Design and Manufacturing Considerations for Shockproof and Corrosion-Immune Superelastic Nickel-Titanium Bearings for a Space Station Application

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Abstract

An intermetallic nickel-titanium alloy, 60NiTi (60wt%Ni, 40wt%Ti), is a promising tribological material for space mechanisms. 60NiTi offers a broad combination of physical properties that make it unique among bearing materials. 60NiTi is hard, electrically conductive, highly corrosion resistant, readily machined prior to final heat treatment, easily lubricated and is non-magnetic. It also falls within the class of superelastic alloys and can elastically endure large strains (beyond 5 percent) making it highly resistant to excessive and unexpected (shock) loads. Key material properties and characteristics such as elastic modulus, tensile fracture sensitivity and residual stress behavior, however, differ from conventional alloys such as steel and this significantly affects bearing design and manufacturing. In this paper, the preliminary design and manufacture of ball bearings made from 60NiTi are considered for a highly corrosive, lightly loaded, low speed bearing application found inside the International Space Station's water recycling system. The information presented is expected to help guide more widespread commercialization of this new technology into space mechanism and other applications.

Introduction

Recent research on binary nickel-titanium (Ni-Ti) alloys has identified them as promising candidates for bearings and mechanical components (Ref. 1). The nickel-rich alloy, 60NiTi in particular, exhibits a remarkable combination of properties and characteristics relevant to rolling element bearings for space mechanism applications. For instance, 60NiTi is hard, electrically conductive, highly corrosion resistant, readily machined prior to final heat treatment, easily lubricated and is non-magnetic (Refs. 2 and 3). 60NiTi is also in the family of superelastic alloys and can elastically endure large strains (beyond 5 percent) making it highly resistant to shock loads. Table I lists many of these properties as they are currently known alongside the conventional shape memory alloy 55NiTi and more traditional bearing materials. As an emerging material, some of these published properties are estimated or preliminary.

Shock loading is a significant design challenge for space mechanisms. On orbit bearing loads, in the absence of gravity tend to be very low but the severe launch vibration environment can lead to bearing damage through the Brinell effect in which hard rolling elements dent more vulnerable races (Ref. 4). For applications that demand long life and ultra smooth operation, such Brinell damage can be catastophic. In such cases, great care is taken using vibration isolation features and tie-down systems to avoid the problem. These add weight and complexity. At times, load capacity design margins are increased for bearings and this leads to increased mass and power consumption. Clearly, the development of more resilient bearings is an advantage for aerospace bearings and mechanisms.

Recent investigations into the hardness and Brinell damage sensitivity of 60NiTi show a potential pathway to engineer ball bearings that are highly resistant to indentation damage (Ref. 1). In preliminary indentation tests either Si_3N_4 or 60NiTi balls (12.7 mm diameter) were pressed into flat plates made from 60NiTi and the bearing alloys 440C, M50, and Stellite 6B. Initial experiments were carried out at light loads that were increased on subsequent trials. In this manner, both the classic Brinell Hardness Number

TABLE I.—REPRESENTATIVE THERMOPHYSICAL AND MECHANICAL PROPERTIES OF BEARING MATERIALS

Property	60NiTi	55NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	6.5 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 Rc	35 to 40 Rc	58 to 62 Rc	1300 to 1500 Hv	60 to 65 Rc
Thermal conductivity W/m-°K	18	9	24	33	~36
Thermal expansion	~10×10^{-6}/°C	~10×10^{-6}/°C	10×10^{-6}/°C	2.6×10^{-6}	~11×10^{-6}/°C
Magnetic	Non	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent	Excellent	Marginal	Excellent	Poor
Tensile/Flexural strength	~1000 MPa	~900 MPa	1900 MPa	600 to 1200 MPa (Bend strength)	2500 MPa
Young's modulus	~114 GPa	~100 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	~0.34	0.3	0.27	0.30
Fracture toughness	TBD	TBD	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Max. use temp	~400 °C	~400 °C	~400 °C	~1100 °C	~400 °C
Elect. resistivity	~80×10^{-6} Ω-cm	~80×10^{-6} Ω-cm	~36×10^{-6} Ω-cm	Insulator	~60×10^{-6} Ω-cm

TBD means "to be determined"

TABLE II.—HERTZ CONTACT STRESSES AND CONTACT DIAMETER AT THE THRESHOLD LOAD
FOR VARIOUS PLATE AND INDENTER MATERIAL COMBINATIONS

Plate	Indenter	Threshold load, kgf (lbs)	Peak stress, GPa (ksi)	Contact diameter, mm (in.)	Avg. stress, GPa (ksi)
Stellite 6B	Si_3N_4	10 (22)	2.06 (299)	0.30 (0.012)	1.37 (199)
440C	Si_3N_4	51 (112)	3.48 (504)	0.52 (0.021)	2.32 (336)
M50	Si_3N_4	150 (331)	5.09 (738)	0.74 (0.029)	3.39 (491)
60NiTi	Si_3N_4	[a]552 (1214)	5.56 (806)	1.36 (0.054)	3.71 (537)
Stellite 6B	60NiTi	15 (33)	1.56 (226)	0.42 (0.017)	1.04 (151)
440C	60NiTi	150 (331)	3.33 (483)	0.92 (0.036)	2.22 (322)
M50	60NiTi	501 (1102)	5.02 (728)	1.37 (0.054)	3.35 (486)
60NiTi	60NiTi	1512 (3327)	5.90 (856)	2.19 (0.086)	3.94 (571)

[a]Using 1.2 µm (50 µin.) dent depth fatigue criterion. Threshold load is ~360 kgf (~800 lb) using more stringent 0.6 µm (25 µin.) dent depth criterion for quiet running bearing.

(BHN) and the threshold load to achieve the first observable dent was obtained. The data, tabulated in Table II, shows that 60NiTi provides significantly more static load capacity (higher threshold load) than the other materials tested.

The reasons for this behavior are complex and discussed in detail in Reference 1 but briefly, the large elastic deformation range of 60NiTi combined with its high hardness and relatively low elastic modulus result in an increased contact area, reduced peak and average stresses and enhanced static load capacity. Given these somewhat unexpected results and capabilities, the next logical steps are to design and fabricate bearings from 60NiTi for evaluation.

Bearing design and manufacturing is a field that is mature and well developed for steels and, in the case of rolling elements (balls and rollers), silicon nitride ceramics. 60NiTi is a superelastic material in the class of intermetallics (neither a metal or ceramic with respect to atomic bonding) and has key physical properties and attributes that differ from the traditional bearing materials. Among the relevant differences are a relatively low elastic modulus, limited tensile ductility (a tendency for brittle failure in tension), and a requirement for a rapid quench during heat treatment which leads to significant residual stresses. These three key differences along with other second order attributes affect bearing design and manufacturing processes.

The following sections describe the general design and manufacturing process for 60NiTi bearings by considering a specfic space mechanism bearing application; the Distillation Assembly (DA) centrifuge that is part of the ISS Environmental Control System (ECLSS) on the International Space Station (ISS). The ball bearings used in this application operate in a highly corrosive environment at low speed under very low average loads thus fatigue is not a great concern. However, the bearings must endure high launch loads without damage. Based upon preliminary data, 60NiTi appears to be a viable candidate

bearing material. This paper lays out the design process and the results of pathfinder manufacturing investigations to develop a more generalized methodlology for incorporating superelastic materials into space mechanisms.

Materials and Procedures

Bearing grade 60NiTi is manufactured via a proprietary high-temperature powder metallurgy (PM) process roughly similar to that described in the literature (Ref. 5). Pre-alloyed 60NiTi powder is hot iso-static pressed (HIPed) into various shapes and sizes depending upon the desired end product. To make 60NiTi balls, the powder is HIPed into rough, spherical ball blanks that were then ground, polished and lapped. Because the PM process yields ball blanks that have isotropic mechanical properties high quality (Grade 5) bearing balls can be readily produced. The finished 60NiTi ball specimens, shown in the photograph in Figure 1, are bright and shiny in appearance and resemble conventional polished steel balls.

To make other shapes such as bearing races and mechanical and thermo-physical property measurement specimens, 60NiTi rods and ingots were first made using the same PM process. Figure 2 shows such specimens produced by the PM process.

Once the ingots and other shapes are produced, a series of steps that include wire electrode discharge machining (EDM), conventional machining using carbide tools and grinding are employed. A multi-step thermal process (heat treatment) generally occurs after rough machining to near final dimensions but before final grinding and polishing in the case of balls and bearing raceways. For parts that are not dimensionally critical, simple wear plates for example, final grinding after heat treatment may be unnecessary.

A typical heat treatment includes solution treating at 1000 °C in vacuum or inert gas atmosphere followed by a rapid quench in water. The solution treating dissolves precipitate phases like Ni_4Ti_3 and Ni_3Ti forming the preferable NiTi phase. Rapid quenching locks in the dominant NiTi phase and discourages the formation of the other phases that can lead to brittleness and low hardness. Details regarding the processing and resulting properties are the subject of ongoing research and are partially described elsewhere (Ref. 6, to be published). Using the generalized processes described above, specimens are being fabricated to enable rolling contact fatigue stress limits, bend strength, Charpy impact toughness, compressive strength and thermal properties such as thermal expansion, thermal conductivity and thermal diffusivity. This data will be available in the future but initial bearing design can proceed using information available and estimated.

Figure 1.—60NiTi grade 5 test balls.

Figure 2.—60NiTi ingots and blanks produced by PM process.

Design and Manufacturing Considerations

A baseline bearing can be designed using the preliminary and estimated 60NiTi materials properties. This design can then be reviewed and analyzed for its general appropriateness the DA bearing application. Using the preliminary design, a manufacturing method must be then developed and tested. Since key structural properties of 60NiTi differ from bearing steel (notably the elastic modulus is low and high machining forces are needed for material removal), the manufacturing process and tooling may differ from the norm. If the manufacturing investigation identifies design deficiencies it can be revised in an iterative manner. Further, as additional material properties are obtained, such as rolling contact fatigue stress limits, the design can be revisited. The following sections expand upon the preliminary design analysis and a pathfinder manufacturing trial.

Results and Discussion

The DA bearing application currently under consideration is characterized as highly corrosive and mechanically benign. The bearings are nominally 50 mm bore deep groove ball bearings operating at low speed (a few hundred rpm) under very modest axial preload. In space, there is virtually no imposed radial load. Table III gives the representative baseline bearing conditions.

When reviewing the data and parameters in Table III it becomes clear that the environmental stresses on the bearings, namely the warm and highly acidic environment, far outpace the modest mechanical loads and stresses. In fact, during early system development, the originally specified martensitic stainless steel bearings (440C) experienced unacceptable surface corrosion. Following bench top corrosion studies in a simulated environment, the steel bearings were replaced with the cobalt race-Si_3N_4 ball hybrid bearing design as a baseline.

Figure 3(a) shows a photograph of the DA assembly during ground tests. This device is essentially a rotating drum evaporator that utilizes a belt drive to provide a low pressure, warm internal chamber that boils wastewater on the ISS. The steam coming off of the drum section is collected and condensed and is then further treated before re-use. Further details of this system can be found in the literature (Refs. 7 to 9). In cross section (Figure 3(b) shows a representative design), the subject rotor system is a simple configuration of two shielded ball bearings that are lightly spring preloaded and operate in the warm, moist and acidic environment.

TABLE III.—REPRESENTATIVE APPLICATION BEARING PARAMETERS
AND OPERATING CONDITIONS

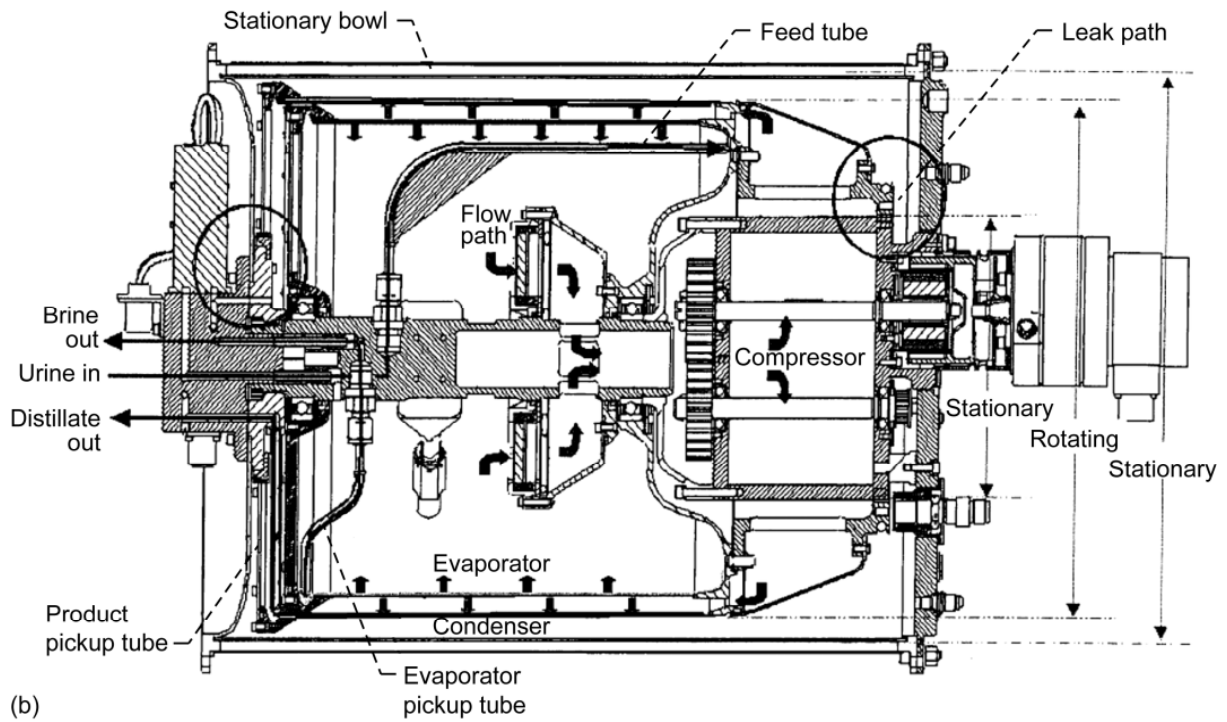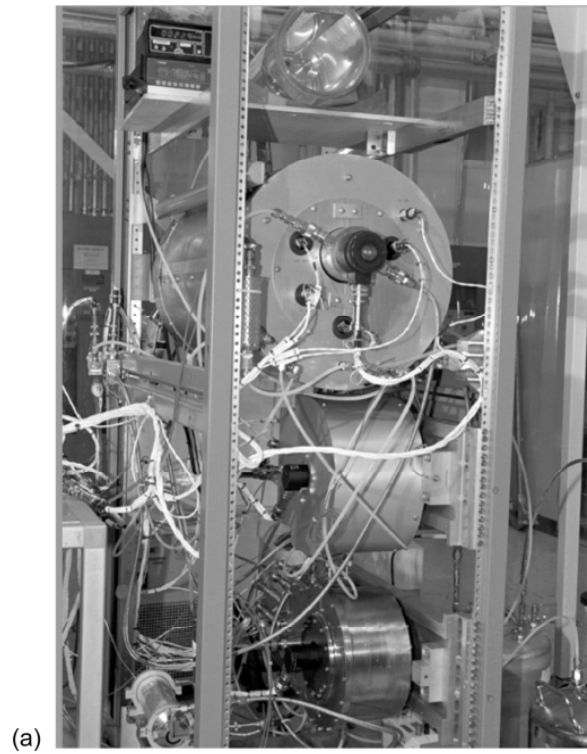| Parameter	Value or Condition
Outer diameter, O.D.	~80 mm
Inner diameter, I.D.	~50 mm
Width, W	~16 mm
Ball size, D	~9 mm
Ball material	Si_3N_4
Race material	Cobalt alloy
Cage	Snap fit, polymer
Lubricant	Lithium based grease
Ball-race stress limit	~2 MPa
Ball-race mean stress	~1 MPa
Axial preload	~200 N
Radial load (terrestrial)	~100 N/bearing
Speed	100 to 300 rpm
Environment	Warm, highly acidic aqueous solution
Ambient pressure	Slight vacuum

Figure 3.—ISS Distillation Assembly. (a) In ground tests. (b) Cross-section taken from Reference 9.

Figure 4 shows a photograph of the centrifuge bearings after removal from service. The bearings are a straight ball bearing design and utilize a cobalt alloy for the races and silicon nitride for the balls to achieve maximum corrosion resistance.

The performance of the current DA bearings has not been completely satisfactory. The very first system launched suffered from raceway damage that occurred during bearing assembly and installation. Though this damage did not result in system failure, long life could not be assured. The second system launched was returned to earth after a short period of use for repair of an unrelated system component. During a routine bearing inspection significant race wear was observed. Figure 5 shows a photograph of the surface of a worn inner race in which the ball has created a pronounced wear track.

The wear was attributed to the lack of hardness of the cobalt-based races compared to the ceramic balls. The bearings still functioned, but again, long-life was not assured. It is these shortcomings of the current bearing race materials that provides the impetus to consider 60NiTi. Among the first material selection criteria to be assessed is corrosion resistance to the process fluid.

A variety of candidate bearing alloys including steel, 60NiTi and the baseline cobalt alloy were evaluated for corrosion resistance. In this test, ball sized specimens were immersed in a warm and highly acidic aqueous solution that simulates the application. The specimens were weighed before and after exposure for times up to one week and the immersion fluid was analyzed to determine its metal ion content as a means to assess corrosion behavior of the alloys. Table IV shows a summary of the results.

Not surprisingly, the corrosion resistance of 60NiTi is excellent. Unlike stainless steels, nickel and cobalt alloys do not rely upon the formation of chrome rich passivation layers for their corrosion resistance. Rather, such alloys employ intrinsically corrosion resistant constituents in their chemistry. For Ni-Ti alloys, such as 60NiTi, both nickel and titanium are regarded as highly immune to aqueous acidic corrosion thus the corrosion resistance for the alloy is to be expected. For corroboration, the current cobalt alloy bearing races have not shown any evidence of corrosion problems even after months of service. Since the 60NiTi fares better, in terms of corrosion, than the current cobalt alloy is it justifiable to expect the superelastic bearings will not suffer corrosion. In terms of mechanical properties, however, deeper consideration is warranted.

The bulk hardness of 60NiTi (Table I) ranges from Rc 58 to 63 depending upon the heat treatment employed and the dimensions and geometry of the specimen. This is comparable to traditional bearing steels and much harder than the baseline cobalt alloy race material. Rolling and sliding wear tests of 60NiTi under dry and grease lubricated conditions yield tribological behavior comparable to that for hardened bearing steels like 440C (Refs. 2 and 3). For these reasons, the wear observed in the current bearings is not expected for bearings made from the much harder 60NiTi. 60NiTi, however, has a much lower elastic modulus than both traditional steels and the cobalt alloy. This could affect bearing operation.

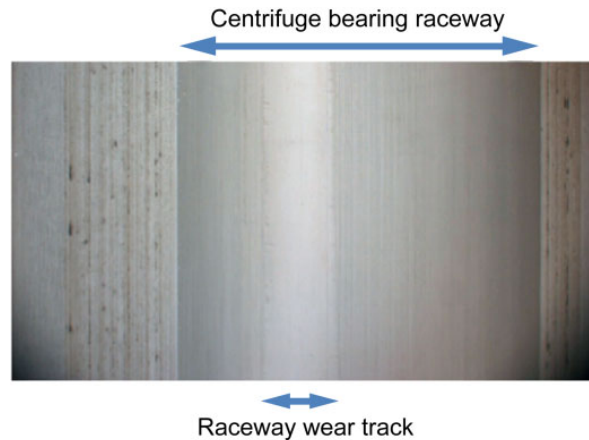Figure 4.—ISS distillation assembly centrifuge bearings.

Figure 5.—Photograph of an ISS distillation assembly centrifuge bearing showing wear track following operation on orbit.

TABLE IV.—CORROSION MASS LOSS FOR BALLS (12.7 mm DIAMETER)
SOAKED IN SIMULATED DA SOLUTION (115 hr, 65 °C, pH 1.0)

M50 tool steel	27,600 μg
Cobalt alloy	389 μg
60NiTi	224 μg

The elastic modulus for 60NiTi closely resembles titanium and is less than half that of steel and superalloys (Table I). Thus under load, one expects to encounter deformations and deflections that are approximately twice the level of comparable steel or superalloy components. For mechanical systems in which rigidity and position control is paramount, such a change in elastic behavior can be a design challenge. In a bearing, the radial and axial stiffness are direct functions of the material elastic modulus and thus shaft deflections, for a given load, will increase when going to a superelastic bearing design. At the ball-race contact within a bearing, the lower modulus results in larger hertz contact areas and commensurately lower stresses. Recently reported analyses of 60NiTi roller bearings suggest that comparing all steel to all 60NiTi cases can be complex (Ref. 10). The reduced modulus of 60NiTi can be viewed as a higher compliance. Under load in a full bearing system, every rolling element deforms to a higher degree than a steel roller and thus shares the bearing load more readily with its neighboring rolling elements. This effectively reduces the load on each rolling element and may actually increase the ultimate load capacity beyond that estimated from the static load capacity data contained in Table II.

From a design perspective, larger contact areas, lower stresses and higher deflections arising from the use of low modulus materials implies that the a careful and thorough detailed design review must be undertaken for all highly loaded bearing applications especially those in which precise orbit control and positioning is vital. For the DA bearing application, the loads are very low and the positioning (bearing stiffness) requirements are minimal. The only continuous loads on the bearings arise from spring preload washers and modest fluid motion-dynamic unbalance forces during normal rotation (relatively low speed of 200 rpm). For completeness, a cursory design stress and stiffness review was done and it concluded that from a mechanical perspective, for this application, the elastic modulus of the bearing race material is not a critical parameter as long as the static load capacity exceeds that of the baseline superalloy and it does (Table II).

Based upon the results from the mechanical loads and stresses review and the preliminary corrosion studies, it appears that a 60NiTi bearing utilizing the very same geometry and dimensions as the cobalt-hybrid baseline design is a good initial baseline design to consider for manufacturability. Before a manufacturing pathfinder trial can begin, a computer-generated model of the target bearing was developed. This model helps the manufacturing engineer visualize the bearing geometry and devise a manufacturing plan. The bearing model is shown in Figure 6.
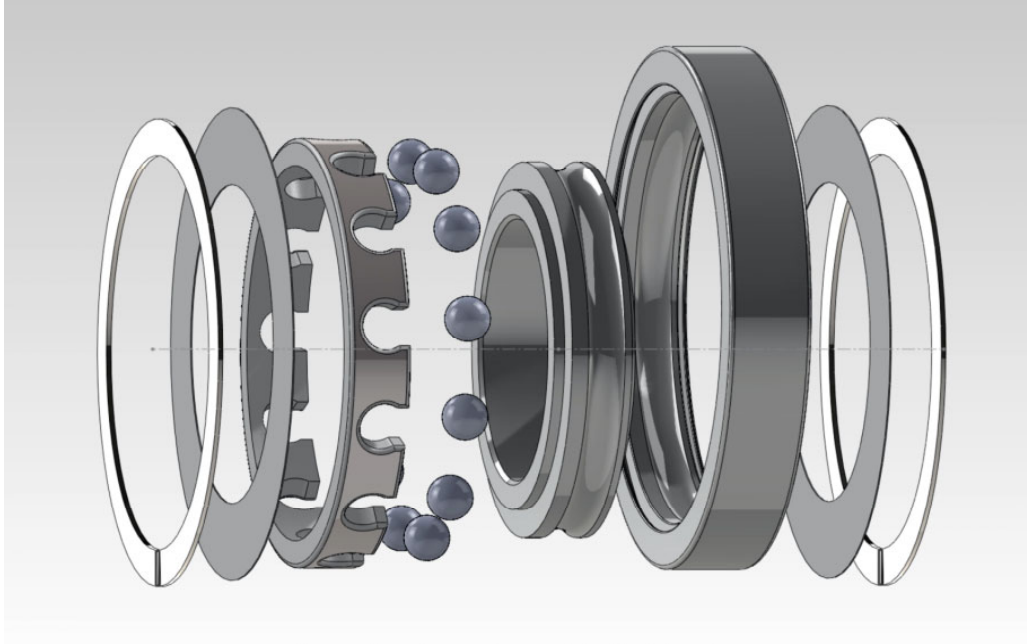
Figure 6.—Computer model of DA bearing.

The manufacture of 60NiTi balls is a fully commercialized process and many standard ball sizes are available. The steps needed to make precise raceways from 60NiTi to a desired geometry are not yet fully developed. Decades of experience with various steels has resulted in numerous rules-of-thumb (ROT) for their manufacture. Preferred annealing, rough machining, hard turning, heat treatment, grinding, polishing, acidic surface passivation, normalizing and other processes for steels are well understood and accepted by the manufacturing community. For 60NiTi these ROT's remain undefined. The following paragraphs attempt to layout an acceptable, by not necessarily an optimal, processing path driven by 60NiTi's several unique properties and characteristics, namely its low elastic modulus, resistance to metal cutting and deformation (i.e., low ductility), and its intrinsically brittle tensile behavior.

The basic manufacturing steps employed to go from ingots to finished bearings are as follows: rough machining to near final shape and size using a combination of wire electro discharge machining (EDM) and carbide tool based machining, heat treating to develop high hardness, finish grinding and polishing. Because 60NiTi exhibits limited ductility and is susceptible to brittle tensile behavior, heavy machining operations such as drilling, high removal turning and milling should be avoided. Instead, we have successfully employed a combination of plunge and wire EDM to generate simple blanks from larger ingots and these are then rough machined to near final shape using more conventional machining methods. Figure 7 shows a slice of 60NiTi made by wire EDM and subsequently cut into cylindrical (donut shaped) race blanks. The ingot, made by powder metallurgy has a rind and center core of steel with 60NiTi filling the annular space. This is part of the PM process and enables more efficient use of the relatively high cost 60NiTi materials.

The resulting ring blanks are then shaped into race rings using properly shaped carbide tooling through a plunge turning operation. With this operation, the ring inside diameter is first turned or ground to ensure it is uniform and close to finish dimension (within ~0.01 mm). The ring is then mounted on an expanding type mandrel and care is taken to avoid excessive clamping forces. Because the elastic modulus is half that of steel, excessive clamping force on the inside diameter can result in considerable stretching of the I.D. leading to unpredictable dimensions after turned race is removed from the mandrel. Once mounted, the O.D. is plunge turned using a carbide tool previously shaped to match the desired race ring profile. In our tests, we used wire EDM to manufacture the plunge tool from a standard carbide lathe bit. Figure 8 shows the process for turning an inner race ring prior to the heat treatment step.

60NiTi slice from ingot

EDM drill and cut donut shaped race blanks

Outer race blank

Inner race blank

Figure 7.—60NiTi race blanks cut from ingot using EDM processes.

Ring clamped on expanding fixture

Finished rings ready for hardening

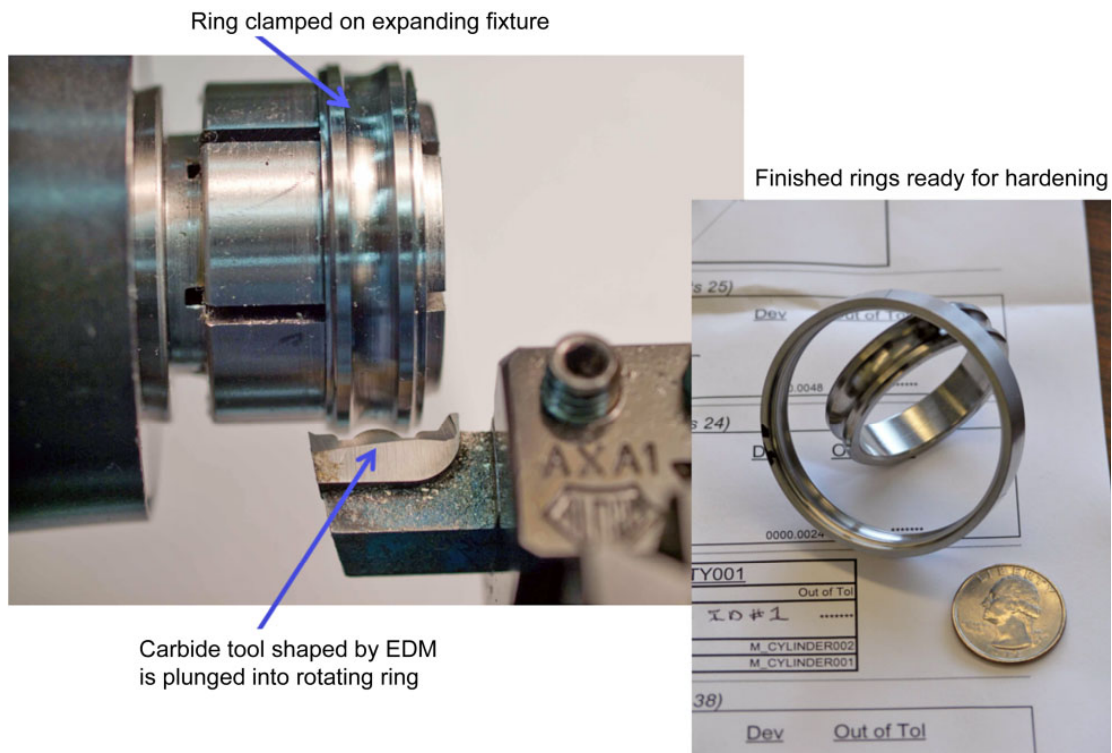Carbide tool shaped by EDM is plunged into rotating ring

Figure 8.—Plunge turning of 60NiTi race rings using a carbide tool profiled to match the desired race geometry using wire EDM.

The final steps include heat treatment and finish grinding and lapping. The heat treatment has been described in detail in Reference 6 and briefly includes a solution treatment at 1000 °C followed by a rapid water quenching. A vacuum or inert atmosphere is used to prevent excessive surface oxidation. Figure 9 shows the microstructure of 60NiTi prior to and after heat treatment. The heat treatment dissolves undesirable higher order phases resulting in a largely homogenous NiTi phase structure with hardness in the range of 58 to 63 on the Rockwell C scale.

After heat treatment, standard industry grinding and polishing are employed to yield a finished bearing. Care must be taken to avoid excessive tensile stresses during bearing assembly. Unlike steel that can endure high tensile deformation without fracture, 60NiTi is brittle in tension and outer races, in particular, can break during bearing assembly when hoop stresses are high. To overcome this problem, either separable bearing designs or the use of differential inner ring cooling and outer ring heating are recommended. Beyond that, no other special considerations are needed. Figure 10 shows a photograph of a finished hybrid bearing made with 60NiTi races and silicon nitride bearing balls.

The bearings behave and perform as one expects based upon the geometry and lubricant selected. Future efforts to fully characterize the rolling contact fatigue stress-life relationships and gain a better understanding of the tensile strength and toughness behavior of 60 NiTi are underway to guide more mechanically demanding bearing applications.
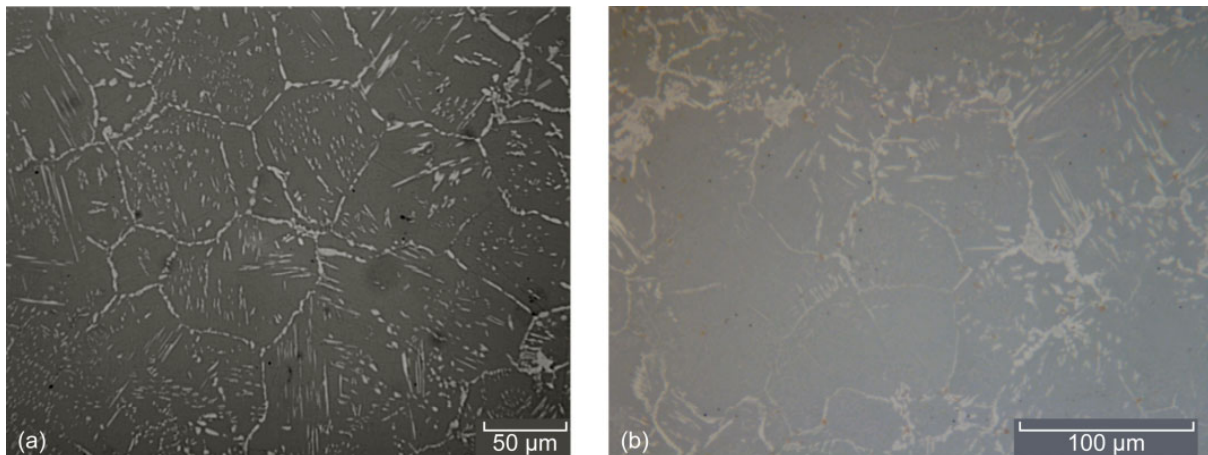

Figure 9.—Microstructure of 60NiTi before and after heat treatment. (a) As-received 60NiTi (lighter phase is Ni_3Ti). (b) Heat-treated 60NiTi.

Figure 10.—Finished hybrid bearing made with 60NiTi races and Si_3N_4 bearing balls.

Summary Remarks

60NiTi offers a viable path towards rolling element bearings that have exemplary corrosion and wear resistance. Though sensitive to brittle fracture in tension, research suggests that extreme static load capacity and resilience imparted by its superelastic behavior is possible. The reduced elastic modulus, compared to steel, may impact highly loaded bearing internal geometry but for the DA bearing application being considered, a direct 60NiTi replacement is reasonable. Lastly, manufacturing research shows that with proper care, modern manufacturing methods are capable of producing high precision ball bearings from 60NiTi.

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