

Failure Analysis and Recovery of a 50mm Highly Elastic Intermetallic NiTi Ball Bearing for an ISS Application

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Abstract:

Inside the ISS Distillation Assembly centrifuge, superior corrosion and shock resistance are required to withstand acidic wastewater exposure and heavy spacecraft launch related loads. These requirements challenge conventional steel bearings and provide an ideal pathfinder application for 50mm bore, deep-groove ball bearings made from the corrosion immune and highly elastic intermetallic material 60NiTi. During early ground testing in 2014 one 60NiTi bearing unexpectedly and catastrophically failed after operating for only 200 hours. A second bearing running on the same shaft was completely unaffected. An investigation into the root cause of the failure determined that an excessively tight press-fit of the bearing outer race coupled with NiTi's relatively low elastic modulus were key contributing factors. The proposed failure mode was successfully duplicated by experiment. To further corroborate the root cause theory, a successful bearing life test using improved installation practices (selective fitting) was conducted. The results show that NiTi bearings are suitable for space applications provided that care is taken to accommodate their unique material characteristics.

Keywords: Bearings, Failure Analyses, and Mechanical Components

Introduction:

Bearings, gears and other mechanical components can be made from a wide variety of materials depending upon application requirements that typically include load, temperature, environment and cost. Often, one overriding performance requirement dictates that a specific material be selected. In cases where multiple

requirements preclude certain classes of materials, practical designs can become difficult. For instance, if a bearing must operate at high temperature but also be lightweight neither plastic nor steel would suffice. In such cases, the designer might have to turn to higher cost ceramics.

Alternatively, the application requirements could be altered through system design changes to accommodate material capabilities. A common engineering solution for the aforementioned high temperature example is to employ active cooling which enables the use of low-density plastics or non-ferrous alloys. Such accommodations add cost and complexity and in many aerospace applications are not practical. Therefore, it is apparent that aerospace mechanical component field would benefit from the development of new materials with performance attributes that are not found in existing technologies.

Over the last decade, NASA has been working to advance Nickel-Titanium based bearing and gear materials to address unmet challenges faced by aeronautics and space mechanisms. Two highly sought after performance attributes are extreme corrosion resistance and tolerance to severe static loads (shock events). Taken separately, these attributes can be found in austenitic stainless steels or superalloys (corrosion resistance) and ceramics or high carbide tool steels (shock load resistance). However, currently available bearing materials cannot simultaneously meet these challenges. Unfortunately, just such a challenging application exists inside the International Space Station (ISS) wastewater treatment system's Urine Processor Distillation Assembly.

The Urine Processor Distillation Assembly (DA) is a key part of the wastewater treatment system on the ISS. The DA a rotating still into which waste fluids are heated, turned into steam which is condensed downstream into clean water for re-use. Figure 1 shows a cross section of the Urine Processor. Through centrifugal action, the rotating motion of the drum forces the wastewater to remain in contact with the drum walls that are heated forming steam that is then drawn from the drum and condensed further treated downstream into clean water. The bearings that support the rotating drum are directly exposed to the acidic wastewater and the steam environment.

Nickel-Titanium based materials are not new. W.J. Buehler and his colleagues at the Naval Ordnance Laboratory first investigated them in the late 1950's [8]. Among Buehler's early compositions, 60NiTi (60weight% Nickel and 40weight% Titanium), also known as NiTiNOL 60, was a candidate structural alloy with increased temperature capability intended as a replacement for then the state-of-art nickel-copper (Monel) alloys, for military applications. During his investigations, he found that NiTi compositions closer to 50NiTi exhibit shape memory effects. Since 60NiTi was dimensionally stable with no shape memory behavior and was hard to machine and prone to fracture during heat treatment hardening, it was abandoned as a line of research. Instead, development efforts were focused on the shape memory

compositions like 50NiTi [9, 10]. Today, a robust industrial-base exists for the near equiatomic NiTi alloys, such as 50NiTi, that are exploited for their unique shape memory characteristics and are used in medical and solid-state actuator applications as well as for high deformation range (superelastic) springs [11-13].

The recent application of modern ceramic processing techniques, notably powder metallurgy processing using pre-alloyed powders, to 60NiTi and other hard and dimensionally stable nickel-rich NiTi compositions has resulted in the availability of high quality raw material appropriate for the production of rolling element bearings [14]. As a class of materials, these nickel-rich NiTi possess a unique combination of physical and chemical properties not found in any other material, particularly those materials normally used in bearings.

As an example, 60NiTi is highly corrosion resistant, non-magnetic, electrically conductive, wear resistant, readily machined in the annealed state and exhibits good tribological properties. Further, as a member of the superelastic family, it exhibits a moderate elastic modulus coupled with an ability to endure large strains elastically. These elastic traits make 60NiTi extremely dent resistant compared to steels and conventional metals [15, 16]. The more recent 60NiTi materials development is captured in literature publications and the reader is urged to review these for details [17]. Previous work related to contact fatigue of an early cast form of 60NiTi is briefly reviewed in the following paragraphs in order to properly introduce the present effort.

Prior to the successful development of fine-grained, high purity 60NiTi made by a modern powder metallurgy process, RCF rods were cut from commercially sourced 60NiTi plate stock made by conventional casting followed by hot rolling. The RCF fatigue behavior was evaluated and the specimens were cross-sectioned to better understand the results [7]. In general, the fatigue life, even at low stress levels (less than 1.7GPa) was erratic. Some specimens failed (surface spalls) after just a few hours while others survived the test conditions for over 800 hours at which point the tests were intentionally suspended without failure.

Examination of the rods revealed substantial microstructural flaws such as voids and inclusions that were likely failure initiation sites. Figure 1 is a photograph of an RCF rod in a region of surface fatigue failure. The failure appeared as a classical fatigue spall likely originating at subsurface flaws, a characteristic common for hard, limited ductility materials undergoing repeated contact.



Figure 1. Spall damage on a hardened 60NiTi rod surface following testing at 3.0GPa.

Figure 2 shows typical cross-section of the cast and rolled 60NiTi. The cross-section reveals stringers of oxides and other hard inclusions, residual porosity and multiple coarse phases within the NiTi matrix.

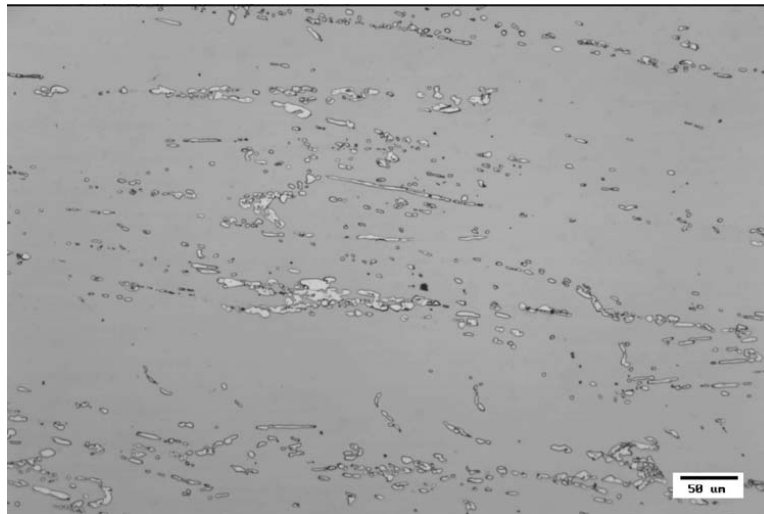


Figure 2. Cross-section optical micrograph of a cast and rolled 60NiTi RCF rod showing voids and second phase precipitates.

These flaws and the large variability in their sizes are undoubtedly contributing factors to the life data scatter and early failures seen in many of the tests. It is likely that those samples that exhibited superior fatigue performance, nearing that of commercial steels, had smaller and fewer subsurface defects than those with shorter lives. These early fatigue results provided impetus to develop higher quality microstructures using powder metallurgy processing routes for 60NiTi. Using a

newly established powder metallurgy process, high quality RCF test rods have been made and further advancements through compositional tailoring (alloying) are well underway.

Current research efforts include alloy development through the addition of other elements such as Hf and Zr that seem to improve microstructural homogeneity. The resulting ternary and tertiary alloys also seem to improve selected processing characteristics such as required heat treatment temperatures and quenching rates needed to achieve high hardness. Because of the ongoing nature of the alloy development, less emphasis has been placed on developing full-scale bearings though the baseline 60NiTi composition has been used successfully to make bearings up to 50mm bore in size. Thus there exists a critical need to evaluate the generalized fatigue-stress behavior of 60NiTi and its derivative alloys to help guide materials development and early applications of these materials.

For this reason, the three ball-on-rod RCF test is used in the present study for the evaluation of powder metallurgy produced 60NiTi. The goal of the effort is to establish a stress capability threshold below which long-life is expected. In addition, the underlying factors that influence fatigue failure are to be studied as a means to guide further materials development. In addition to establishing fatigue stress limits for the baseline material, a second composition not yet available as a powder metallurgy product, 57.6Ni-39.2-Ti-3.2Hf by weight%, made via casting, is also fatigue tested to determine its desirability for further development. On an atomic percentage basis, this alloy is 54Ni-45Ti-1Hf. By weight percent, the alloy is 57.6Ni-39.2Ti-3.2Hf.

Materials and Specimens:

60NiTi (60Ni and 40Ti by weight%) RCF rods are tested in contact with steel bearing balls. Baseline material properties for 60NiTi and, for comparison, other bearing materials are given in table I.

<i>Table I. Thermophysical and mechanical properties of 60NiTi and other bearing materials.</i>				
Property	60NiTi	440C	Si ₃ N ₄	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56–62 Rc	58–62 Rc	1300–1500 Hv*	60–65Rc
Thermal Cond. W/m-°K	~9–14	24	33	~36
Thermal Expansion	~11.2 × 10 ⁻⁶ /°C	10 × 10 ⁻⁶ /°C	2.6 × 10 ⁻⁶	~11 × 10 ⁻⁶ /°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion Resistance	Acceptable (in acids)	Marginal	Acceptable	Poor
Tensile/Flexural	~1000/1500 MPa	1900 MPa	600–1200 MPa	2500 MPa

Strength			(Bend Strength)	
Young's Modulus	~90–115 GPa	200 GPa	310 GPa	210 GPa
Poisson's Ratio	~0.34	0.30	0.27	0.30
Fracture Toughness	~20 MPa/√m	22 MPa/√m	5–7 MPa/√m	20–23 MPa/√m
Max. Use Temp	~400°C	~400°C	~1100°C	~400°C
Elect. Resistivity	~1.04 × 10 ⁻⁶ Ω-m	~0.60 × 10 ⁻⁶ Ω-m	Insulator	~0.18 × 10 ⁻⁶ Ω-m

*Vicker's hardness, Hv, is a scale used for ceramic materials with hardness values beyond HRC 75.

The 60NiTi RCF rods are made from ingots of bearing grade 60NiTi manufactured via a high-temperature PM process similar to that depicted in Figure 3 and more fully described in the literature [18, 19].

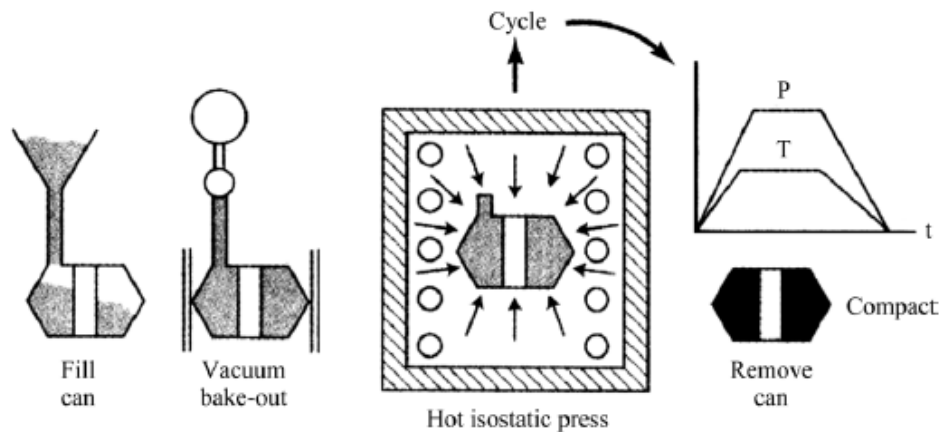


Figure 3. PM processing route for 60NiTi

Briefly, pre-alloyed 60NiTi powder made by gas atomization is placed into a steel container that is vacuum baked to remove air and moisture prior to being welded closed. The sealed powder is then hot isostatically pressed (HIP). The desired ingot geometry is achieved by using different size and shape steel containers. Figure 4 shows ingots of various sizes and shapes produced using the powder metallurgy process.



Figure 4. 60NiTi ingots and blanks produced by PM process.

Because the process is carried out below the powder melting point, it is dominated by solid-state diffusion bonding of adjacent particles. The resulting microstructure of PM 60NiTi differs substantially from 60NiTi castings. In general, cross-sections of PM processed 60NiTi (Figure 5) resemble tightly packed particles with a grain size and shape similar to the original particle size. Voids, inclusions, and other flaws tend to be found between grains and are smaller than those found in cast products. Cleanliness and purity of the starting powder is critical to the quality of the finished product. The minimization of flaw size and population tends to improve a material's resistance to fracture and fatigue.

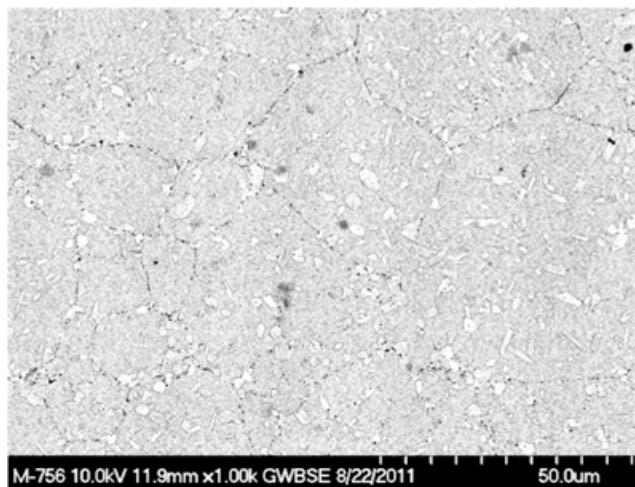


Figure 5. Metallurgical cross-sections of PM processed 60NiTi backscattered electron image.

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 RCF rods. For parts that are not dimensionally critical, simple wear plates for example, final grinding after heat treatment may be unnecessary. The heat treatment used for the rods includes solution treating at 1000°C in vacuum or inert gas atmosphere for one hour followed by a rapid quench in water. The solution treating dissolves precipitate phases like Ni₄Ti₃ and Ni₃Ti and encourages the formation of 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. Figure 6 below shows a photograph of a finished 60NiTi RCF rod ready for testing. The rod surface is polished to attain a roughness comparable to a bearing raceway, typically better than 0.05 micrometers Ra.



Figure 6. Polished 60NiTi RCF rods.

The balls used for the fatigue tests are standard 12.7mm (1/2 inch) grade 10 bearing balls made from hardened (HRC 58-62) AISI 52100-type tool steel. Oil drip feed lubrication at a rate of 8-10 drops per minute using Mil-L-7808-J turbine oil is provided throughout the test period.

Procedures:

The three ball-on-rod test is used to evaluate the 60NiTi RCF behavior. Using this test, depicted in Figure 7, three steel bearing balls are loaded against a polished,

NiTi rod rotated at 3600 rpm. An oil drip system provides lubrication and an accelerometer is used to monitor surface damage, such as the formation of a pit, signaled by a rise in detected vibration. Using collet spacers of differing thicknesses, up to 14 separate wear tracks (fatigue experiments) can be run on each rod. The steel balls and the loading races typically do not fail even after many rod tests because they experience fewer stress cycles than the rod. Each hour of test time results in the accumulation of approximately one-half million stress cycles on the test rod.

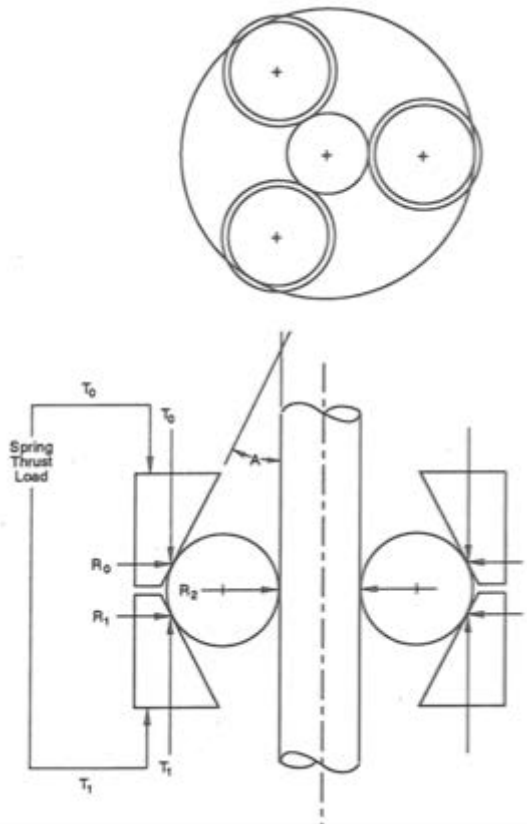


Figure 7. Specimen configuration for the three ball-on-rod RCF test.

Generally, the test load presents a higher continuous level of contact stress than normally encountered in bearings. The use of high stress accelerates the test so that relative discrimination between materials can be made in shortened test periods. Such an approach is reasonable for well-characterized conventional bearing materials for which a database exists that correlates RCF rod endurance life to full-scale bearing life tests. As discussed earlier, however, for an emerging material like NiTi, no such full-scale bearing life versus stress database exists. Thus, interpretation of the results can be difficult.

To partially mitigate this uncertainty, a step-wise loading method was used. Under this scheme, the lowest practical stress levels were tested first. If a sample rod achieved the pre-determined cut-off period of 800 hours (~4.1 million stress cycles)

without the detection of a fatigue spall (unacceptable vibration), the test was suspended and the life is considered essentially infinite. After several repeat tests were conducted at the modest stress level on unused portions (wear paths or tracks) of the rod, the test load was increased. When rod surface damage and increased vibration was observed in less than 800 hours, the testing was stopped and the load (stress) level reached prior to the current load (stress) was deemed the material's relative stress capability limit. For conventional bearing steels like 440C, the RCF rod stress limit is about 3.5 GPa. For high performance bearing steels like M50, the stress limit for fatigue is much higher (~5.5 GPa).

Results and Discussion:

Table II presents representative RCF data for smooth steel balls loaded against various NiTi rods at increasing stress levels from 1.7 to 4.1 GPa. Tests are suspended when surface damage is detected by increased vibration or when 800 hours of testing is reached without failure indicating infinite life. Of course, successful operation for just 800 hr. does not preclude failure at 900, 1000 or even 2000 hr. To increase confidence that test suspension after 800 hr. indicates essentially unlimited life, several long duration test runs are done as well and are reported alongside the data as footnotes.

Table II. Three Ball-on-Rod RCF Preliminary Results				
(Test duration to first detected surface damage or when 800 test hours reached)				
{3600 rpm, steel balls, NiTi rods, oil drip lubrication, 1 hr equals 0.51 million stress cycles}				
Rod Specimen	Peak Contact Stress (GPa)			
	1.7 GPa	2.5 GPa	3.3 GPa	4.1 GPa
PM-60NiTi (Baseline) Avg. Max/Min #Tests	>800*hr N/A 4	291hr >800/~1 31	3.6hr 15.4/~1 9	-----
PM-60NiTi (With inclusions) Avg. Max/Min #Tests	192hr 240/~1 8	220hr >800/~1 11	47hr 218/~1 11	-----
58Ni39Ti-3Hf (Cast) Avg. Max/Min #Tests	>800hr N/A 1	>800hr N/A 4	262hr >800/~1 7	0.1hr 0.2/0.2 3
58Ni39Ti-3Hf (Cast and extruded) Avg. Max/Min #Tests	>800hr N/A 1	528hr >800/~1 16	16.4hr 132/~1 9	-----

*These tests are ongoing. Several specimens logged more than 6000 hr. at time of writing 1/2014.

Figures 8-11 show cross section and surface micrographs of the rod wear tracks inside and in the vicinity of the failure sites. The cross section image (Figure 8) reveals that the damaged surface at the bottom of the fatigue pit includes grain boundary and grain interior regions.

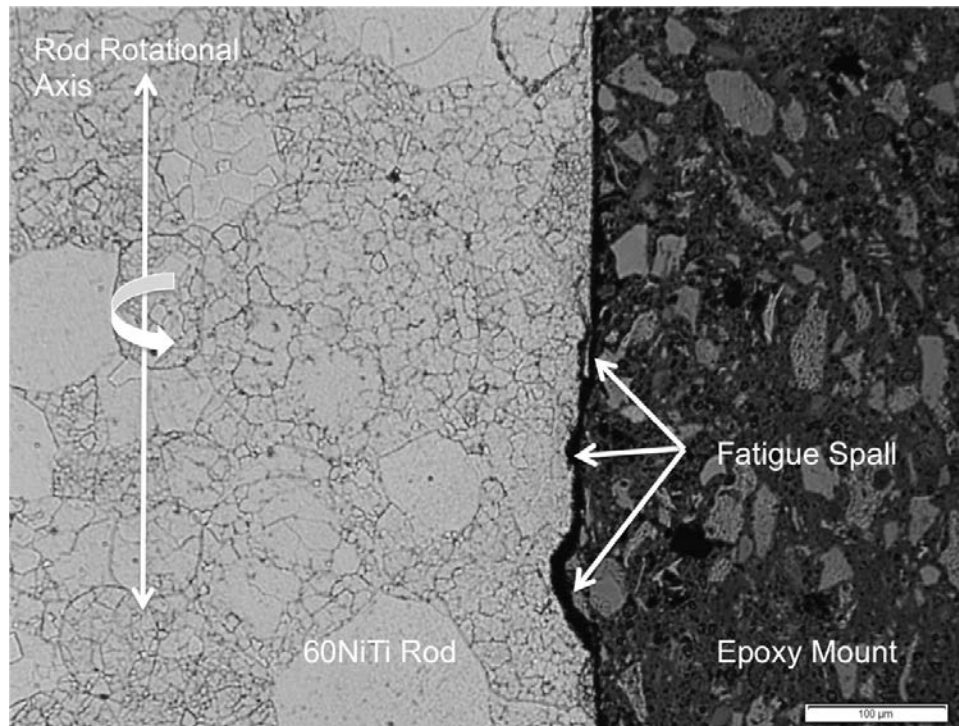


Figure 8. PM-60NiTi RCF rod cross-section showing typical damage site.

This suggests that, once initiated, the fatigue cracks propagate both along grain boundaries (intergranular) and through the grains (intragranular).

As seen in figure 9, surface micrographs using an SEM, which have the advantage over optical images in that the depth of field (in-focus region) is high, clearly show features of both types of fracture. Damage (cracking) that propagates along grain boundaries eventually results in removal of a large particle revealing relatively broad, smooth and faceted surface features at the bottom of the fatigue pit. In contrast, damage that propagates through individual grains typically results in small, fine grain damage features that resemble ripples that are sometimes referred to as "river patterns". Figure 10 depicts these failure features.

This type of damage has been observed in samples of 60NiTi subjected to impact toughness fracture tests [22]. In that work, both annealed (soft) and heat-treated (hard) 60NiTi was fractured under controlled impact conditions and then the fracture surfaces and cross sections were carefully assessed. The annealed material failed in an intergranular manner (along grain boundaries). The hardened samples failed in intergranular and intragranular (through the grain) manners. Since our fatigue rods have all been hardened through heat treatment they show evidence of mixed fracture modes.



Figure 9. PM-60NiTi RCF rod surface view (SEM) of fatigue spall.

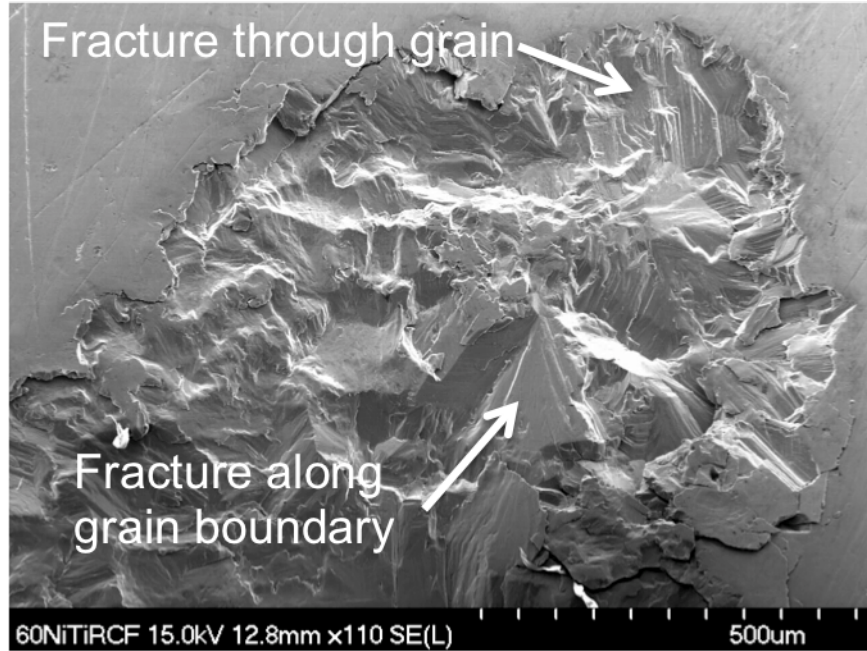


Figure 10. PM-60NiTi RCF rod close-up surface view (SEM) of initiation damage area of fatigue spall.

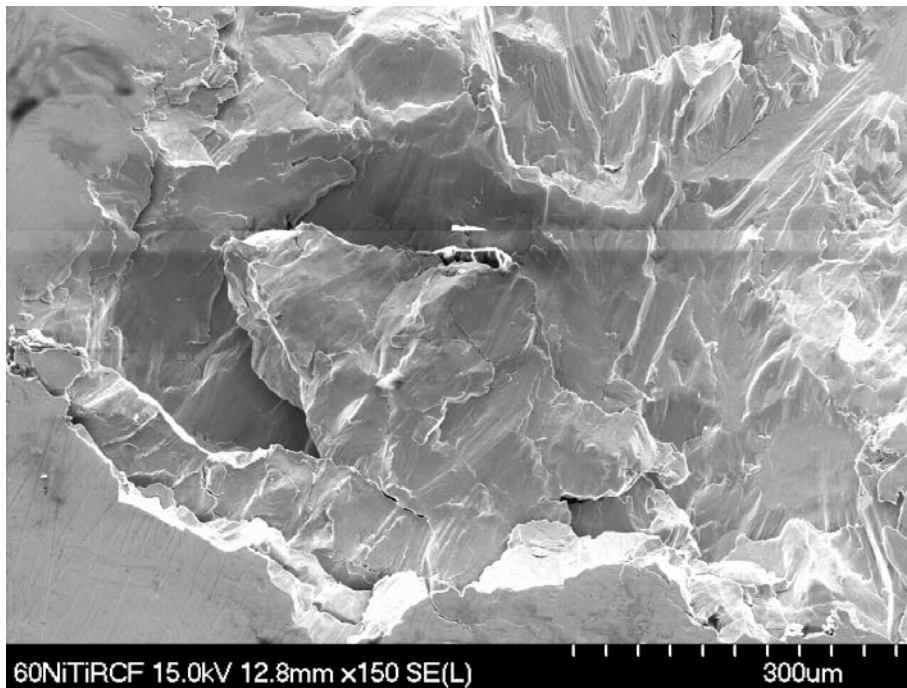


Figure 11. PM-60NiTi RCF rod close-up surface view (SEM) of propagating edge of fatigue spall.

Examination of the numerical data in table II reveals additional characteristics. One is that the RCF life decreases with increasing contact stress level. For all the specimen variants, the baseline PM-60NiTi, cast-60NiTi, cast and hot-rolled-60NiTi, alloyed 58Ni39Ti + 3Hf and even the PM-60NiTi with inclusions, higher contact stress results in reduced rolling contact lifetimes. This is hardly a surprising result given that the energy required to initiate and then to propagate damage increases with increased load and stress.

Another characteristic of the data is that the overall threshold stress level, above which life is short, is significantly lower for NiTi and its alloys than the stress capability levels for conventional bearing steels. Conventional bearing steels such as M50, 440C stainless and 52100 routinely exhibit long lifetimes in these tests at stress levels about two times greater (3-5GPa) than those used to test NiTi [21, 22].

In fact, in much of the literature reported RCF data for steel, the test balls are intentionally roughened by grit blasting to further accelerate the tests [3]. Prior to the present test campaign, roughened steel balls were run against 60NiTi rods but this led to near immediate rod spalls. Apparently, 60NiTi is much more sensitive to ball surface roughness than steel perhaps because of its intermetallic nature which has limited ductility. Whatever the reason, in order to achieve reasonable and measureable test times, only smooth steel balls were used to load the 60NiTi rods.

Following the tests, many specimens were cross-sectioned and their microstructures examined. The earlier RCF research on cast and hot-rolled 60NiTi revealed significant inclusions, microstructural flaws and internal voids (Figures 1 and 2) in the material that was implicated in the erratic fatigue life observed. 60NiTi manufactured via powder metallurgy was expected to be largely free from such defects and therefore be capable of significantly enduring higher stresses. This result, however, was not always observed. The PM-60NiTi specimens sometimes failed after only a few hours of run time at even the lowest stress level (1.7GPa). Examination of these early failures of the PM-60NiTi revealed the presence of flaws.

For PM-processed material, flaws arise from two common sources: oxidation of the starting powder particles, and particle contaminants. Metal and oxide particle contaminants result in inclusions that act as stress concentrators and lead to crack growth. Oxidation of NiTi particle surfaces inhibits proper particle consolidation resulting in poorly bonded particles in the finished material. Etched cross-sections of the early failure PM-60NiTi rods clearly show the presence of unconsolidated particles (Figure 12). Unconsolidated particles are poorly bonded and can become dislodged, especially when they are present at or near the contacting surface, which leads to pits and spalls. Figure 13 shows a cross-section micrograph of a properly formed PM-60NiTi microstructure at a magnification level comparable to the image in the previous figure.

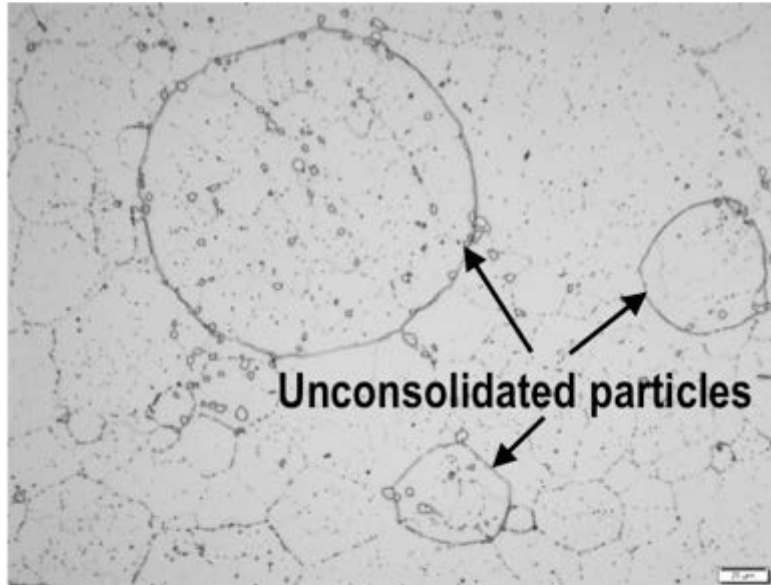


Figure 12. PM-60NiTi RCF rod specimen cross-section showing unconsolidated particle flaw.

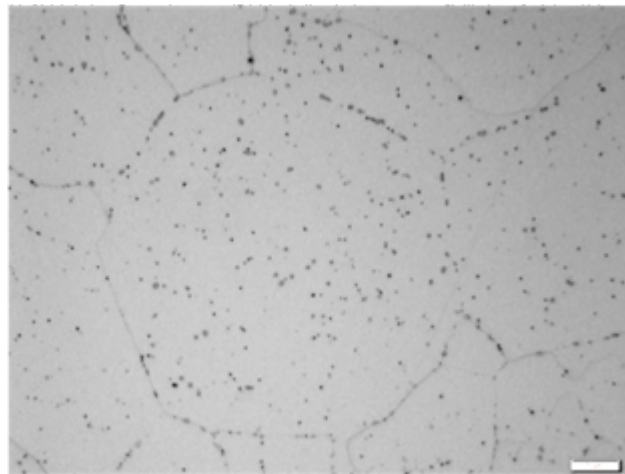


Figure 13. PM-60NiTi RCF rod specimen cross-section showing properly consolidated microstructure.

Based upon post-test cross-section metallography, the PM-60NiTi rods were divided into two groups. The first group, designated "Baseline" was prepared using powder with very low incidence of particle oxidation. The baseline material cross-sections were free from unconsolidated particles and only occasionally had inclusions, voids and other flaws. The second group designated "With inclusions" suffered from widely dispersed oxidized particles that prevented full particle-particle bonding. The RCF life data shows that when the PM-60NiTi rods are considered based upon the cleanliness of their microstructure the data is more consistent. Baseline 60NiTi can withstand 1.7GPa stress and only begins to sporadically fail at 2.5GPa and above. Flawed PM-60NiTi sporadically fails at even the lowest stress level, 1.7GPa.

The data also shows that alloyed derivatives of 60NiTi can exhibit good RCF life even when produced using casting. In a parallel research effort, the 60NiTi composition is altered by adding ~3% by weight of the element Hf. The exact composition by weight percent is 57.6%Ni-39.2%Ti-3.2%Hf and is designated as 58Ni39Ti-3Hf in Table II. It is made by vacuum casting with some specimens further processed using hot extrusion. This new alloy of NiTi exhibits RCF lifetimes at least as long as the baseline PM-60NiTi. Examinations of the 58Ni39Ti-3Hf microstructures help explain their good RCF performance.

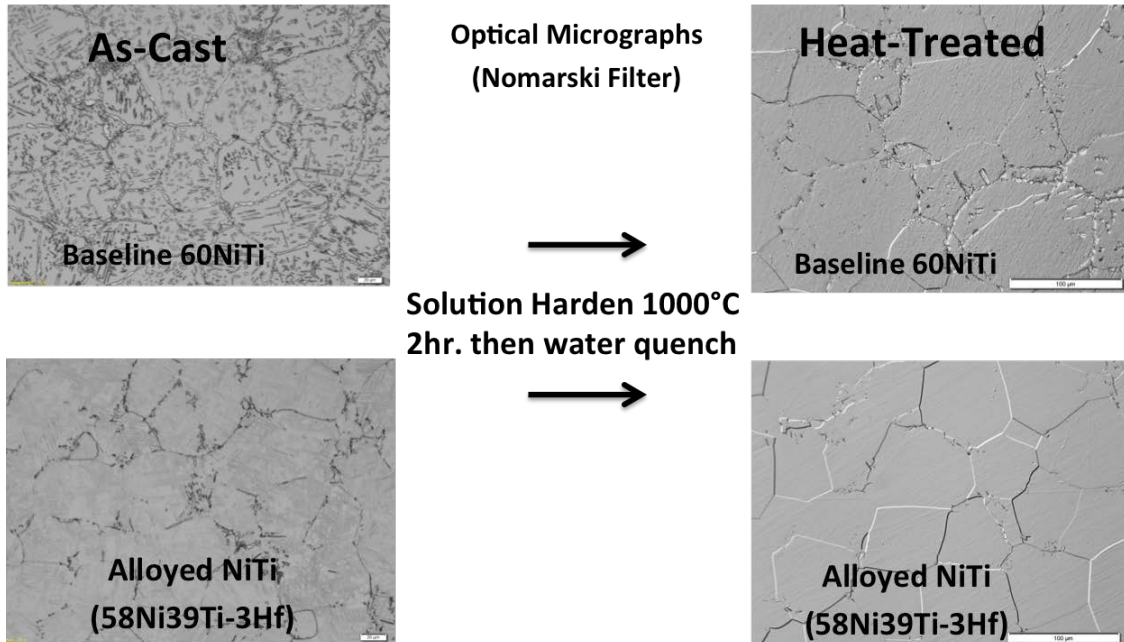


Figure 14. Comparison of microstructures of 60NiTi (upper images) to Hf containing alloyed NiTi (lower images) before and after heat treatment.

Compared to conventionally cast 60NiTi (upper portion of figure 14), the microstructures of the alloy (lower portion of figure 14) are uniform and free from flaws because the hafnium alloying addition acts as “getters” for contaminant elements. For these new alloys, fatigue performance matches or exceeds even the best-prepared baseline PM specimens. It is expected that such alloys, once the composition is finalized, will become mainstream bearing alloys. Until such development work is concluded, the stress capability (~1.7GPa) of the baseline 60NiTi must be taken into consideration when designing and applying the bearing technology.

The primary inference is that to achieve consistent and adequate RCF life, material processing and resulting microstructures must be adequately controlled. Fortunately, the production of such favorable microstructures is achievable. In addition, the data does show that even for flawed PM 60NiTi, restricting an application to modest continuous stress levels yields long life. In bearings used in space applications where power consumption (speed and torque) must be

minimized, continuous stresses are low (typically less than 1GPa) and fatigue is rarely a concern.

Concluding Remarks:

Ball-rod RCF tests have been conducted on 60NiTi to ascertain a generalized stress limit below which one can expect long rolling contact fatigue life for bearing applications. Though the data must yet be corroborated with full-scale bearing tests before such limits can be used with confidence, these RCF results offer insight into the behavior of NiTi materials for rolling contact applications.

The test results show that the 60NiTi is susceptible to spall type surface fatigue failure at modest stress levels (above 1.7GPa). Compared to conventional bearing steels, the stress capability of NiTi is lower by at least a factor of two. The performance difference between 60NiTi and steel is further accentuated when it is considered that the present tests were run using smooth steel counter-face balls whereas the stress capability of steel (typically 3.5GPa) is measured under accelerated test conditions using intentionally roughened balls.

Despite their modest contact stress capability, it must be remembered that in full-scale bearings continuous stress levels, particularly for space mechanism applications, are rarely above 1.7GPa. In such applications where machine power is limited, speeds (accumulated cycles) and constant load levels are typically low as well. Nonetheless, the modest fatigue stress limit observed for NiTi indicates a need for improvement before highly loaded, high speed applications are advanced.

The results also suggest that a homogeneous, fine-grained microstructure largely free from voids, inclusions and other flaws leads to improved stress capability. This is consistent with earlier mechanical strength property measurements made on 60NiTi in which internal microstructural flaws acted as stress concentrations and were the sites for fracture initiation. Experiments using alloying additions like hafnium indicate that microstructural improvements lead to improvements in fatigue stress capability. Further, relatively small percentages of such additives can be made without degrading other material properties, like hardness and strength.

Though currently the NiTi technology is relatively immature, it appears to provide an adequate rolling contact fatigue capability for lightly loaded, high-speed applications or those in which the total number of accumulated cycles is low. Based upon the inherent corrosion resistance of the Ni-Ti chemistry and the highly resilient nature of its superelastic characteristics, the most appropriate near-term applications are those that are chemically and dynamically aggressive but mechanically benign. It is expected that high cycle mechanical properties, such as rolling contact fatigue, will improve through alloying and processing that result in clean microstructures free from large flaws.

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