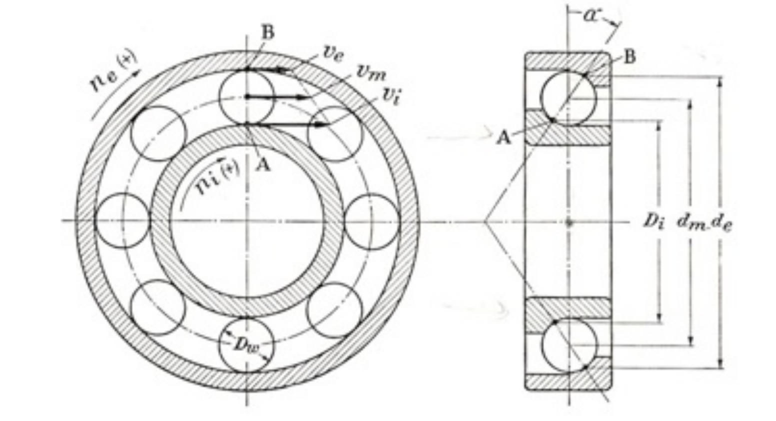
Bearings 101: The what, where, whys and hows

- **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).
- Typically made from hard, stiff steel.



Bearings 102: Lubrication, load/stress, friction, life

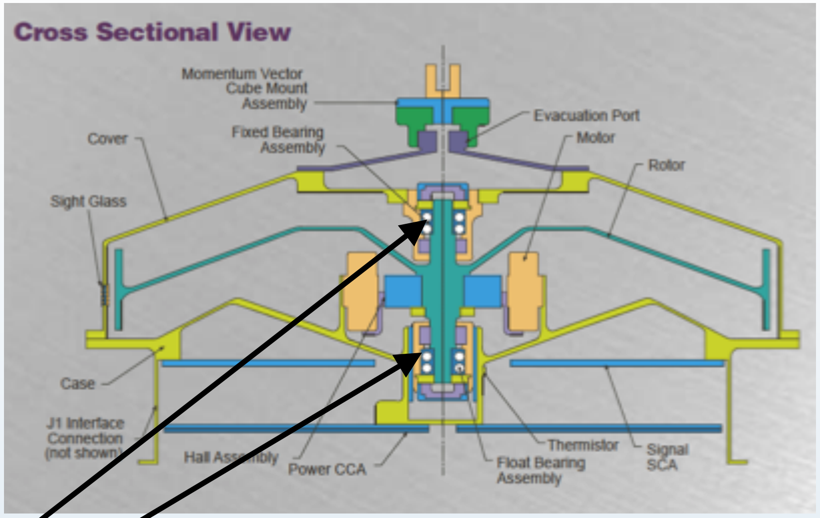
- **Lubrication: As balls rotate in races, microscopic sliding occurs, especially at edges, lubricants are needed to reduce friction and wear.**
  - Oil: best lube, but can float away.
  - Solid film coating: stable but limited life.
  - Grease: Oil plus thickener, common.



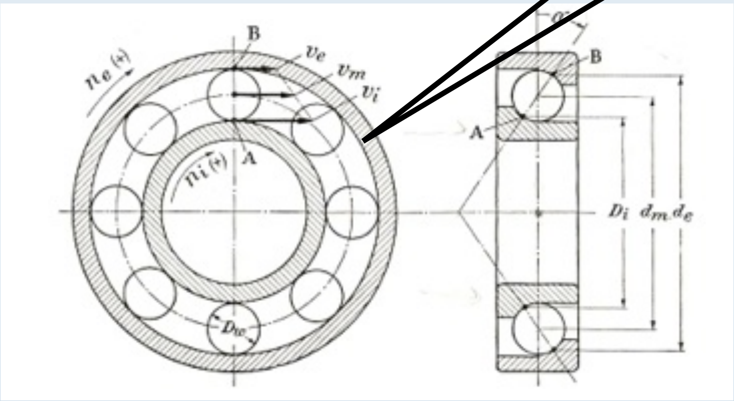
- **Load/Stress: If contact stress (load/area) exceeds metal strength damage (dents) occurs.**
- **Friction: Minimize by using the thinnest possible oils and smallest bearings**
- **Life: long life results from a good design and adequate lubrication.**

Teaching Example: Reaction Wheel Bearings

- **Reaction wheel bearings must:**
  - Impervious to launch vibe loads.
  - Provide low and constant torque.
  - Operate over wide temperature range.
  - Resistant to space radiation.
  - Operate at constant speed or variable speed including zero-crossings.
  - Provide high stiffness to rotor.
  - Meet size, volume and cost constraints.



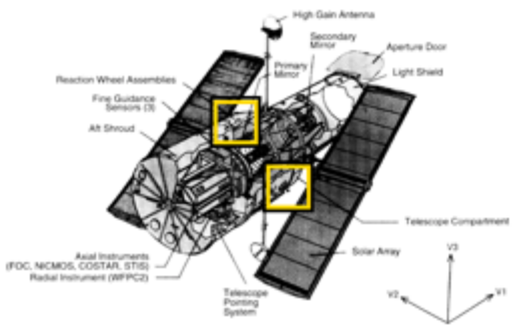
Typical Reaction Wheel.

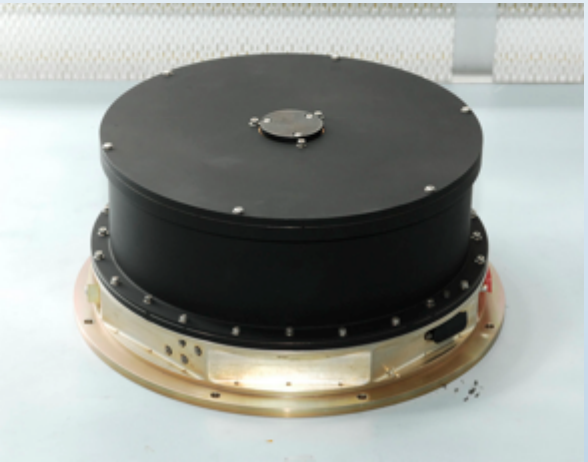


Ball Bearing.

Wheel Bearings: Recent Failures

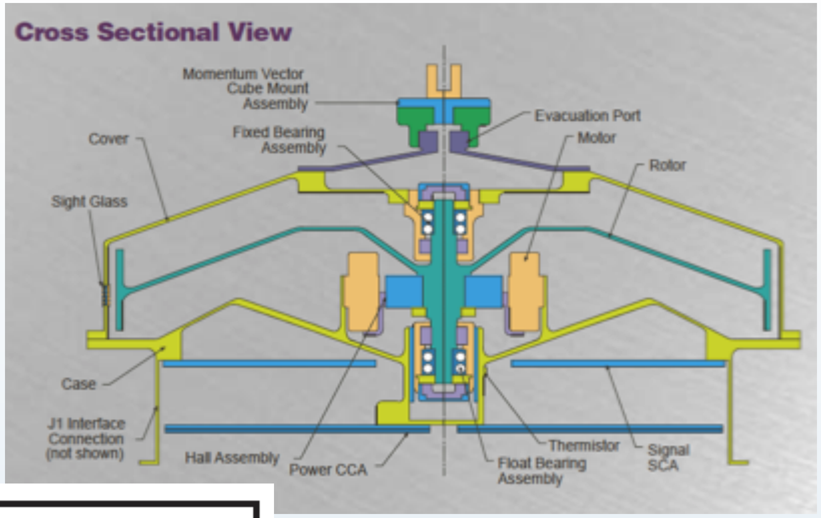
- Bearings implicated in recent high value wheel failures:
  - Hubble Space Telescope
  - ISS CMG's
  - Kepler Space Telescope





Smoking Gun: Competing bearing req'ts

- **Wheel Bearings caught between a rock and a hard place:**
  - High preload to ensure stiffness
  - High duty cycle (run for years)
  - Minimal lubrication to lower power loss.
  - Minimum size to reduce weight.



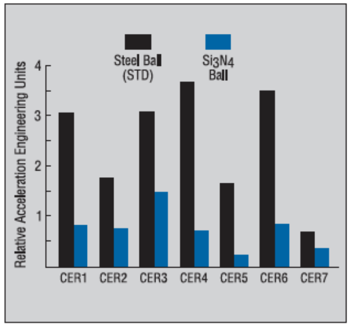
PARAMETER	UNIT	CAPABILITY
Angular Momentum at Max.Speed	N-m-s	4 to 12
Output Torque at Max.Speed	N-m	.055
Peak Power at Max. Torque and Speed	Watts	<80
Power Holding at Max.Speed	Watts	<15
Power Bus Voltage	Volts	14 to 23
Wheel Speed	rpm	6000
Mass	kg	3.6 to 5.0
Outside Diameter	mm	267
Height	mm	120
Integrated Electronics	Yes/No	Yes
Life Requirement	Years	>10
Radiation Hard	krad(Si)	300
Part Screening	Level	S
Bearing	Size	R4
Operational Temperature Range	deg C-Lo	-15
	deg C-Hi	+60
Vibration	Grms	19.8
Motor Type	AC/DC	DC
Interface	Analog/Digital	Analog
Static Unbalance	gm-cm	<0.2*
Dynamic Unbalance	gm-cm²	<3.1*

Source: Honeywell H-610 Product Brochure.

New Technology: Ceramic balls

- **Ceramic Hybrid bearings:**
  - Ceramic balls are increasingly specified to increase stiffness and lube life.
  - Hybrid bearings suffer from reduced static load capacity (Brinell).
  - Launch vibe susceptibility.
- **New Approach:**
  - New bearing material (something other than steel)

Ceramic Hybrid Bearings



Vibration tests comparing spindles with steel ball bearings and the same spindle retrofit with ceramic hybrids. Vibration levels averaged two to seven times lower with silicon nitride balls.

Comparison of Bearing Steel and Silicon Nitride Properties

Property	Steel	Ceramic
Density (g/cm³)	7.8	3.2
Elastic Modulus (10^6 psi)	30	45
Hardness	R_c60	R_c78
Coefficient of thermal expansion ($X10^{-6}$/°F)	6.7	1.7
Coefficient of friction	0.42 dry	0.17 dry
Poisson's ratio	0.3	0.26
Maximum use temperature (°F)	620	2000
Chemically inert	No	Yes
Electrically non-conductive	No	Yes
Non-magnetic	No	Yes

Ceramic balls are lighter and harder than steel balls, characteristics which improve overall bearing performance.

X-Life Ultra bearings offer unsurpassed toughness and corrosion resistance. They outlast conventional hybrid bearings by up to 4x or more.

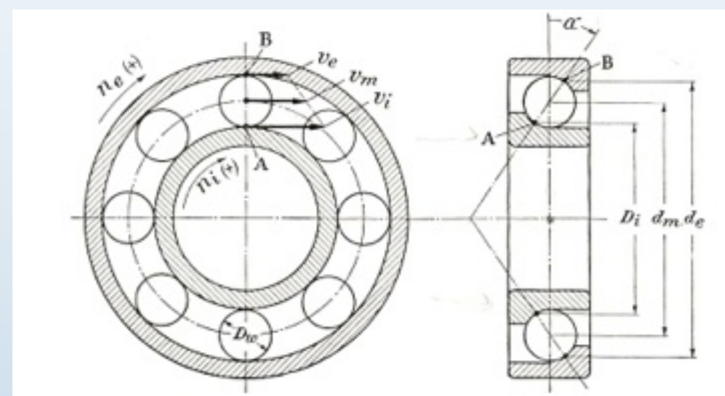
X-Life Ultra Bearings

X-Life Ultra bearings were developed for the highest demands with respect to speed and loading capability. These bearings are hybrid ceramic bearings with bearing rings made from Cronidur 30®, a high nitrogen, corrosion resistant steel. Cronidur 30® shows a much finer grain structure compared with the conventional bearing steel 100Cr6 (SAE 52100) resulting in cooler running and higher permissible contact stresses. Basically all bearing types are available as X-Life Ultra bearings.

The longer service life of X-Life Ultra bearings when compared to conventional bearings also contributes to an overall reduction in the total system costs. When calculating the indirect costs of frequent bearing replacement — which include not just inventory, but machine down time, lost productivity and labor — the cost savings potential of Cronidur 30® bearings become significant.

Challenge: Resilient and Long-life Bearings

- **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



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.

Superelastic Bearings: NiTi based intermetallics

(Hard but resilient material related to shape memory alloys)

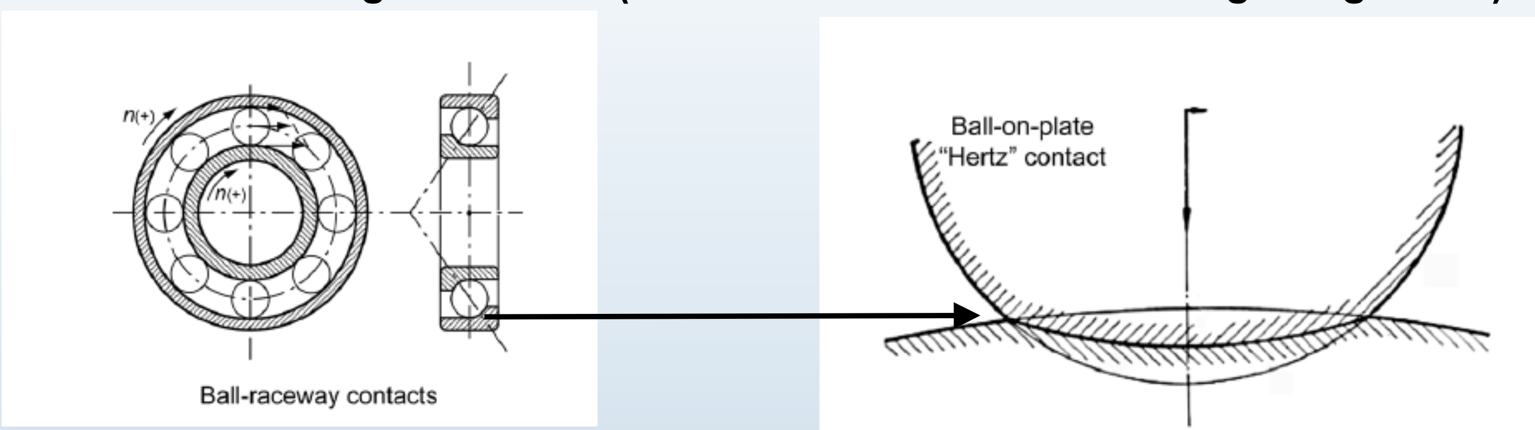
- **60NiTi Basics: market name NiTiNOL 60**
  - W.J. Buehler invented NiTiNOL in the 1950's. Acronym for Ni-Ti-Naval-Ordnance-Laboratory.
  - 60NiTi (60 wt% Ni) is the baseline composition. Alloying with Hf, Zr, and Ta improves microstructure and processing.
  - 60NiTi is not a metal or a ceramic: a 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

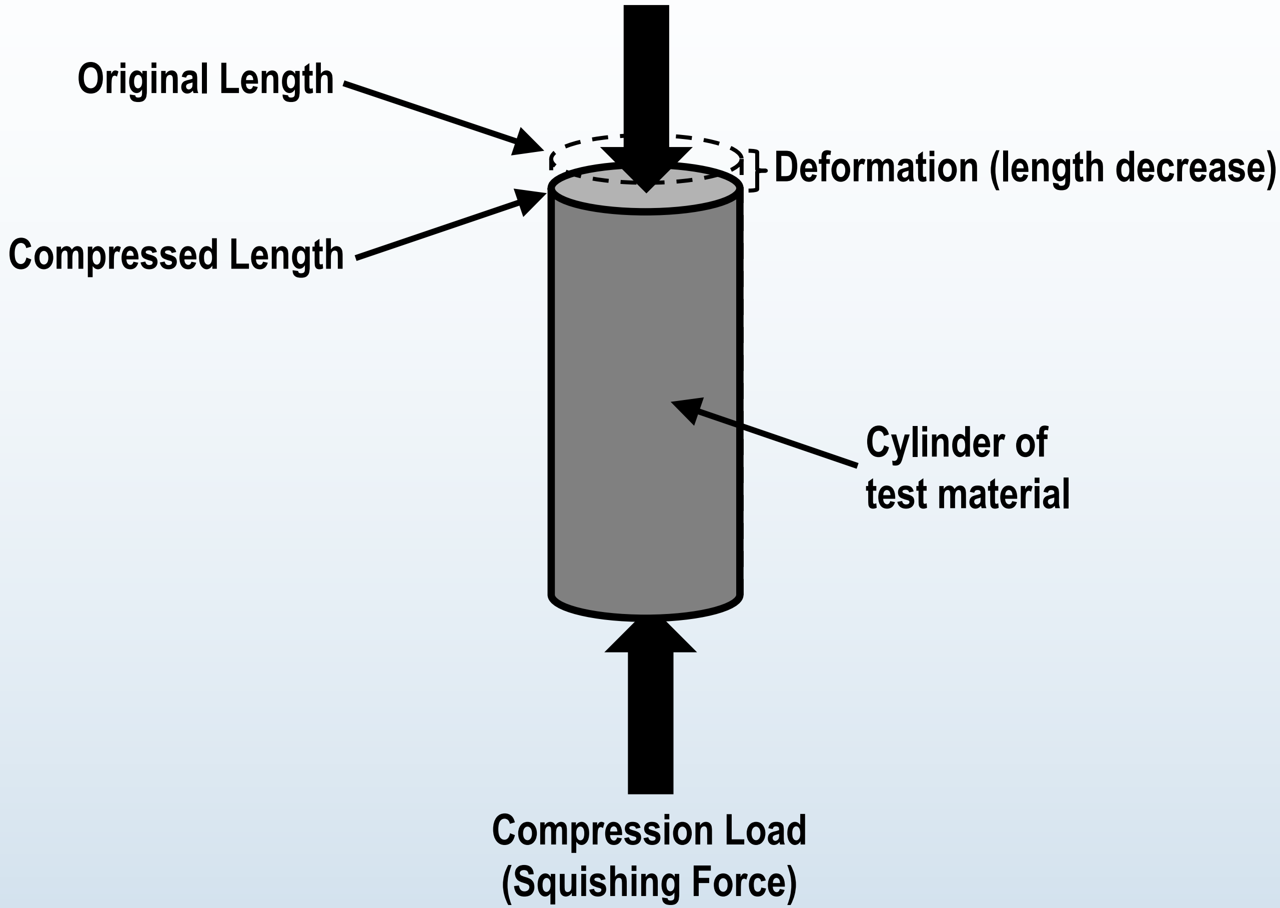
Contact Engineering: Ball-Race

- **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).**



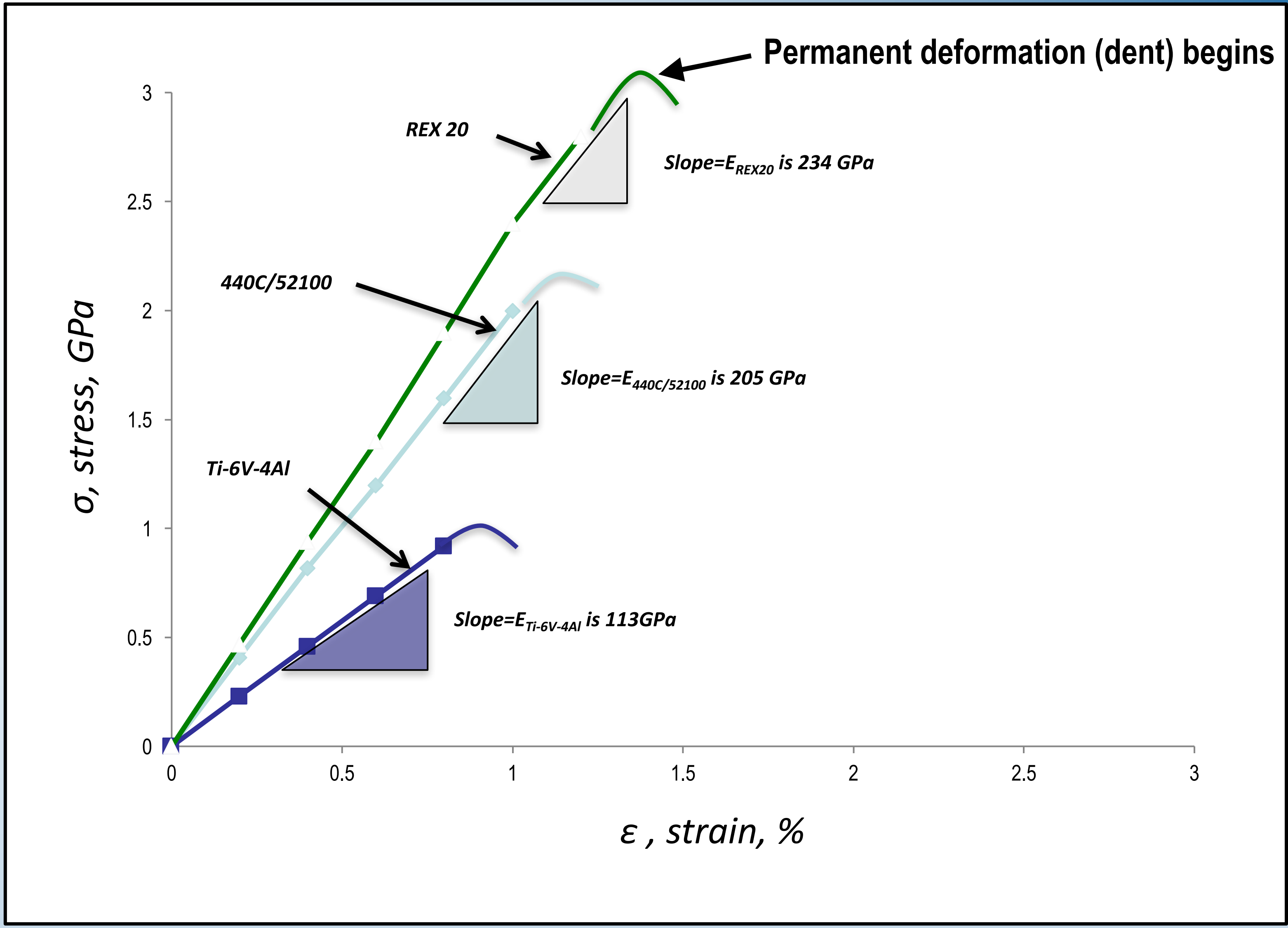
- ***Hard surfaces can dent***
  - ***Even modest loads can exceed stress capability limits.***
  - ***Bearing raceways are particularly prone to Brinell dent damage.***

Conventional Metals: Elastic Behavior

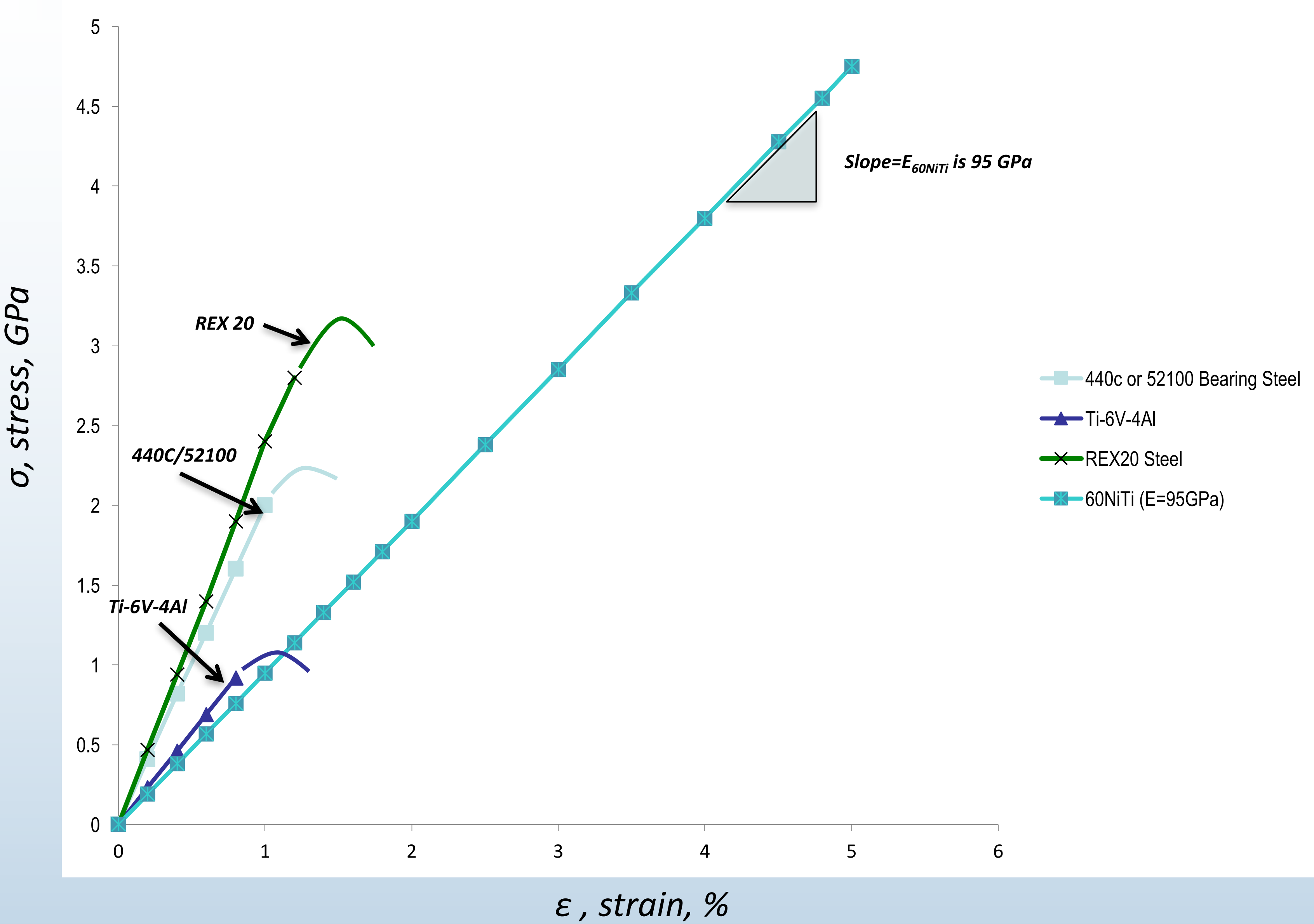


- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior

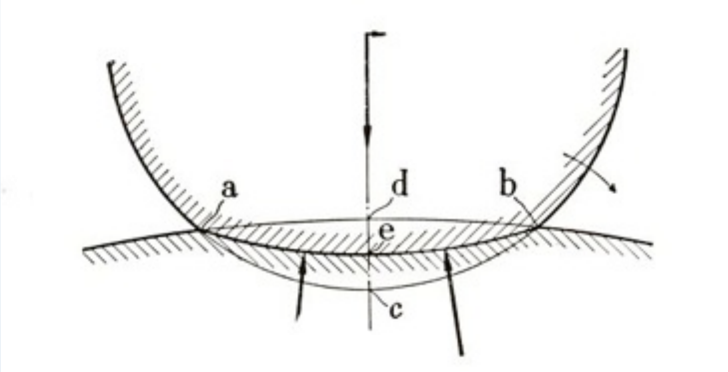


60NiTi: Stress-Strain Behavior

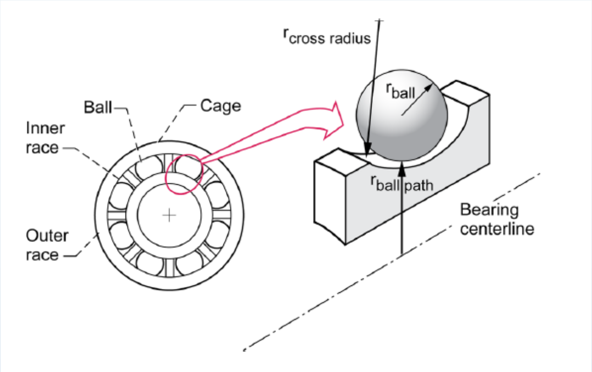


Low Modulus + Hard: A Technical Opportunity

- **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.



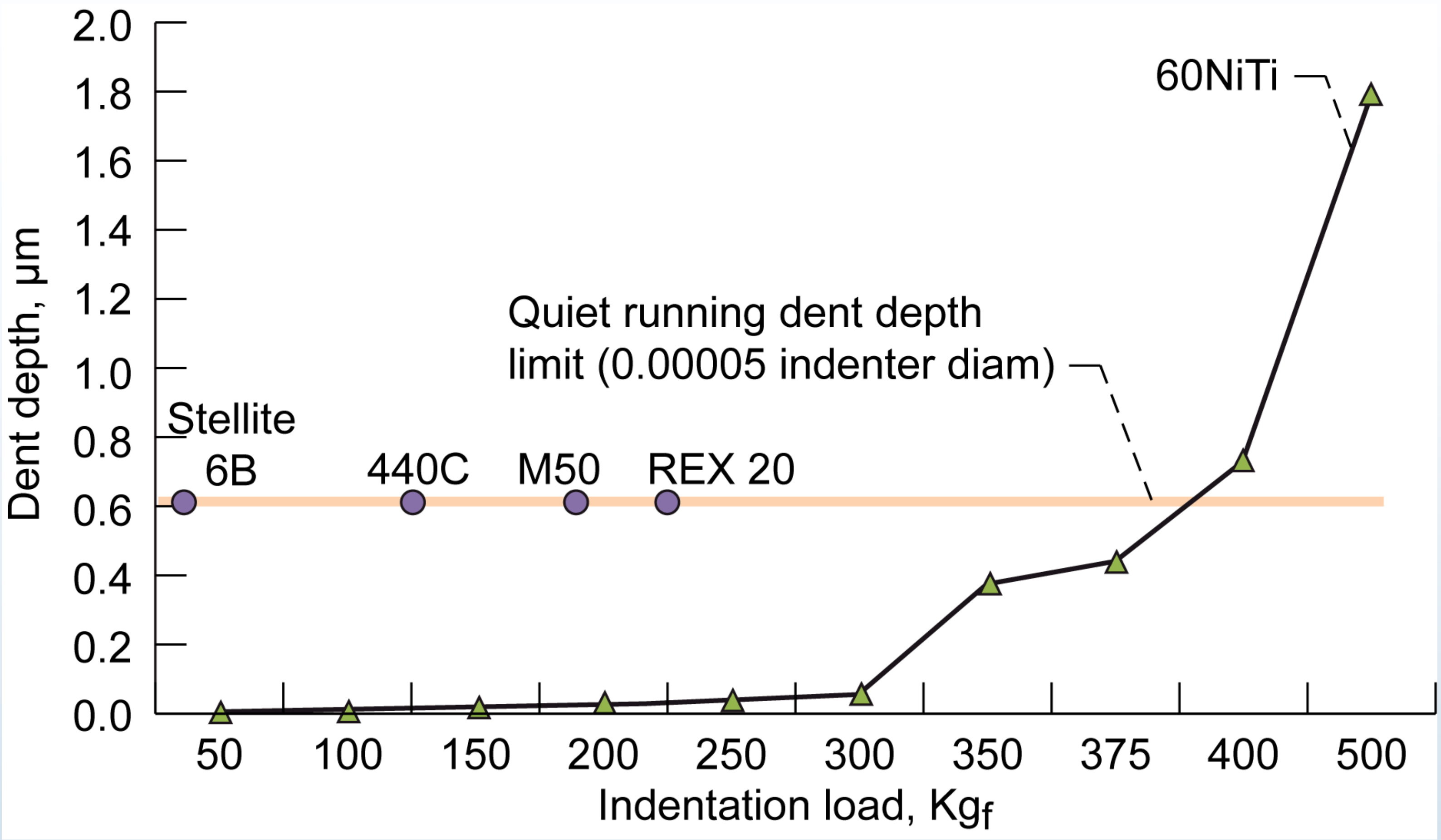
Balls touch races at small points causing race surface dents



Dents on race surface cause rough running and premature failure

Dent Depth vs. Load

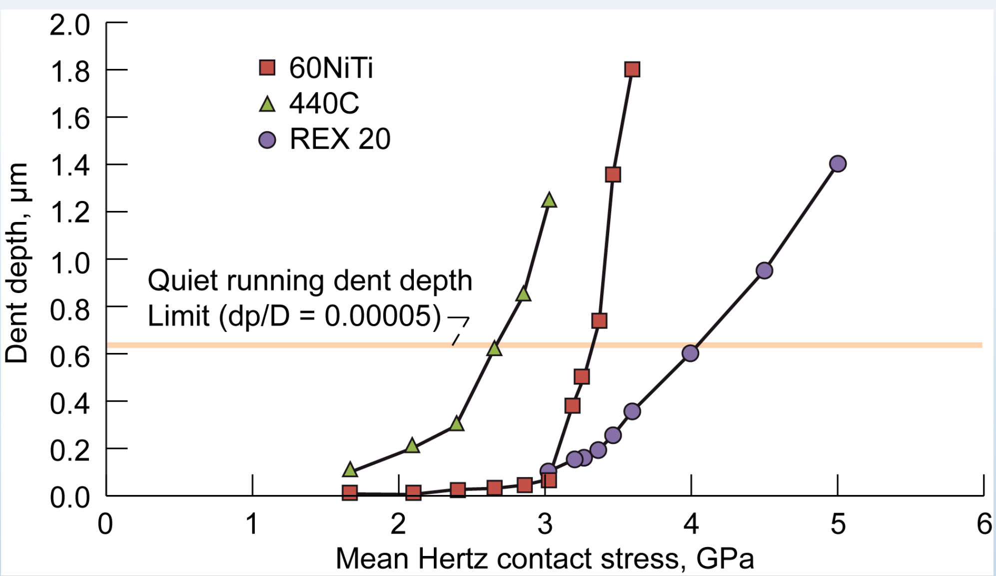
(Si_3N_4 ceramic ball pressed against 60NiTi plate)



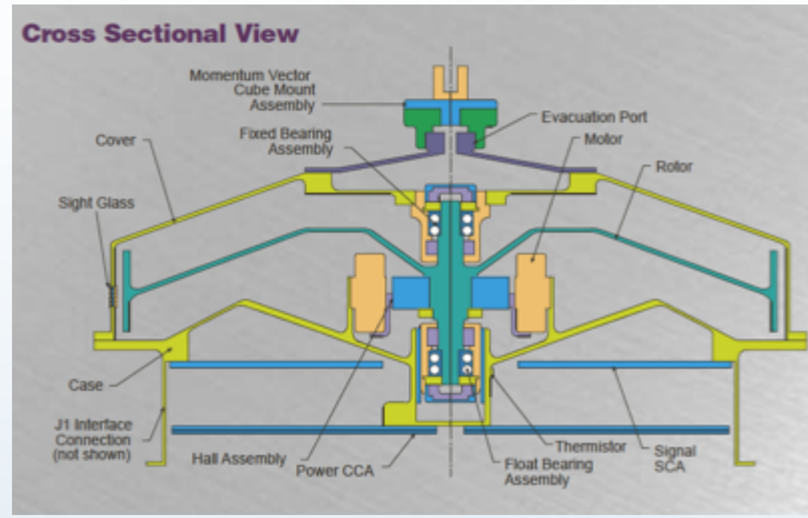
60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus.

Trade Study: Compare NiTi vs Steel Vs. Ceramic Hybrid Bearings for RWA

- **Reaction Wheel Assembly:**
  - Currently uses two duplex R4 bearings.
  - Analyzed wheel for launch vibe loads.
  - Related loads to race stress limit.
  - Evaluated benefits of using NiTi.



Notional Honeywell Wheel



Standard Practice: 2 duplex pairs of 440C ball bearings.

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 enable other designs such as smaller or fewer bearings.

Current Status: Reaction wheel sized bearings

- NiTi bearings:
  - Development driven by ISS Wastewater machinery requirements.
  - 50, 35 and 12.7mm bore bearings have been made.
  - 12.7, 6.35 and 4.76mm diameter NiTi balls have been made.
  - Now producing R4 (6.35 bore) bearings needed by typical reaction wheels.

35 and 50mm bore hybrid NiTi bearings.

12.7mm 60NiTi bearing balls.

12.7mm bore 60NiTi Compressor bearing.

6.35mm NiTi-Hf bearing balls.

Demo: Next Steps

- **Engage Industry:**
  - Identify suitable RWA test bed.
  - Manufacture R4 NiTi-Hf bearings
- **Integrate NiTi-Hf bearings in Reaction Wheel.**
- **Conduct vibe and life tests of wheels.**
- **Compare to steel wheels.**
- **Assess technology gaps and opportunities.**

Spacecraft Reaction Wheels

BCT Reaction Wheels provide an efficient, high performance solution for spacecraft attitude control. These wheels are available in a range of sizes, providing the combination of torque and momentum storage to suit your spacecraft and mission requirements. Control electronics are included in each reaction wheel, simplifying your system integration and operations.

Drive Electronics

Flexible interface options include direct analog torque command as well as a digital command and telemetry option. Standalone drive electronics can drive up to four Reaction Wheels, or integrated drive electronics can be provided for each Reaction Wheel Assembly. Brushless DC motors, ultra-smooth bearings, and the BCT Reaction Wheel lubrication system insure easy system integration, jitter-free performance, and long life for your mission.

BCT Micro RW Datasheet (CubeSat compatible)

BCT_RWp100 (Nanosat compatible)

						Future Products				
Model #		RWp015	RWp100	RWp500	RW1	*RW4*	*RW6*	*RW12*	*RW25*	*RW50*
Spec Torque	Nm	0.006	0.008	0.050	0.1	0.03	0.05	0.1	0.1	0.25
Max Momentum	Nms	0.015	0.100	0.500	1	4	6	12	25	50
Diameter	cm	4.3	7.0	11	13	15	17	19	21	25
Height	cm	1.8	3.5	8	8	9	9	11	11	12
RWA Total Mass	kg	0.115	0.35	0.7	1	3.1	3.3	4.9	6.9	9.3
Max Power	Watts	1.7	5	6	16	23	36	53	53	127
Nominal Power	Watts	0.05	1.8	3	4	4	5	5	5	9

Summary Remarks and Closing Thoughts

- NASA Space Telescope missions push the state-of-art
- Technical challenges, problems and failures drive the hunt for new technologies.
- Such "Technology Pull" goals are the lifeblood of the US's superiority in technology development.
- NASA projects are often the first application of new technologies and serve as examples for both the space industry and industrial spin-offs closer to home.
- Resilient superelastic NiTi ball bearing technology originally developed for the ISS water treatment system is emerging as a potential solution for launch load tolerant wheel bearings.
- Long life reaction wheels, launch tolerant mechanisms and corrosion immune fluids pumps benefit from NiTi.
- Spin-offs into water turbines, dentists drills, food processing equipment and even high-performance bicycle wheels follow.

Thank You!

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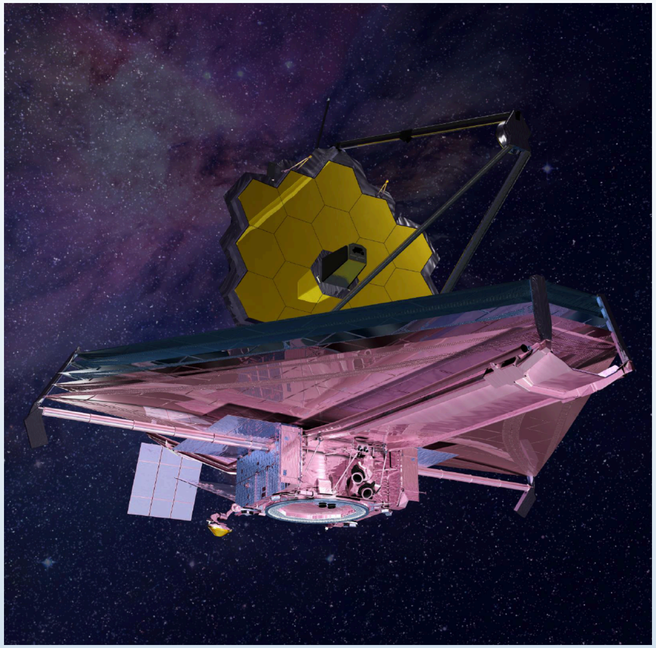
Dr. Christopher DellaCorte

Senior Technologist, Tribology and Rotating Machinery

NASA, Glenn

Cleveland, Ohio

USA



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