Novel Super-elastic Materials for Advanced Bearing Applications

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Abstract. Tribological surfaces of mechanical components encounter harsh conditions in terrestrial, marine and aerospace environments. Brinell denting, abrasive wear and fatigue often lead to life-limiting bearing and gear failures. Novel superelastic materials based upon Nickel-Titanium (NiTi) alloys are an emerging solution. NiTi alloys are intermetallic materials that possess characteristics of both metals and ceramics. NiTi alloys have intrinsically good aqueous corrosion resistance (they cannot rust), high hardness, relatively low elastic modulus, are chemically inert and readily lubricated. NiTi alloys also belong to the family of superelastics and, despite high hardness, are able to withstand large strains without suffering permanent plastic deformation. In this paper, the use of a hard, resilient NiTi alloy for corrosion-proof, shockproof bearing and gear applications is presented. Through a series of bearing and gear development projects, it is demonstrated that NiTi's unique blend of material properties lead to significantly improved load capacity, reduced weight and intrinsic corrosion resistance not found in any other bearing materials. NiTi thus represents a new materials solution to demanding tribological applications.

Introduction

Materials that are suitable for use in rolling element bearings are generally limited to four broad categories each of which have advantages and disadvantages [1]. The four categories are: 1) hardening steels, 2) superalloys and austenitic stainless steels, 3) ceramics and lastly, 4) non-ferrous alloys which include copper, zinc, and plastics. The hardening steels, such as M50 tool steel and 440C are inexpensive and have high hardness but generally poor corrosion resistance. Superalloys and austenitic stainless steels exhibit excellent corrosion resistance but low hardness. Ceramics such as silicon nitride are hard and chemically inert but are brittle and difficult to incorporate into machine designs because of their extreme rigidity and low thermal expansion coefficients. Finally, the non-ferrous alloys are inexpensive to produce but are weak and lack high temperature capability [2]. In most applications, design accommodations can be made to account for a bearing material's shortcomings. In some instances, however, benefits could be realized through the use of a material that simultaneously provides high hardness, corrosion resistance, ease of manufacture and design incorporation into mechanical systems. Since 2004, the potential to realize such benefits has motivated NASA to research and develop NiTi intermetallics for bearing applications [2-4]. The concept, however, began much earlier in another government laboratory.

The consideration of NiTi alloys for bearings can be traced to the pioneering work of William J. Buehler and his colleagues at the Naval Ordinance Laboratory during the late 1950's [5,6]. The designation NITINOL often used for these alloys is an abbreviation for Nickel-Titanium Naval Ordinance Laboratory. At that time, research was underway to develop high temperature, non-magnetic alloys for missile cone applications. Buehler’s early efforts identified both the Nitinol 55 and Nitinol 60 alloys, which contain 55 and 60-weight percent nickel, respectively. Nitinol 55 is soft and exhibits remarkable shape memory effects while Nitinol 60 is hard and is dimensionally stable. Both alloys have apparent elastic moduli comparable to titanium. Buehler abandoned work on the hard Nitinol 60 because it was very difficult to process and machine and it had the tendency to spontaneously fracture upon cooling after casting [7]. By applying modern powder metallurgy manufacturing methods, bearing quality balls and races have been routinely produced opening the potential for bearings that exhibit excellent corrosion resistance and tribological behavior [3,4].

Table 1 presents 60NiTi’s nominal material properties alongside traditional bearing materials. All of these materials have high hardness, high strength and temperature capability. Compared to the two metals 440C and M-50 tool steel, 60NiTi is about 15% lighter, has comparable thermal expansion coefficient, similar fracture toughness and Poisson’s ratio. 60NiTi is somewhat brittle and prone to tensile fracture thus its tensile strength, like many ceramics, is significantly lower than its compressive strength. In addition, 60NiTi has much lower (half) elastic stiffness (Young’s modulus) than the steels and one-third that of the ceramic silicon nitride. Like the ceramic, 60NiTi is immune to atmospheric corrosion. This blend of properties is unique and leads to a number of performance benefits with regards to bearings that are not immediately apparent from a cursory review of the properties alone.

TABLE 1.—NOMINAL PROPERTIES FOR 60NiTi, Si_3N_4 AND CONVENTIONAL BEARING STEELS

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	~9 to 14 W/m-°K	24 W/m-°K	33 W/m-°K	~36 W/m-°K
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

For instance, when used in a highly stressed, concentrated contact like a ball bearing, 60NiTi can withstand higher loads without suffering from permanent damage (e.g., denting) than a conventional all steel bearing [8]. The basis for this behavior lies within the contact mechanics of the ball-race interface. 60NiTi has a reduced modulus and yet is hard. These properties lead to a broadened contact area, reduced stresses and higher load capacity. Figure 1 shows this effect.

The use of 60NiTi and other emerging hard superelastic, low modulus alloys for bearings enables an expanded design space. Higher loads, smaller sizes and intrinsic corrosion resistance are all positive side effects of replacing iron-based alloys (steels). In the following discussions several notional bearing and other mechanical component applications will be considered that challenge conventional materials. In these

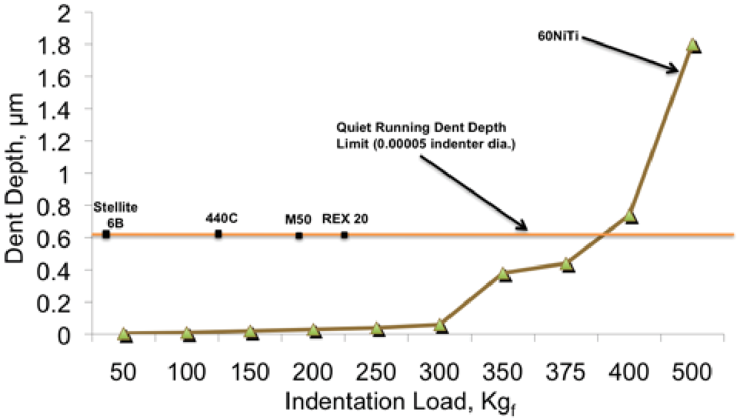

Figure 1.—Dent depth versus indentation load for 12.7 mm diameter Si_3N_4 ball pressed onto flat plate specimens [8].

applications, the use of conventional materials introduces design trade-offs that negatively impact mass, cost, performance and life. It will be shown that the use of novel NiTi superelastic materials can help overcome these challenges and enable new capabilities.

Applications. In Table 2 below, a range of mechanical component applications is listed. Each application represents a severe bearing or gear application that has long challenged the bearing community. In this table the needs or requirements are qualitatively ranked from “low need” meaning the associated characteristic is not essential to the success of the application, to “critical need” which implies that the application cannot be satisfied unless the material meets design requirements.

As an example, X-ray tube bearings need not have shock load capability, corrosion resistance, abrasion resistance or low mass. On the other hand, X-ray tube bearing materials must be capable of high temperature operation, conduct electricity so as to dissipate charge build-up, and be non-magnetic so as not to create magnetic fields that can disrupt the workings of the device. In addition, materials used for X-ray tube bearings must be able to operate in a vacuum (little or no outgassing tendency), tolerate radiation and be compatible with solid film lubrication.

TABLE 2.—FIELD OF APPLICATION (LOW NEED, MODERATE NEED, CRITICAL NEED)

Design requirement	Water treatment and food processing	Marine machinery	Space gyros	Aircraft landing gear	Aircraft control surface bearings	Mining vehicle bearings	X-ray tube bearings
Shock/high loads	Low	Low	Critical	Critical	Moderate	Critical	Low
High temp.	Low	Low	Moderate	Low	Low	Low	Critical
Corrosion	Critical	Critical	Low	Critical	Critical	Low	Low
Electrical conduction	Low	Low	Moderate	Low	Low	Low	Critical
Magnetic flux	Low	Low	Critical	Low	Low	Low	Critical
Mass/ constraints	Low	Low	Moderate	Critical	Critical	Low	Low
Abrasion	Moderate	Moderate	Low	Moderate	Moderate	Critical	Low
Other	Withstand steam cleaning and autoclave	Impervious to salt water ingestion	High rolling contact fatigue life	High scuff resistance	Compatible with aircraft hydraulic and deicing fluids	Interface with steel housings	Vacuum, radiation, and solid lubricant compatible

In a similar vein, bearings and gears for mining vehicle applications must be able to endure excessive static and shock load levels while offering low wear in the presence of abrasive particles and be amenable to integration with adjacent structural components made of steel or cast iron. NiTi alloys exhibit high hardness that provides good abrasion resistance and have thermal expansion coefficients that match those of steel and this reduces thermal mismatch induced stresses that can hinder the use of low expansion materials like ceramics. To further demonstrate the unique enabling characteristics of NiTi three additional applications are presented in the sections that follow. These are a low speed ball bearing application exposed to wet acidic steam environment, a dry film lubricated lightly loaded timing gear set exposed warm steam (not acidic) and ball bearings used for a space reaction wheel assembly. By studying these examples, the advantages, disadvantages and future potential for NiTi alloy use in mechanical components can be revealed.

Case I: Distillation Assembly Centrifuge Bearings. The Distillation Assembly (DA) is a key part of the International Space Station (ISS) wastewater processing system that produces potable water from various liquid waste streams on the spacecraft. The DA is a rotary still that resembles a front load style washing machine. See Fig. 2 for a cross-section view of the DA.

The centrifuge drum support bearings are simple 50 mm ball bearings that rotate at low speed (200 rpm) under very modest loads (~100 to 300 N). Such benign mechanical requirements are not normally a challenge for ball bearings. However, these bearings are directed exposed to the highly acidic (pH~2.0) waste fluid that causes corrosion for even the highest-grade hardened stainless steels like 440C. The current design utilizes relatively soft (HRC~40) cobalt alloy bearings that can wear in use and be damaged during machine assembly. To address both the corrosion and wear concerns, 50 mm bore bearings (Fig. 3) have been made with 60NiTi races and Si_3N_4 balls (hybrid style) and successfully tested (Fig. 4) under wet and warm rotational operation [9].

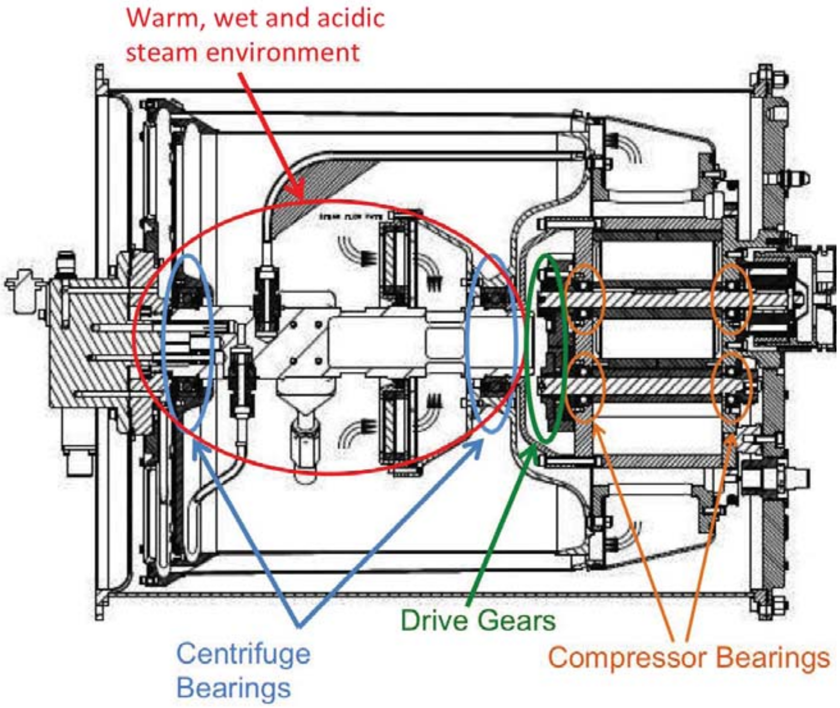

Figure 2.—Cross-section view of rotating distillation assembly.

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Figure 3.—Finished hybrid bearing made with 60NiTi races and Si_3N_4 bearing balls.

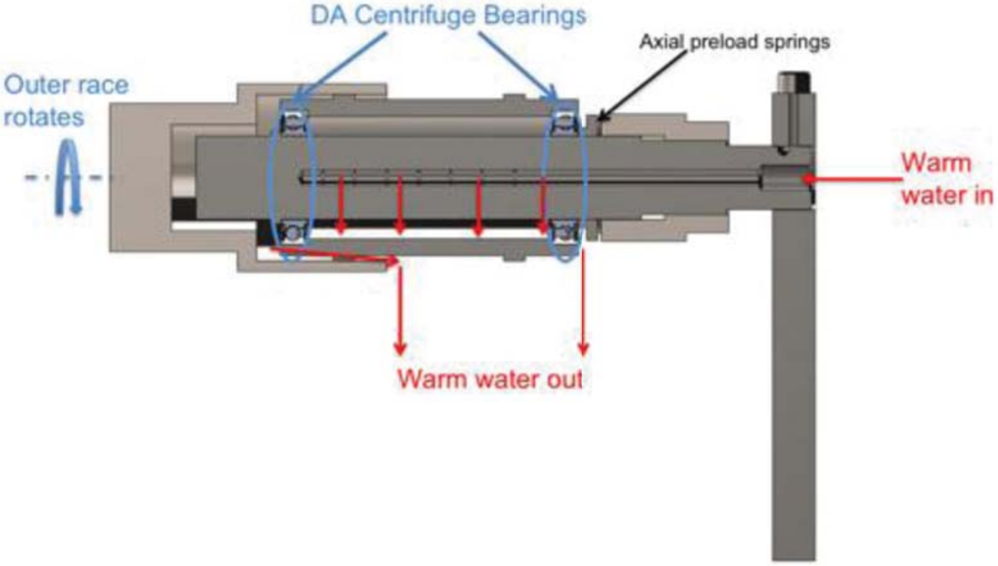

Figure 4.—Cross-section schematic of DA bearing proof-of-concept test rig.

Following testing, the 60NiTi hybrid bearings were disassembled and inspected. No discernable differences from new were observed. Given the intrinsic corrosion resistance of NiTi alloys and its high hardness, it is apparent that this challenging application is well met by these NiTi alloys.

Case II: Distillation Assembly Compressor-Vacuum Pump Drive Gears. The second example is also a mechanical component of the DA. In this case, it is the pair of gears that drive the lobes of the DA vacuum pump (compressor) and keep them precisely timed during operation. In Fig. 2, these drive gears are deep inside the DA between the right-hand centrifuge bearing and the left-hand compressor bearings. They are largely shielded from the acidic wastewater but are exposed to hot steam. In this application, the gears ensure accurate timing of the pump lobes to prevent lobe-to-lobe contact. As such, excessive wear of the gear mesh, as opposed to frictional power losses, is a primary consideration. The gears run at high speed but low torque. Solid lubrication using a food grade, non-toxic dry film lubricant (DFL) approach must be considered to ensure long life and avoid contamination of the process fluid. Ideally, hardened steel gears would be used but without the presence of a corrosion inhibiting grease, corrosion is a concern. This application seems ideally suited to the hard, corrosion resistant 60NiTi lubricated with an appropriate DFL.

To assess this option, a series of pin-on-disk tribological tests were done to simulate the gears. The test load and speeds were selected to screen candidate DFL's and compare them to a conventional stainless steel-polymer gear tribo-pair. The data is shown in Table 3 below.

TABLE 3.—FRICTION AND PIN WEAR DATA SUMMARY
(Test conditions: 4.9 N load, 2.7 m/s sliding speed, air at 25 °C)

Pin Material	Disk material/Surface coating	Friction coefficient	Pin wear factor, mm^3/N-m	Surface appearance
SP21 Polyimide	316L SS	0.29±0.07	$1.9\pm0.7\times10^{-6}$	Smooth
SP21 Polyimide	304 SS	0.34±0.08	$0.7\pm0.2\times10^{-6}$	Smooth
SP21 Polyimide	60NiTi	0.28±0.04	$2.1\pm1.5\times10^{-6}$	Smooth
60NiTi	60NiTi	0.18±0.03	$8.3\pm3.2\times10^{-6}$	Rough
60NiTi + SP21	60NiTi	0.15±0.03	$3.1\pm1.9\times10^{-6}$	Smooth
[a]60NiTi	PTFE DFL	0.15±0.02	[b]184 to 348 km	Smooth
[a]60NiTi	Graphite DFL	0.17±0.02	[b]24 to 135 km	Smooth

[a]Tests initiated with pre-worn pin (~3 mm dia. Wear scar).
[b]Tests terminated when DFL wore through to substrate. No additional pin wear was observed.

The test results point to the use of a pair of 60NiTi gears lubricated with a PTFE based DFL. Friction was lower than the baseline polymer-stainless case and wear was very low. In this case, the intrinsic corrosion resistance and high hardness of 60NiTi coupled with its functional compatibility with commercial DFL's make it a suitable candidate for an otherwise challenging gear application.

Case III: Launch Load Tolerant Reaction Wheel Assembly (RWA) Bearings. Reaction wheel assemblies (RWA) are used for spacecraft motion control functions. RWA's consist of a heavy wheel supported on ball bearings driven by an electric motor. A commercially available reaction wheel assembly is shown in Fig. 5 and uses a small, R4 (6.35 mm bore) ball bearing design.

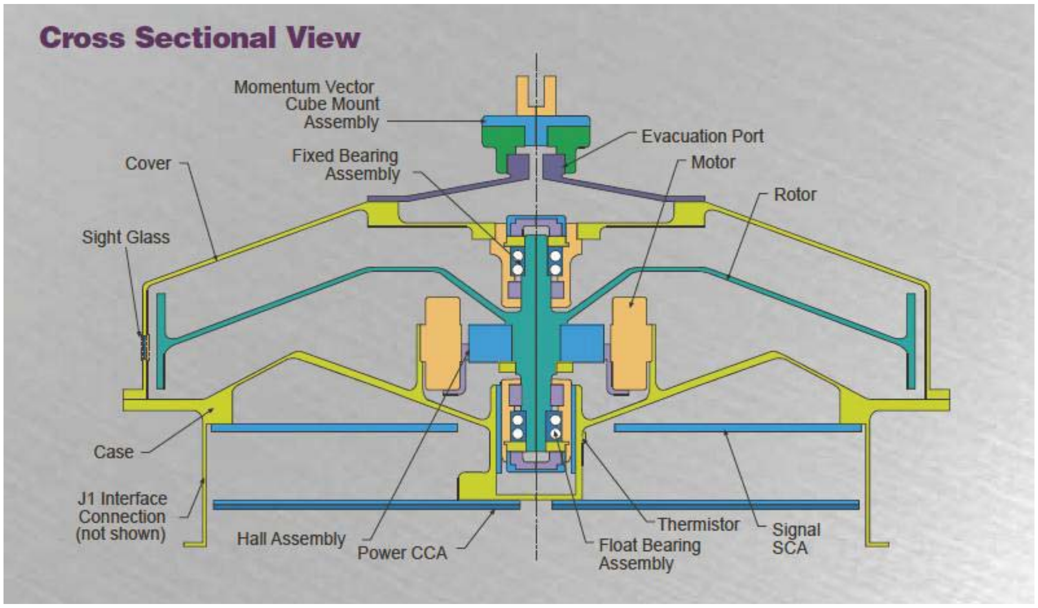

Figure 5.—Typical reaction wheel assembly: based upon Honeywell Corporation Model HR 0610 design [10]. 5 kg wheel supported on four R4 ball bearings.

The bearings must provide low and stable running torque for long periods and survive the rigors of launch without damage. Spacecraft launch loads near 15 g's are not uncommon. The contact between the balls and inner race surface are particularly vulnerable such loads because the small ball-race contact areas experience high stresses even at modest bearing load. Compared to conventional bearing steels, the use of superelastic 60NiTi in reaction wheel bearing applications offers the potential for increased static load margins (Fig. 1).

To determine the potential magnitude of these improvements, a small rotor (5 kg) supported by two duplex pairs of small (R4 size) deep groove ball bearings is considered. Maximum contact stress limits for 60NiTi, 440C and the high carbide content REX20 tool steel are applied to the ball-inner race contact to estimate the maximum allowable g-forces the assembly can withstand. By comparing these resulting maximum load values, the benefits of using superelastic materials for races, and balls in wheel bearings can be determined. The net results are summarized in Table 4 below and each configuration case as designated by roman numerals is described in more detail in a previous publication [11].

TABLE 4.—REACTION WHEEL LAUNCH LOAD CAPACITY
[5 kg wheel mass supported on two duplex pairs of R4 bearings.]

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] Load beyond yield strength of RWA shaft.

The load capacity results reveal some interesting insights. The two conventional ball/race material configurations (I-440C/440C and II-Si_3N_4/440C) have load capacity values near the g force requirements for rocket launch (~15 g's) with additional margin to accommodate bearing preload and other forces neglected in the present simplified analyses. The superelastic-bearing configuration (VI) shows a value well beyond the bending load capability of an RWA wheel shaft sized for the bore of R4 bearings. This revelation suggests that in such an application, a superelastic bearing is essentially shockproof. Further, the availability of more robust bearing materials like 60NiTi may enable the use of fewer and smaller bearings thus reducing weight, power consumption and potentially cost. In addition, the enhanced corrosion resistance and non-magnetic properties of the NiTi alloys could enable mechanism designs with new capabilities.

Summary Remarks

This investigation confirms that bearings made with low modulus, hard and superelastic 60NiTi material offers an enabling path to solve longstanding tribological challenges. NiTi materials are somewhat brittle, generally higher in materials cost and more difficult to manufacture than steels. However, in applications where corrosion, Brinell denting, abrasive wear and fatigue often lead to life-limiting bearing and gear failures, the use of Ni-Ti alloys are an approach that overcomes the limitations of traditional materials. Since Ni-Ti alloys are intermetallic materials they exhibit characteristics of both metals and ceramics. Their intrinsically good aqueous corrosion resistance (they cannot rust), high hardness, relatively low elastic modulus, and lead to extraordinary performance properties. Ni-Ti thus represents a new materials solution to demanding tribological applications. Future efforts to improve the material through alloying suggest a bright future for this research direction.

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