



Resilient and Corrosion-Proof Rolling Element Bearings Made from Ni-Ti Alloys for Aerospace mechanism Applications

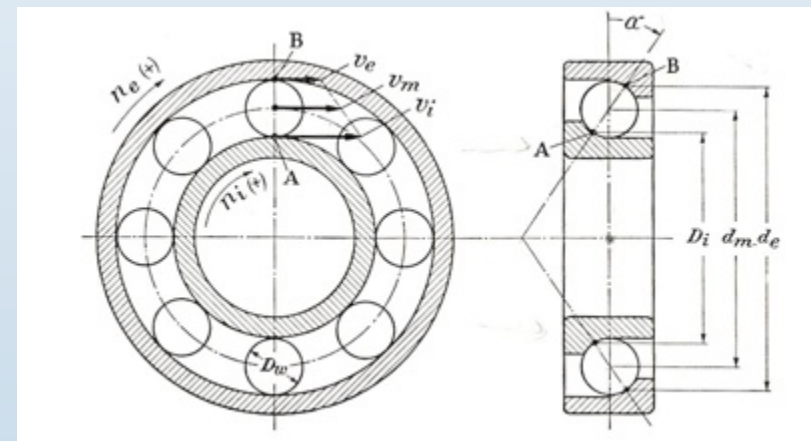
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Bearings 101: The what, where, whys and hows

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





Bearing Material: State-of-Art (SOA)

(Current suite of candidates is severely limited)

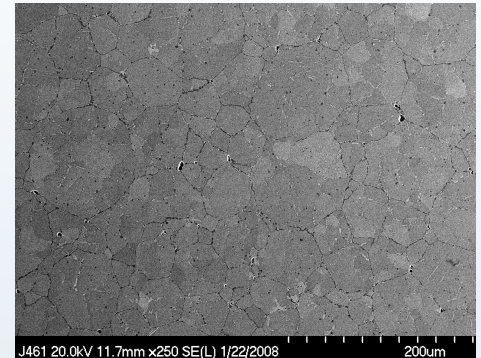
- **Four general types of bearing materials:**
 - **Steels** (Corrosion resistant steels, martensitic, austenitic)
 - **Ceramics** (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
 - **Superalloys** (e.g., jet turbine blade alloys)
 - **Non-ferrous alloys** (bronze, nylon etc.)
- **Each of these 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.



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 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 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



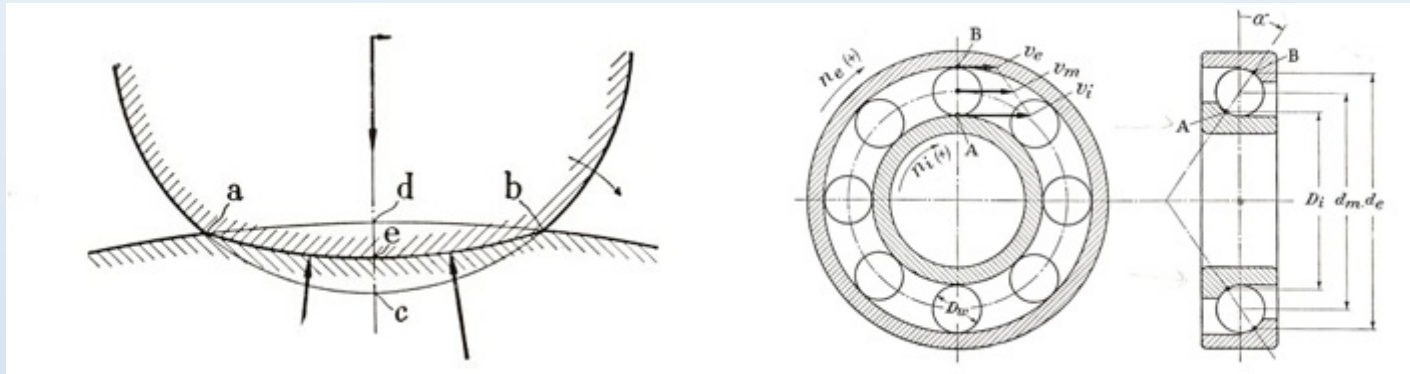
Highly polished 60NiTi bearing balls



Contact Engineering:

(60NiTi's properties affect contact stresses)

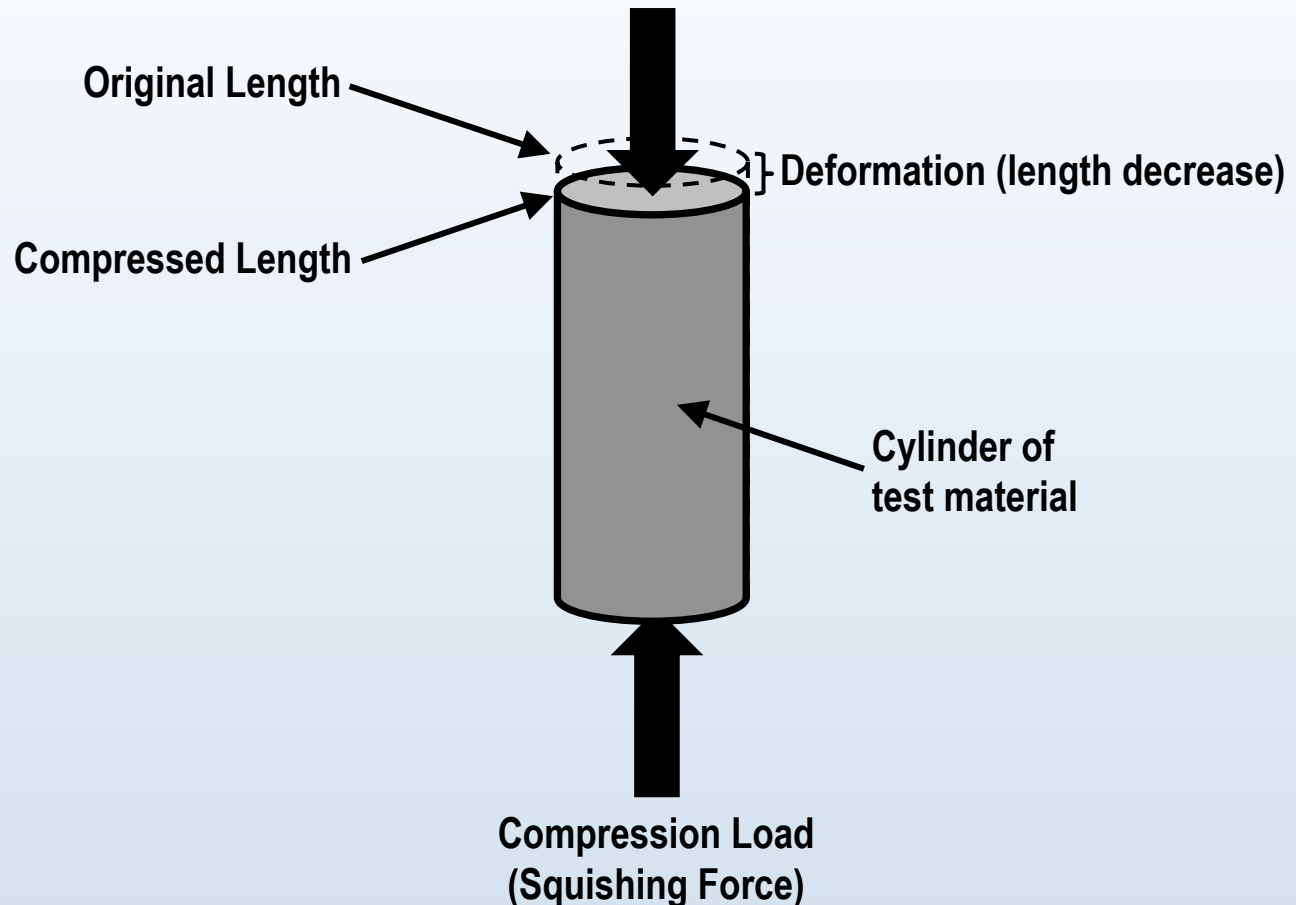
- When hard surfaces contact
 - Forces are transmitted at small, concentrated contact points (Hertz).
 - Resulting stresses cause deformations that help “spread the load”.
 - Contact area is a function of the geometry, material stiffness and load.
 - High stiffness (modulus) inhibits deformations leading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



- Hertz stresses are a function of load, radii of surfaces and elastic moduli.
- High stresses lead to dents especially on race surfaces.
- Understanding how materials properties affect race denting requires brief tutorial on stress and strain.



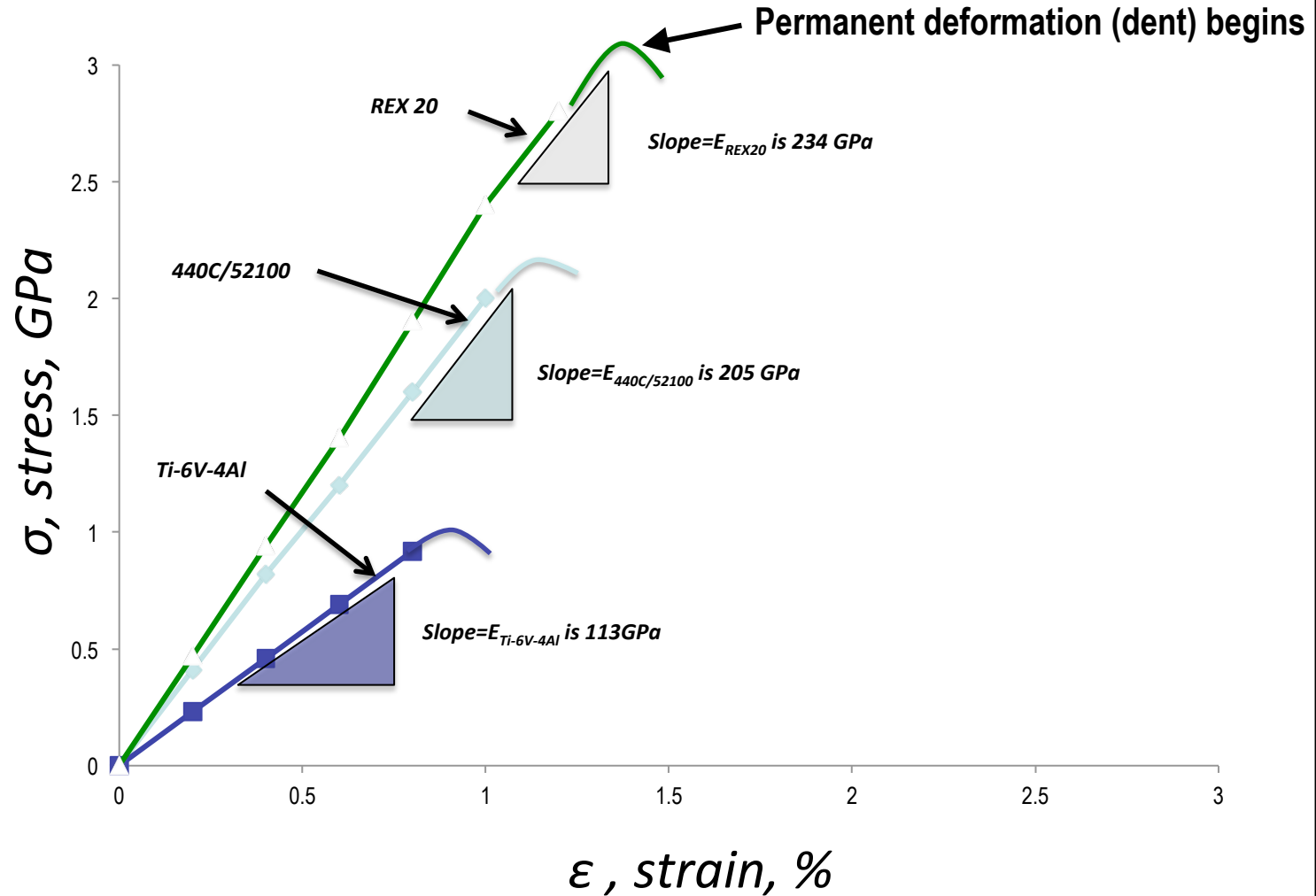
Conventional Metals: Elastic Behavior



- 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.

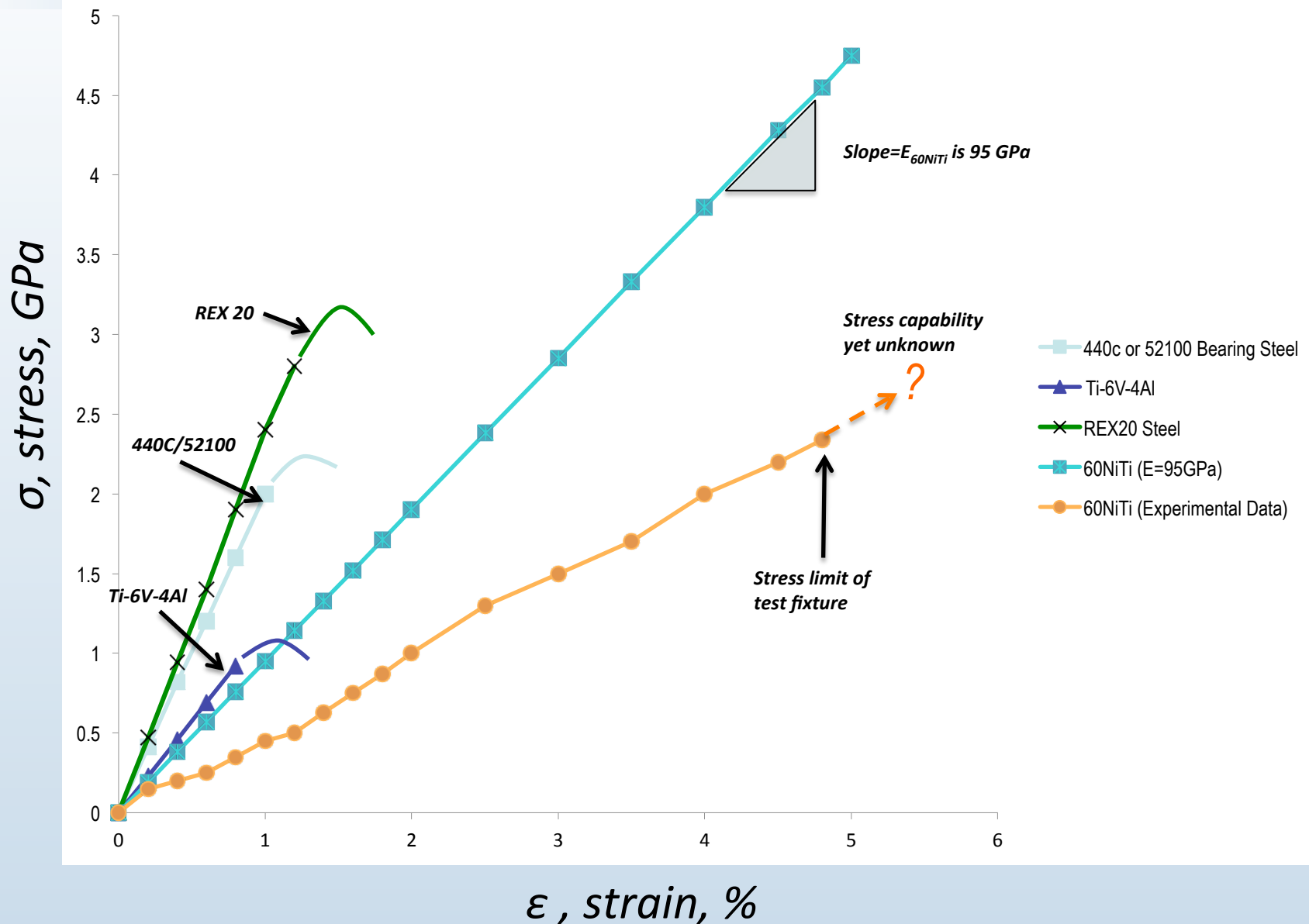


Conventional Metals: Elastic Behavior





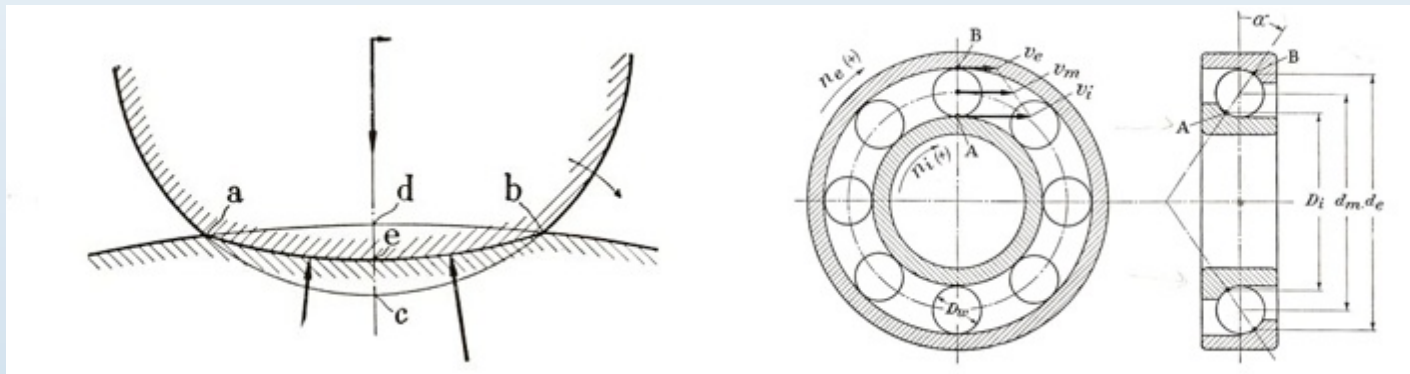
60NiTi: Stress-Strain Behavior





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**

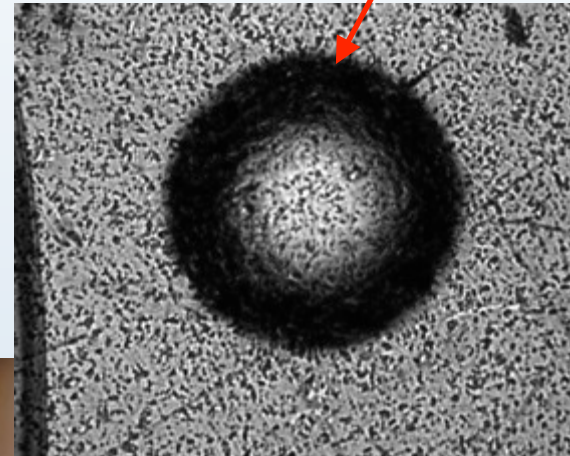
**Dents on race surface cause rough
running and premature failure**



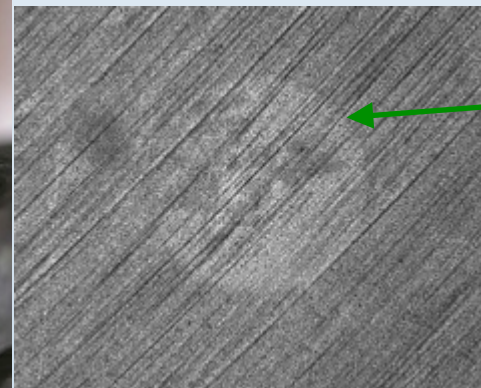
Resilience: Can 60NiTi withstand high dent loads?

(Static denting behavior)

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



Deep Brinell dent.



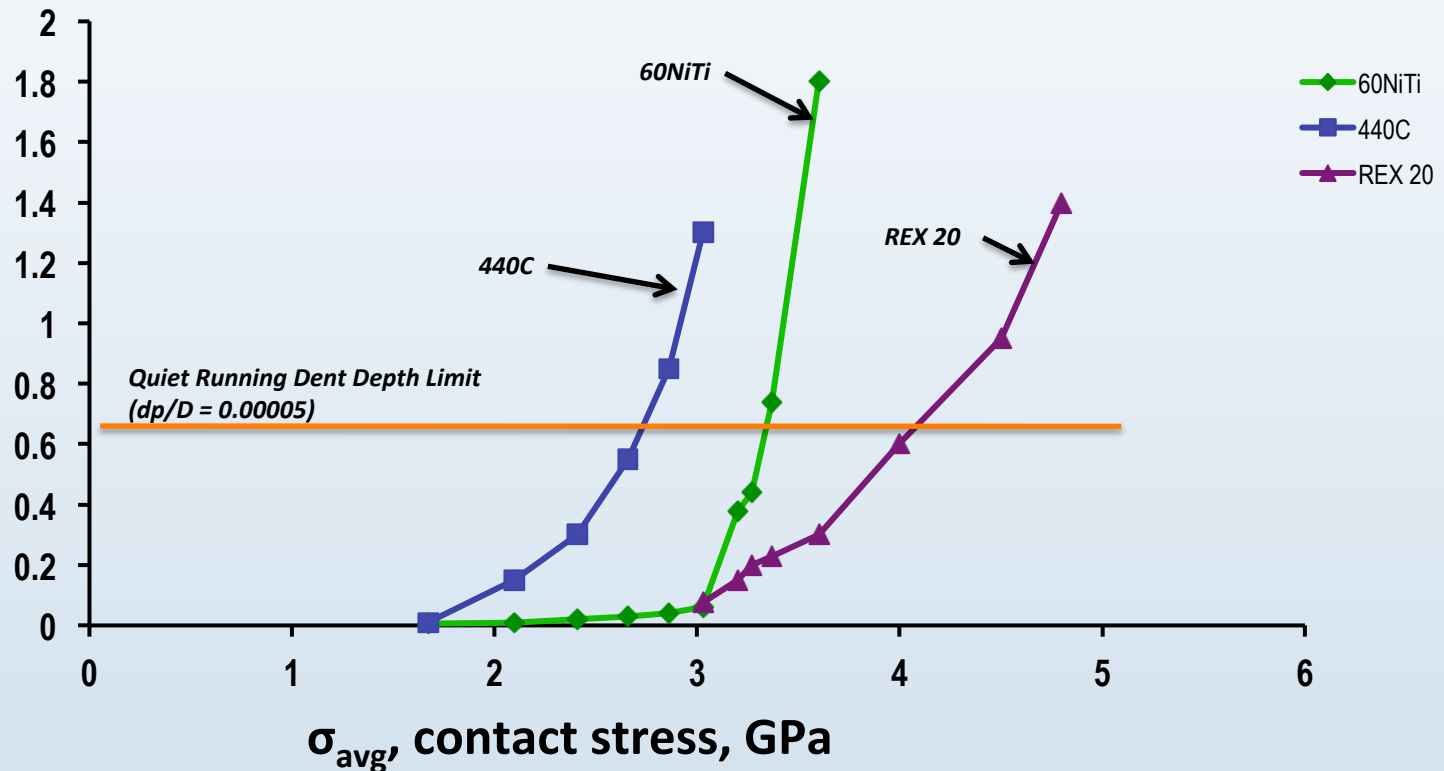
Threshold load visible dent.



Dent Depth vs. Hertz Contact Stress

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)

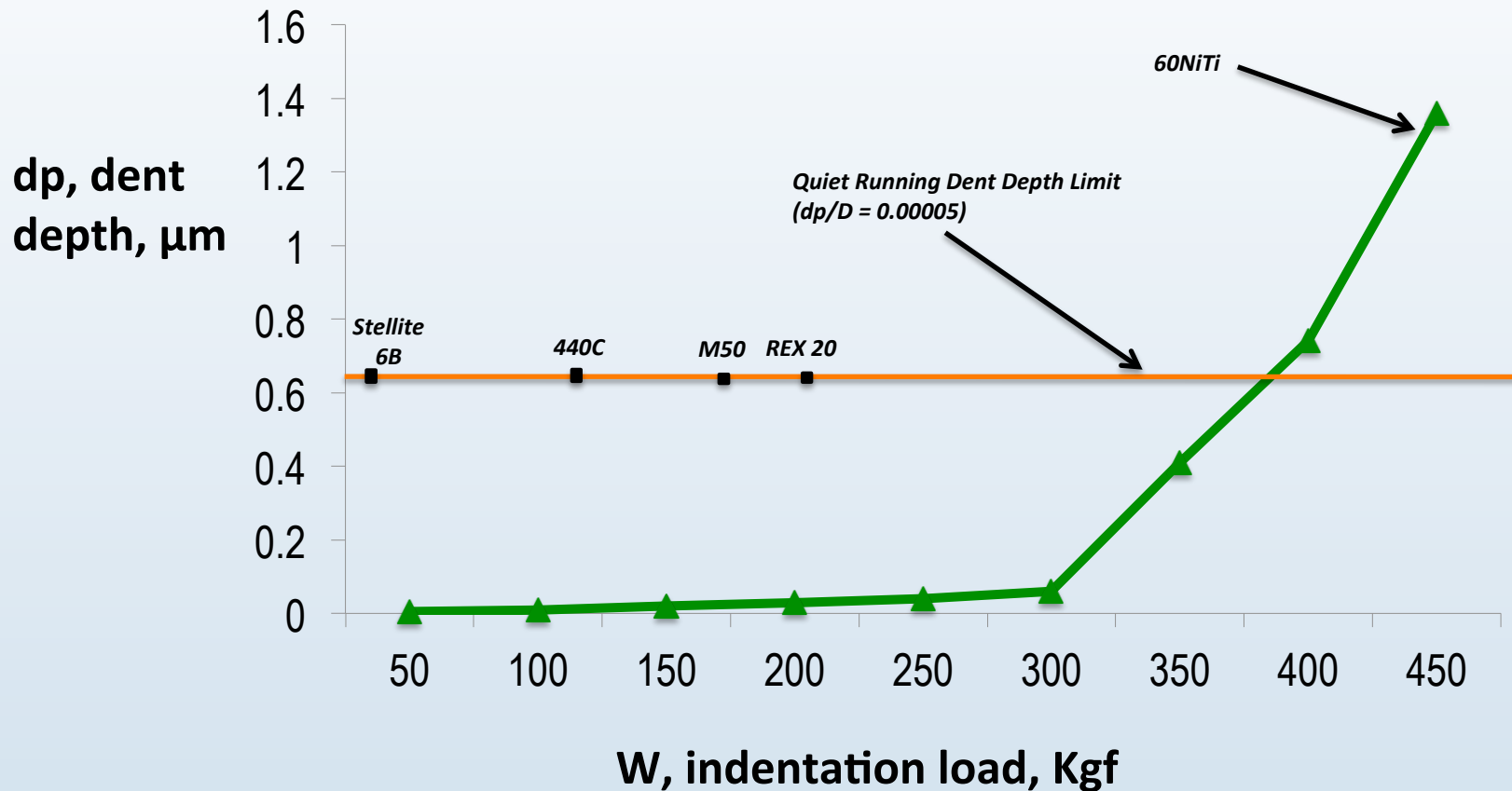
dp, dent
depth, μm





Dent Depth vs. Load

(Si_3N_4 ceramic ball pressed against 60NiTi plate)



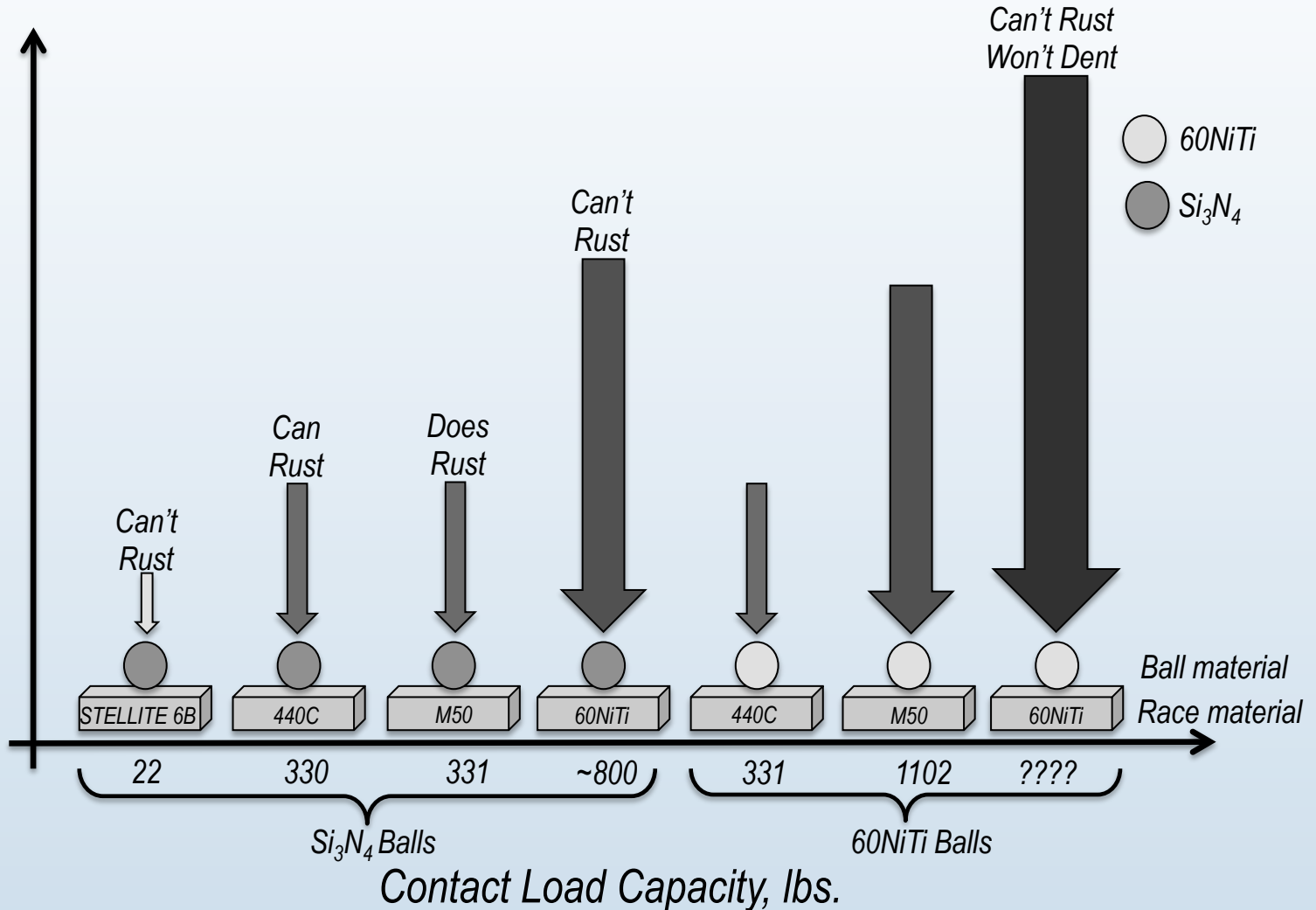
60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!



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



Indent test



Low modulus + high hardness + superelasticity = extreme load capacity



Bearing Manufacturing: 2nd half of the puzzle

60NiTi Ingot Prototype



60NiTi Ingot Slice



Wire Cut Blanks



QC Metallography

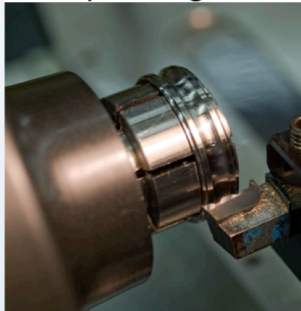


Now the material is ready for shaping into bearing races.

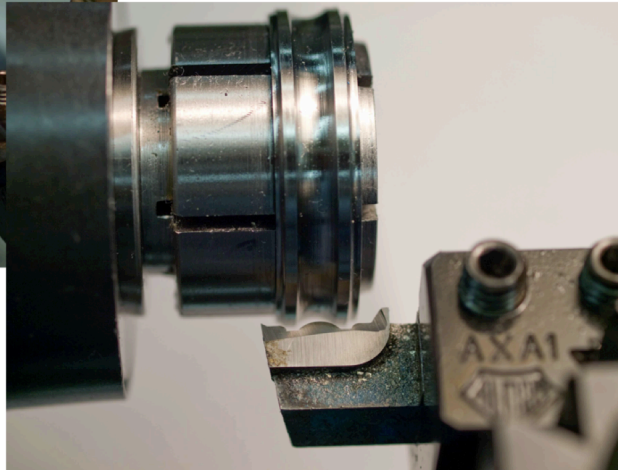


Bearing Manufacturing: Race Turning Details

Ring clamped on
expanding fixture



Carbide tool shaped by EDM
is plunged into rotating ring



Next Step: Heat treating the races to increase hardness.



Bearing Manufacturing: Heat treatment

Unrestrained Races Distorted



*Inconel race fixtures
(vented to allow quenching)*



*Process yields flat, round,
hardened races*



Final steps include finish grind, polish and assembly.



Pathfinder Bearing Manufacturing

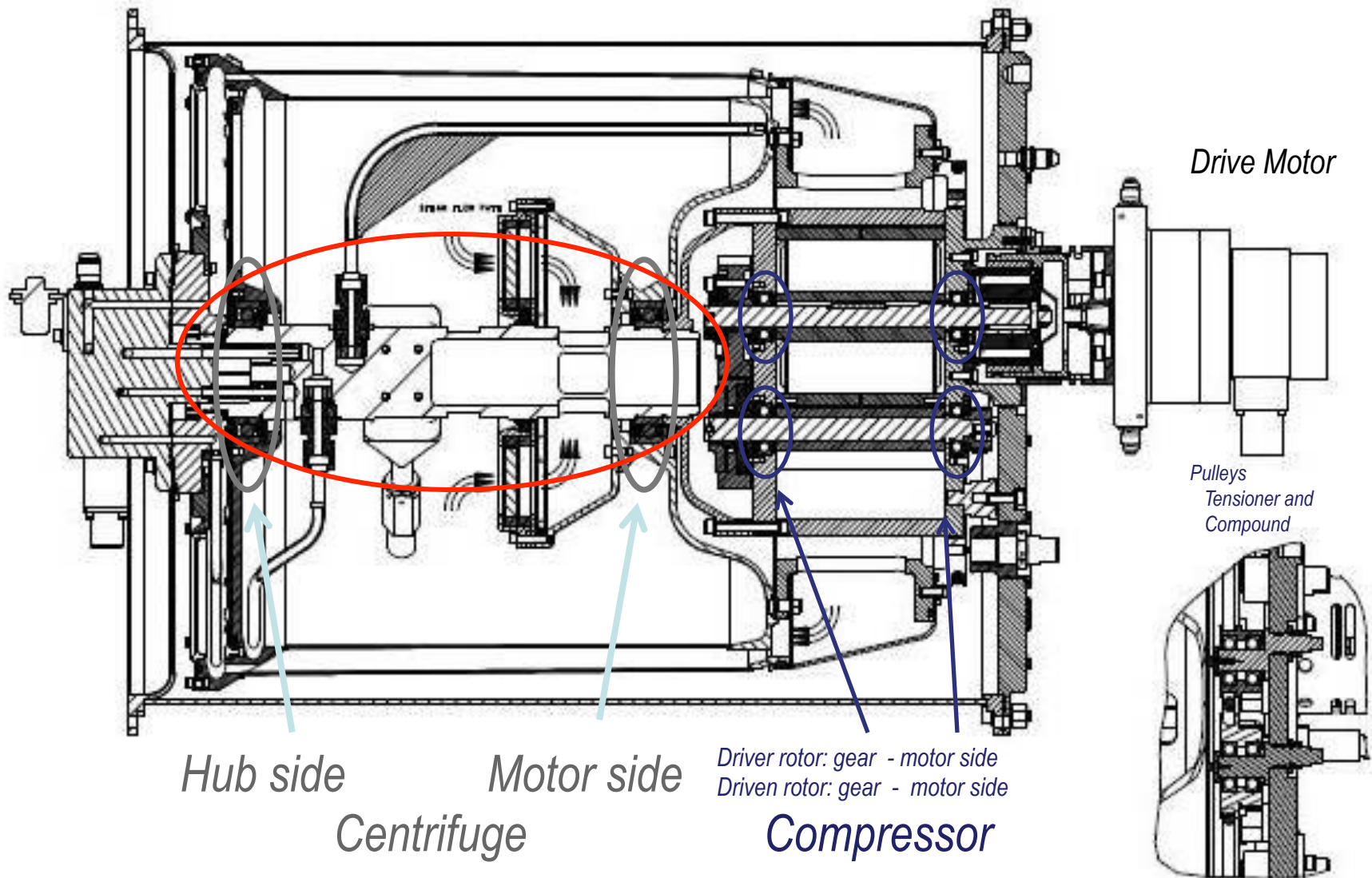
Finished 60NiTi-Hybrid Bearing



Manufacturing Process is now proven. Does the bearing actually work?



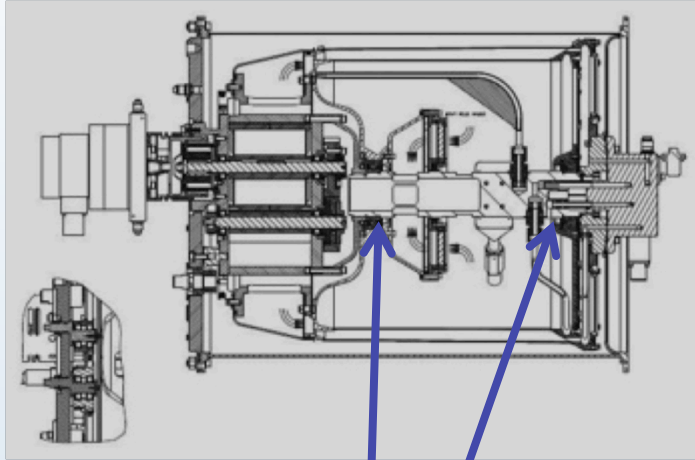
ISS DA Centrifuge Bearings: 60NiTi Application



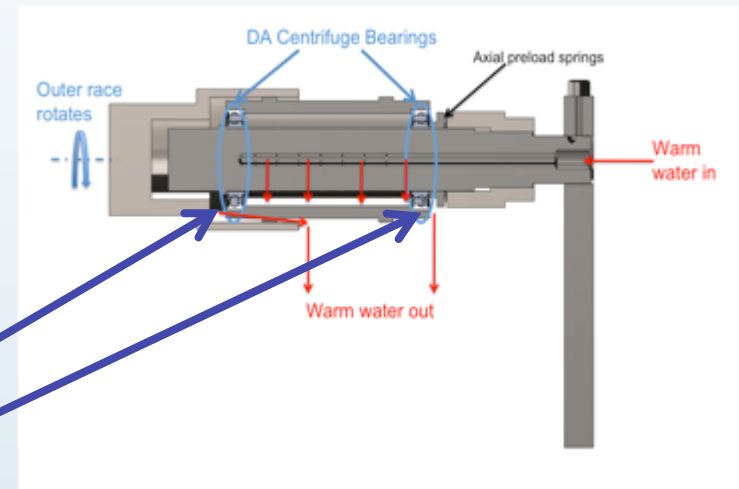


Bearing Testing: (Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator



*DA Centrifuge Bearing Test Rig
Spindle Components*



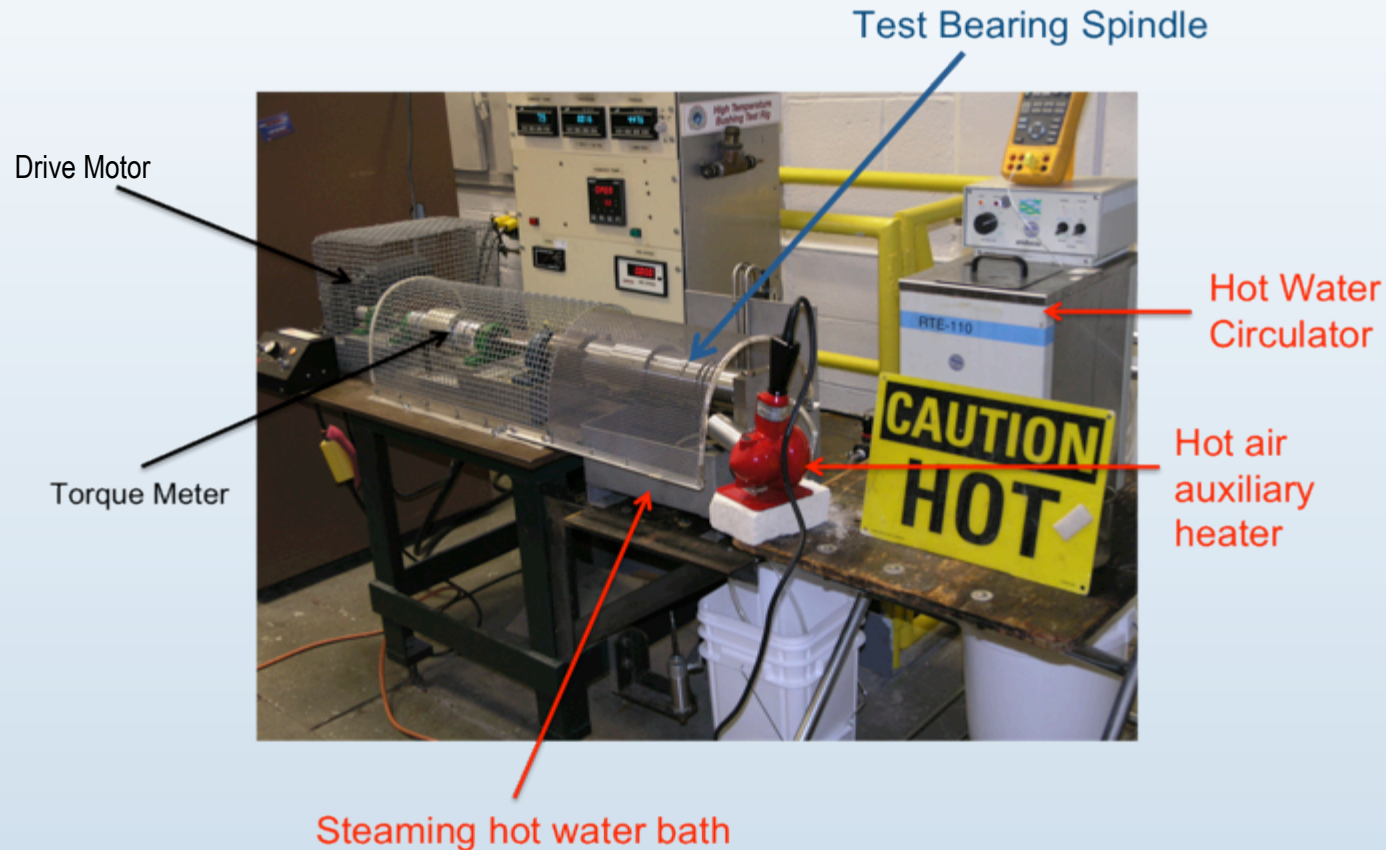
Speed, load, configuration, temperature and moisture match ISS application.



Bearing Testing:

(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor



Short term (20 hour) tests run to prove operations.



DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid



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

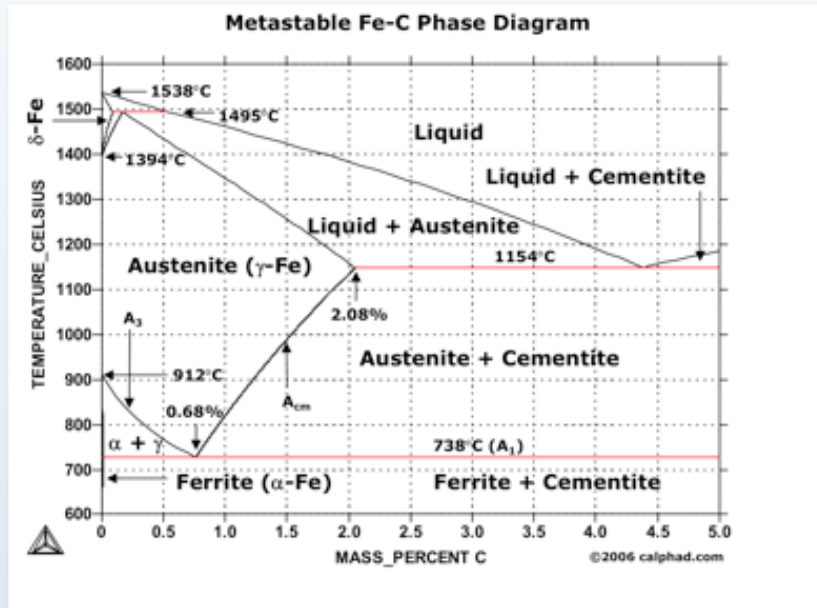


Take Away: 60NiTi is a bearing material!

- **Using modern materials and processing methods, 60NiTi can be manufactured into precision bearings.**
- **Good tribology and corrosion behavior.**
- **High hardness with low modulus and extremely high “super” elasticity are an unusual and valuable combination of characteristics with major implications to bearing technology.**
- **Leads to much more robust bearings and mechanical systems. Ideal for industrial, marine, spacecraft and aero bearings and components.**

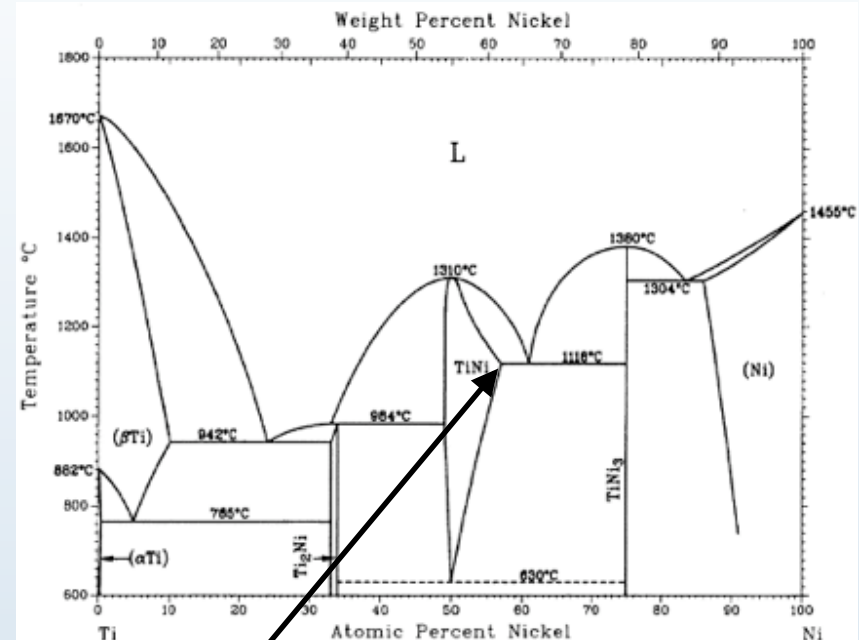


Closing Thoughts: Materials Design Space



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

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.



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



Thank You!