The Effect of Indenter Ball Radius on the Static Load Capacity of the Superelastic 60NiTi for Rolling Element Bearings

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Abstract

Static load capacity is a critical design parameter for rolling element bearings used in space mechanisms because of the potential for Brinell (surface dent) damage due to shock and vibration loading events during rocket launch. Brinell damage to bearing raceways can lead to torque variations (noise) and reduced bearing life. The growing use of ceramic rolling elements with high stiffness in hybrid bearings exacerbates the situation. A new family of hard yet resilient materials based upon nickel-titanium is emerging to address such bearing challenges. 60NiTi is a superelastic material that simultaneously exhibits high hardness and a relatively low elastic modulus (~100 GPa) and has been shown to endure higher indentation loads than conventional and high performance steel. Indentation load capacity has been reported for relatively large (12.7 mm diameter) ceramic (Si_3N_4) indenter balls pressed against flat plates of 60NiTi. In order to develop damage load threshold criteria applicable to a wide range of bearing designs and sizes, the effects of indenter ball radius and the accuracy of interpolation of the Hertz contact stress relations for 60NiTi must be ascertained. In this paper, results of indentation tests involving ceramic balls ranging from 6.4 to 12.7 mm in diameter and highly polished 60NiTi flat plates are presented. When the resulting dent depth data for all the indenter ball sizes are normalized using the Hertz equations, the data (dent depth versus stress) are comparable. Thus when designing bearings made from 60NiTi, the Hertz stress relations can be applied with relative confidence over a range of rolling element sizes and internal geometries.

Introduction

Rolling element bearing (REB) design is a mature, well-understood engineering process that differs from but is closely linked to bearing selection. Bearing selection is characterized by matching a bearing's known characteristics, like stiffness and load capacity, to the requirements of a specific application (Ref. 1). In such instances, a system designer simply looks up the bearing capabilities in a manufacturer's design catalogue and selects the product that meets requirements. In many instances, especially when designing space flight hardware, no commercial off-the-shelf (COTS) bearing is suitable.

Space flight hardware bearing applications often include unusual operating conditions such as vacuum compatibility of lubricants and cage materials, extreme low and high temperatures, ultra-high precision motion and torque noise (ripple) requirements while maintaining extraordinarily low (drag) torque levels (Ref. 2). Among the most challenging bearing requirements is the ability to withstand excessive shock loads resulting from launch vibrations and other common space vehicle effects such as the discharging of pyrotechnic actuators. When faced with such otherworldly challenges, detailed bearing design alterations are often a necessity.

Common bearing design materials alterations include the use of vacuum compatible oils and greases with low viscosity index (VI), space radiation tolerant (e.g., phenolic or polyimide) cage materials and the

use of martensitic stainless steel races and ceramic rolling elements to minimize the potential for corrosion during storage before launch. Careful selection of internal clearances, such as those between the cage diameters and the bearing race lands, are sometimes required to prevent cage binding at extreme temperature conditions. Space bearings often must cope with operating temperatures that can vary by hundreds of degrees Fahrenheit. More nuanced and subtle design changes might include altering raceway curvature and ball diameters to reduce contact stresses and enhance static load capacity. Despite such attention to detail, the extreme dynamic shock loads common in rocket-launched hardware remains a vexing problem (Ref. 3).

System engineering offers approaches to address the static load challenge for space hardware. Designers can include vibration isolation methods to reduce load levels to acceptable values. Such techniques are often complex and costly and add to overall mass. Another engineering approach is to oversize bearing components until the static load capacity exceeds the anticipated load levels. Again, this adds weight and also leads to generally higher bearing power consumption for operating machinery once in orbit. Recently, new, high carbide content, ultra-hard bearing steels have been developed that provide enhanced static load capability and fatigue resistance (Refs. 4 and 5). These steels, like REX 20, offer about 30% higher stress capability against Brinell type damage (static indentation loads) compared to conventional space bearing steels, like 440C. Corrosion resistance however is a serious problem. To date, a need exists for bearing alloys with the corrosion resistance of a stainless steel and load capacity of high-carbide tool steel. The emerging nickel-rich, NiTi alloys offer an avenue to address these challenges.

Nickel-rich, binary nickel-titanium alloys, such as 60NiTi or alternatively NiTiNOL 60, are intriguing candidate materials for use in mechanical components (Ref. 6). 60NiTi (60Ni-40Ti by wt%) exhibits attractive properties that impact the design and performance of mechanical components especially rolling element bearings (Ref. 7). 60NiTi is highly corrosion resistant and because it contains no iron it is immune to the atmospheric rusting behavior experienced by bearing and gear steels, even those deemed "stainless" such as 440C. 60NiTi is dimensionally stable yet exhibits extremely high elasticity (so-called superelasticity) and can deform up to 5% without incurring permanent deformation. 60NiTi can be hardened through simple heat treatment to levels comparable with conventional bearing steels (Rockwell C 58-62). Table I contains the most up-to-date properties known for 60NiTi compared to other bearing materials.

TABLE I.—NOMINAL PROPERTIES FOR CONVENTIONAL BEARING ALLOYS AND 60NiTi

Property	60NiTi	440C	Si_3N_4	M-50
Density, g/cc	6.7	7.7	3.2	8.0
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	~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), MPa	~1000 (1500)	1900	(600 to 1200)	2500
Young's Modulus, GPa	~95	200	310	210
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness, MPa/√m	~20	22	5 to 7	20 to 23
Maximum use temperature, °C	~400	~400	~1100	~400
Electrical resistivity, Ω-m	~1.04×10^{-6}	~0.60×10^{-6}	Insulator	~0.18×10^{-6}

One property that differs substantially from that of bearing steel is elastic modulus. 60NiTi has a modulus similar to titanium and aluminum and is approximately one-half that of steels and superalloys. This unique combination of superelasticity, high hardness and reduced elastic modulus, compared to tool steel, has been shown to result in extraordinarily high static load capacity in highly loaded, concentrated contacts such as those that occur at ball and roller-raceway contacts in rolling element bearings (Figure 1).

Figure 2 depicts a generic ball-on-race Hertz contact with an exaggerated deformation to elucidate this effect. When loads are transmitted through a bearing, the materials must resist permanent deformation. If the loads are applied while the bearing is not rotating (e.g., as would be the case for a space instrument during launch), the contact mimics a ball on plate. From a rolling element bearing perspective, any damage that reduces fatigue life or causes unacceptable bearing operation (torque noise) is to be avoided. An obvious type of damage resulting from an overload condition is denting of bearing raceways.

In earlier studies, indentation experiments were carried out to assess the static load capacity of hardened 60NiTi (Ref. 8). Initially, the load limit, defined as the contact stress (or load) that results in a permanent dent whose depth exceeds 5×10^{-5} of the indenter ball diameter (dp/D), was assessed by pressing 12.7 mm diameter silicon nitride balls against highly polished, heat treated 60NiTi prepared by powder metallurgy techniques. These experiments showed that the static stress capability for 60NiTi exceeded that of 440C by about 25% as shown in Figure 3.

In terms of stress capability, the tool steel REX 20 has about 30% higher capability than 60NiTi. But, as concluded in the earlier research, the reduced modulus of 60NiTi obscures a direct comparison based solely upon contact stress. Indeed, with respect to bearing applications that encounter shock loads, a comparison based upon load is more relevant. The load capacity data is presented in the following Figure 4 and it tells a significantly different story.
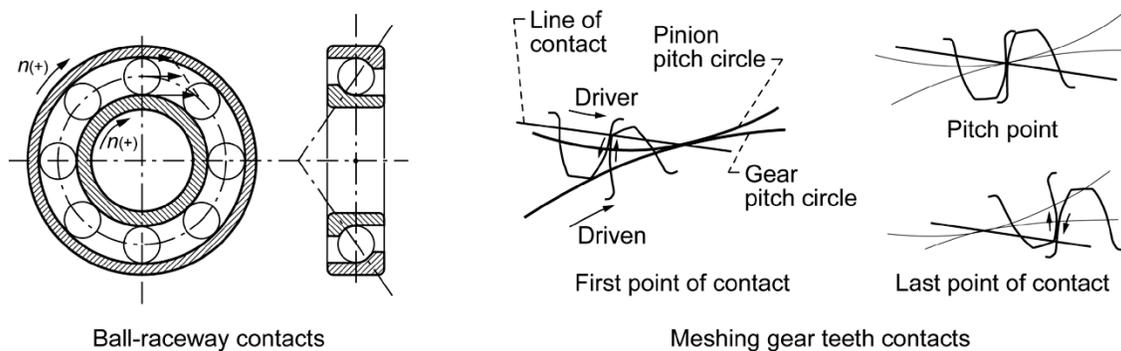

Figure 1.—Hertz concentrated contacts in bearings and gears.
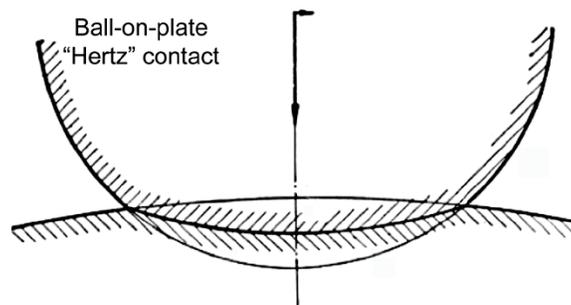

Figure 2.—Single ball-on-race Hertz concentrated contacts in a bearing (exaggerated deformation).
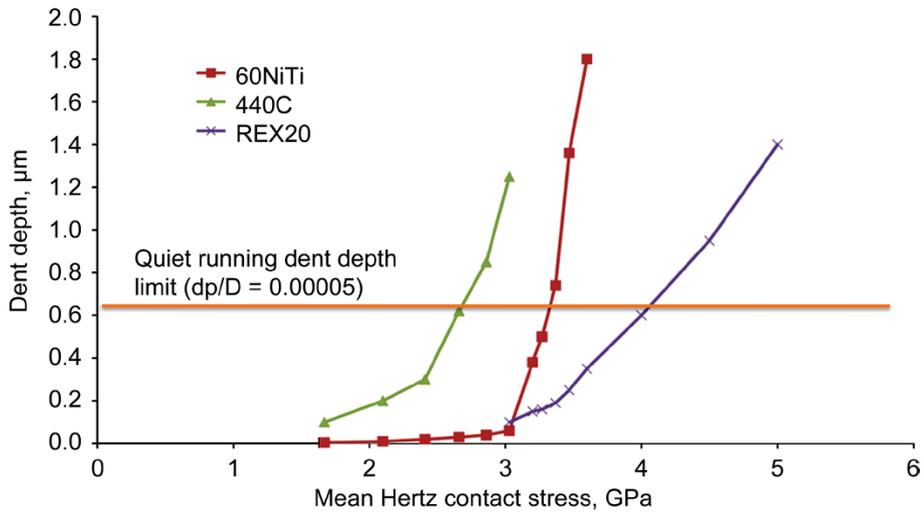
Figure 3.—Indent depths as a function of contact stress for 60NiTi, 440C and REX20 plates loaded
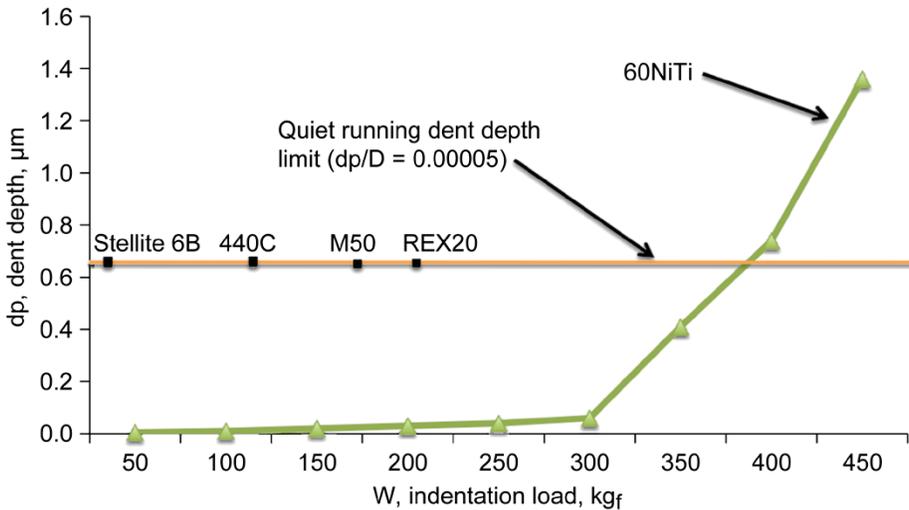

Figure 4.—Indent depths for 60NiTi plate as a function of load when contacted by a 12.7mm diameter Si_3N_4 indenter ball. Data for Stellite 6B, 440C, M50 and REX20 from References 4 and 5.

When plotted against contact load, 60NiTi exhibits nearly twice the load capability of tool steel. Follow-on experiments using the same general test set-up demonstrated that pre-stressing the contact surface prior to indentation could enhance the load capability further (Ref. 9). These results clearly show that 60NiTi exhibits excellent resilience and static load capacity when indented with a 12.7 mm diameter ceramic indenter ball surface. For bearing design purposes, however, a more generalized load-stress relationship must be confirmed.

In the present study, indentation experiments of hardened 60NiTi are carefully carried out using highly polished surfaces loaded against Si_3N_4 spherical indenters with diameters that range from 6.35 to 12.7 mm. The resulting data is then examined to determine if the Hertz contact stress equations can be accurately used to guide future bearing designs employing 60NiTi for high load applications like space mechanisms.

Materials

Vacuum casting is used to produce a 25-mm diameter, 300-mm long 60NiTi rod by melting high purity nickel and titanium pellets in a graphite crucible (Figure 5). The 6.4 mm thick, flat plate indentation specimens are cut using wire Electrode Discharge Machining (EDM). The specimens are hardened by heating treatment (2 hr) at 1000 °C in argon followed by a rapid water quench. The casting process yields a uniform, fine-grained microstructure that sometimes contains flaws, such as voids that can cause spontaneous fracture during quenching (Ref. 10), especially for large (>50 mm diameter) cross section specimens. Such issues are avoided for the relatively small specimens used in the present study and the casting process provides an economical path to obtain large quantities of specimens. Previous work has shown that 60NiTi prepared both my powder metallurgy and casting exhibit similar hardness behavior. Figure 6 shows cross sections of the test material before and after heat treatment that results in hardness typically between 59 and 61 on the Rockwell C scale.

Following heat treatment, one side of the specimen is then metallographically polished with progressively finer grades of abrasive until a mirror smooth and flat surface (Rrms~0.03 μm) results. Such a surface is required to facilitate the measurement of small surface denting.
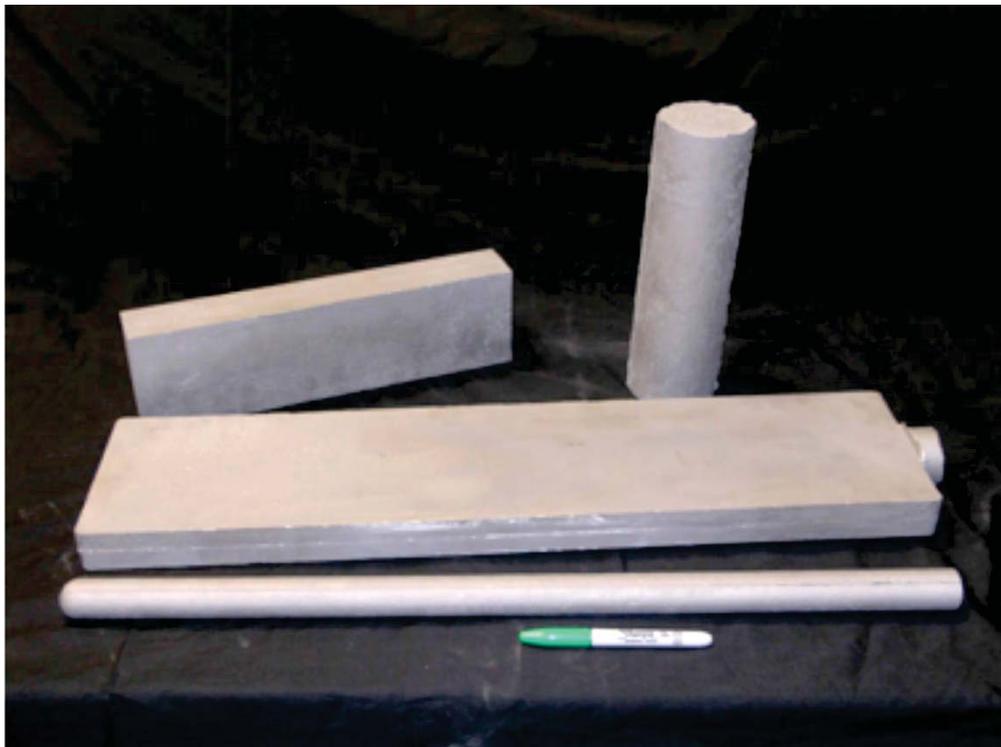

Figure 5.—Cast 60NiTi plate and rod ingots. Forward most cast rod used to produce indentation specimens tested in the present study.
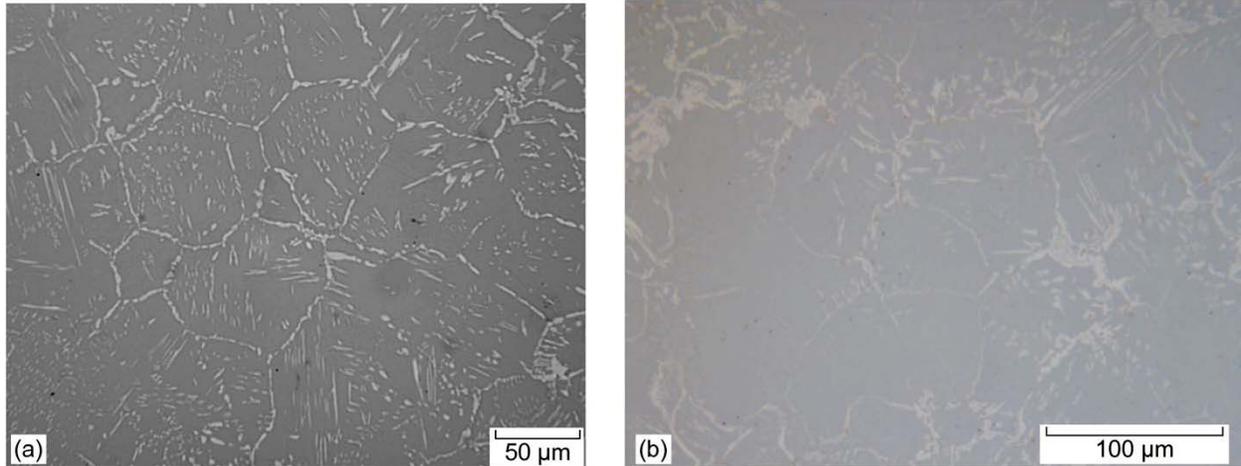
Figure 6.—Microstructure of 60NiTi before and after heat treatment. (a) As-received 60NiTi (lighter phase is Ni_3Ti).
(b) Heat-treated 60NiTi .

Test Setup and Procedures

Four different size (6.35, 7.94, 9.52 and 12.7 mm diameter) indenter balls made from the ceramic Si_3N_4 are used to dent the 60NiTi surfaces in these experiments. The general configuration, shown in Figure 7, is essentially a Brinell test and it closely mimics the approach used by Park and his colleagues to establish the static load capacity of advanced, high carbide content steels (Refs. 4 and 5).

In our tests, the ball is loaded against the flat plate surface using a computer controlled load frame. The indent ball is held in a hemispherical recess machined into a standard steel push rod. A small volume of silicone vacuum grease is applied to the surface of the recess prior to inserting the ball to help secure the ball against gravity and to ease subsequent ball removal. Each 25 mm diameter indent plate specimen is marked using an ink pen in 12 locations that mimic the face of a clock. These markings aid accurate identification of the dent area, which can be invisible to the unaided eye. At least three repeat experiments are conducted at each test load. Because of the wide range of indenter ball diameters, not all test loads are used for every indenter ball. Rather, loads are selected to result in dent depths below the static load capacity and above, based upon earlier work. The tested loads are clearly delineated in the data table.

To conduct a test, the plate specimen is placed directly beneath the ball and aligned by eye such that the indent occurs at the desired position. The push rod-ball assembly is then manually lowered by pressing the "lower head" control button on the load frame controller. When the ball is within 1mm of the surface the control button is released and the operator then engages an automated computer controlled indent program that slowly lowers the ball until a load cell detects contact. The load is then increased linearly at approximately 100 kg_f per minute until the desired static load is reached at which time the load is held steady (within ~5%) by the control system. After a dwell period (typically 1 min) the push rod-ball assembly is raised to remove the load and the test concludes.

Following the indent experiments, the flat plate specimens are measured using a non-contacting optical profilometer. With this technique, first a fairly broad area (square mm) in the vicinity of the dent area is scanned to develop a low-resolution surface topography image. This area image guides subsequent, higher resolution depth measurements to be made on the dent itself, which may not be precisely positioned near the ink markings due to operator error. By stitching multiple measurements together, a top view, topographical plot of the dent and the surrounding undisturbed surface is then made. An example of such a dent measurement plot is shown in Figure 8.
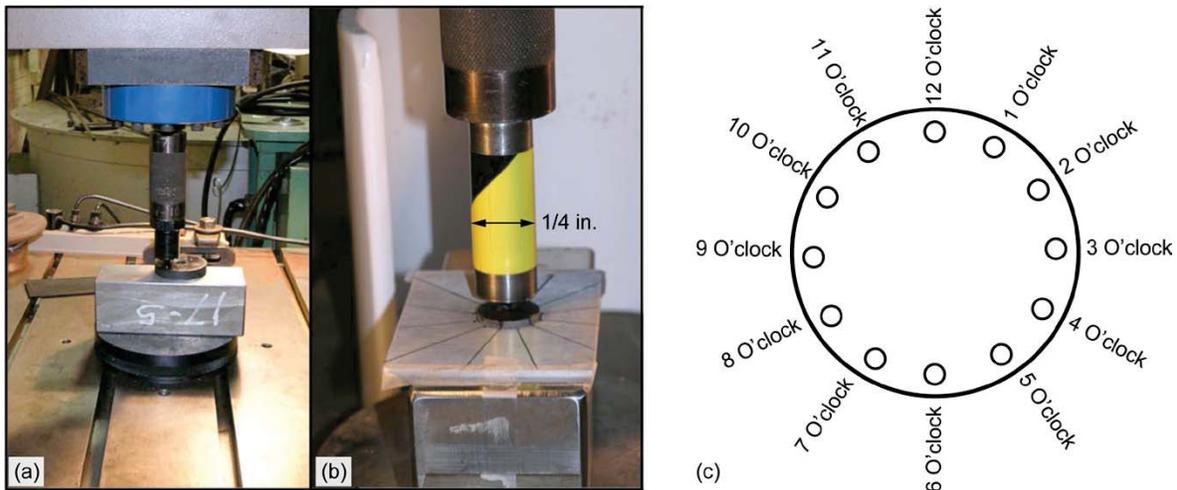
Figure 7.—Brinell test configuration used for indentation experiments to measure static load capacity. (a) Load frame. (b) Ball on disk set-up. (c) Dent map, top view
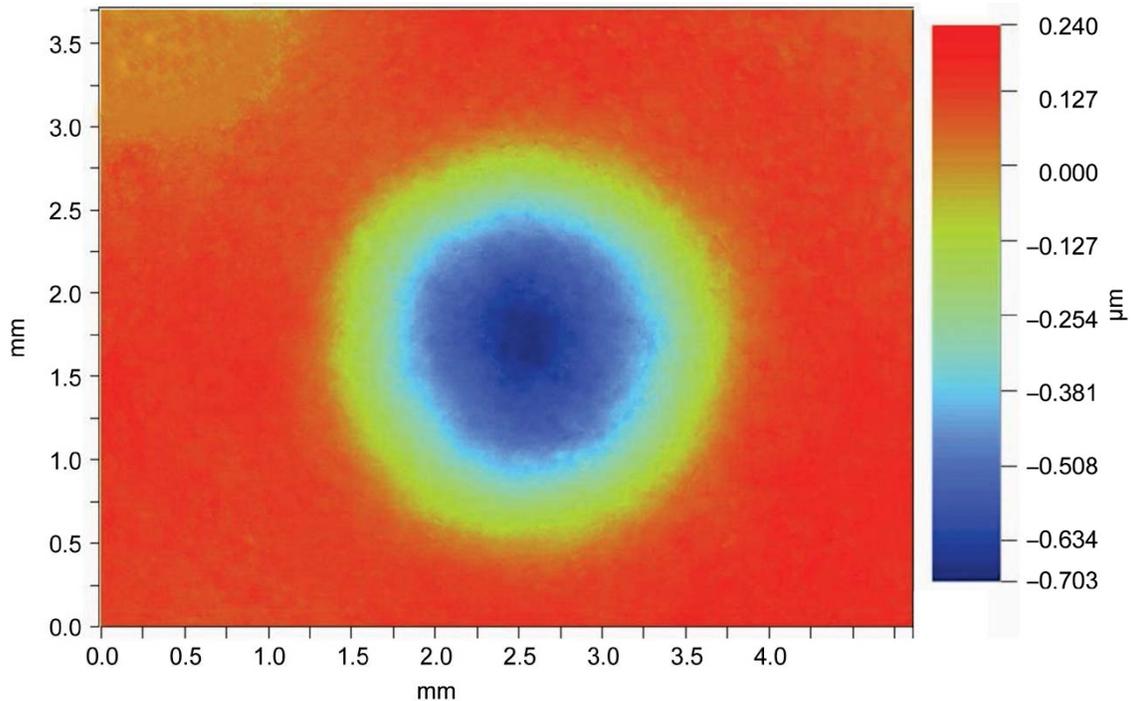

Figure 8.—Topographical contour plot of dented 60NiTi surface as measured by optical (noncontact) surface profilometry.

Results and Discussions

The hardened and polished 60NiTi specimen surfaces were loaded with the Si_3N_4 indenter balls and the resulting dents were examined as described in the previous section. The indentation data is summarized in Table II using a nominal constant value of 100 GPa for the modulus of 60NiTi and 300GPa for the modulus of Si_3N_4. The data table presents the average dent depth values. Dent depth data scatter was low with repeatability typically within 10% of the average. As mentioned previously, not all indenter ball sizes were run at all the test loads. The majority of the data was collected at stress levels between 2.0 and 4.0 GPa based upon earlier testing.

TABLE II.—STATIC LOAD INDENTATION DATA SUMMARY—Si$_3$N$_4$ BALL VERSUS 60NiTi FLAT PLATE
[Cast 60NiTi material, hardened to Rockwell C60 and polished to 0.03 μm rms surface roughness.]

| Load, kg	6.35 mm (1/4 in.) ball			7.94 mm (5/16 in.) ball			9.52 mm (3/8 in.) ball			12.7 mm (1/2 in.) ball		
	Mean stress, GPa	Dent depth (dP), μm	dp/D×10^{-3}	Mean stress, GPa	Dent depth (dP), μm	dp/D×10^{-3}	Mean stress, GPa	Dent depth (dP), μm	dp/D×10^{-3}	Mean stress, GPa	Dent depth (dP), μm	dp/D×10^{-3}
50	2.65	0.11	0.017	2.3	0.06	0.008	2.0	~0	~0	----	----	----
100	3.35	0.56	0.088	2.9	0.19	0.024	2.6	0.15	0.016	----	----	----
150	3.83	1.50	0.236	3.3	0.59	0.074	2.9	0.18	0.019	----	----	----
200	4.20	2.30	0.365	3.6	1.0	0.126	3.2	0.57	0.06	2.7	0.20	0.016
250	4.54	3.60	0.564	3.9	1.7	0.214	3.5	1.0	0.105	2.9	0.36	0.028
300	4.83	5.30	0.84	4.15	3.0	0.378	3.7	1.6	0.17	3.0	0.56	0.044
350	----	----	----	----	----	----	----	----	----	3.2	0.66	0.052
400	----	----	----	----	----	----	----	----	----	3.4	0.83	0.065
450	----	----	----	----	----	----	----	----	----	3.5	1.36	0.107
500	----	----	----	----	----	----	----	----	----	3.6	1.68	0.132
550	----	----	----	----	----	----	----	----	----	3.7	1.99	0.157
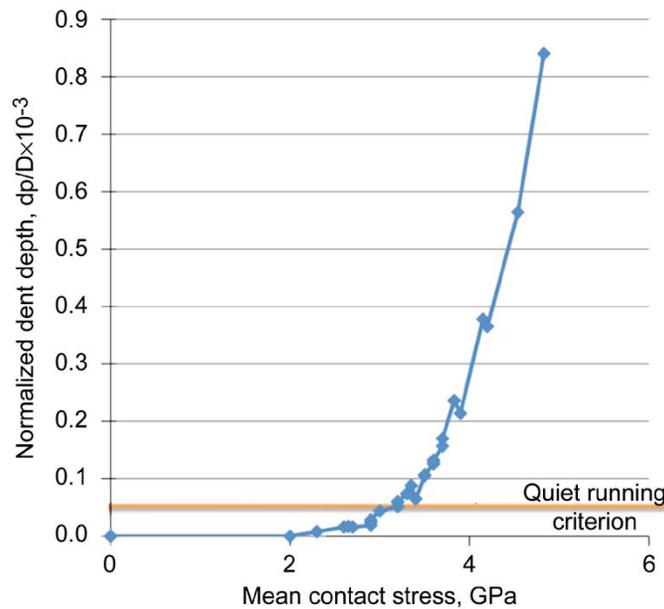
Figure 9.—Normalized dent depth (dp/D) versus mean contact stress for polished 60NiTi plate indented with Si$_3$N$_4$ balls ranging in size from 6.35 to 12.7 mm diameter.

The data is plotted as the ratio of dent depth to indenter diameter as a function of mean contact stress in Figure 9. The Hertz equations are used to calculate the contact stress and utilizing the materials properties found in Table I for both the ceramic indenter and the 60NiTi.

Examination of Figure 9 reveals that when the Hertz stress relations are employed for all the data a rather smooth curve results. Despite the wide range of indenter diameters, all the data falls along the same line crossing the dent depth threshold at a stress level of about 3.0 GPa. This stress limit threshold is, as pointed out previously in the introduction section of this paper, above the stress limit for M50 and 440C steels but well below the limit for the high-carbide tool steel REX 20. Nonetheless, when the low elastic modulus and large elastic deformation range is taken into account, extremely high static loads can be endured when employing 60NiTi in concentrated contacts. Further, the Hertz equations, which can be generalized to both point and line contacts, can be considered appropriate for use in bearing design.

Referring back to the illustration in Figure 1, a bearing designer can readily incorporate the raceway curvature and contact radii between a ball and race to calculate stresses when considering 60NiTi for raceways, balls or both surfaces. By using 3.0 GPa as the static stress capability, internal bearing geometry can be tailored to accommodate design loads in the same manner as traditional steel bearings. The significant difference, however, is that the load capability will be higher than for steels as depicted in Figure 4. This is a direct result of the low elastic modulus that reduces stress through higher elastic deformation coupled by the high hardness and large elastic range of 60NiTi.

This design approach described in the preceding paragraph will, however, be conservative. Recent preliminary stress modeling work for rolling element bearings made using low modulus components, like 60NiTi, has shown that bearing load capacity is further enhanced compared to steel bearings because of compliance effects (Ref. 11). Bearings are more complex than the single ball-on-plate geometry considered in the present study. When loaded radially, multiple ball-raceway contacts are engaged to support the load. The lower stiffness of the superelastic materials (60NiTi) enhances load sharing amongst adjacent ball-race contacts effectively lowering peak stress and increasing the bearing static load capacity. This effect and the detailed quantification of its magnitude are still under investigation, but represent yet another potential of the use of reduced stiffness construction materials in bearings.

As always, care must be taken when extrapolating the results presented here to real applications. Appropriate selection and application of a bearing material cannot be made using one parameter, such as static indent load capacity, alone. Future investigations to quantify the static load capacity of full-scale bearings made with 60NiTi races are needed to verify the true load capability of this emerging class of superelastic bearing materials. Recent experiments using 50 mm bore bearings have shown that durable hybrid (60NiTi races with Si_3N_4 balls) ball bearings can be produced. In time, sufficient quantities of production bearings will be available to more fully explore and exploit this unique class of materials.

Summary Remarks

The results presented in this paper demonstrate that the superelastic 60NiTi exhibits a high tolerance to static indentation loads and has a mean contact stress limit above 3.0 GPa. Because of its low elastic modulus and large elastic deformation range, 60NiTi can withstand static loads that exceed the capabilities of traditional bearing materials. Further, the observation that the dent depth data, when normalized using the Hertz stress relations, falls on the same smooth curves indicates that the generalized Hertz equations can be used to guide bearing design. These results, combined with 60NiTi's intrinsic corrosion resistance and low density provide further reasons to consider 60NiTi as a viable candidate for selected bearing applications.

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