Tribol Lett (2015) 57:26
DOI 10.1007/s11249-014-0456-3

ORIGINAL PAPER

Rolling Contact Fatigue of Superelastic Intermetallic Materials (SIM) for Use as Resilient Corrosion Resistant Bearings

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Received: 17 October 2014 / Accepted: 18 December 2014 / Published online: 23 January 2015
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Abstract Superelastic intermetallic materials (SIM), such as 60NiTi, are emerging as candidates for corrosion and shock-resistant rolling element bearings. Compared with metals, the intermetallic materials are more brittle and may be prone to rolling contact fatigue degradation. In this paper, a series of three ball-on-rod rolling contact fatigue tests were conducted using polished steel balls and NiTi rods prepared by vacuum casting and powder metallurgy techniques. The test protocol matched that used in ASTM STP 771 except that the steel balls were not intentionally roughened. In general, the NiTi rods exhibit fatigue damage at much lower stress levels than commercial bearing steels. At the lowest stress level tested (1.7 GPa), 60NiTi rods that were largely free from processing defects gave acceptably long lives, and testing was terminated without failure after 800 h. At elevated stress (2.5 GPa), failure occurred for some specimens, while others reached the preset test length goal of 800 h. Improperly prepared 60NiTi rods that had unconsolidated particles or significant ceramic inclusions occasionally experienced surface fatigue prior to completion of the test period even at the lowest stress level. Alloyed NiTi rods containing small amounts of Hf as a microstructural processing aid generally endured higher stress levels than the baseline 60NiTi composition. Two predominant fatigue failure mechanisms were observed: intergranular (grain boundary) fracture and intragranular (through the grains) crack propagation. The results suggest that further fatigue capability improvements could be obtained through process improvements, microstructural refinements and alloying. SIM currently available are recommended for mechanically benign applications involving modest stress levels and rates of stress cycle accumulation. Applications that include high continuous loads (stress) and high speeds for long durations should be avoided.

Keywords Bearings · Fatigue · Rolling contact · Super elastic · Materials

1 Introduction

Rolling element bearings are used in mechanical systems and mechanisms throughout modern society to enable the long-life, efficient machines we rely upon such as automobiles, aircraft engines and computer hard disk drives. The most common type of bearing is the ball bearing in which two cylindrical races (rings) are separated by a set of hard, smooth, perfectly spherical balls. This arrangement allows the rotation of the races with low friction and, when properly lubricated, nearly infinite life [1, 2].

Because properly designed and well-lubricated bearings made from modern bearing steels can operate for years without failure, assessing a specific bearing or bearing material's useful life can be a lengthy and costly proposition. To reduce the costs and time required for such life testing, more fundamental materials tests can be used in the place of a full bearing test. One such accelerated test is the three ball-on-rod rolling contact fatigue (RCF) test [3].

The ball-on-rod RCF test was originally invented by Minter and further developed in the 1980s by Federal Mogul to aid in the rapid screening of emerging high-performance bearing materials then under development [4]. Among these emerging materials technologies were

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various ceramics like partially stabilized zirconia and silicon nitride and nitrogen-treated stainless and fine grain high-carbide super-hard tool steels. These new materials were far more difficult to manufacture into full-scale test bearings than conventional steels like M50 or 52100, and this difficulty heightened the need for a materials test machine that utilized easy to produce test specimens.

The RCF material test specimen is a simple flat-ended cylindrical rod, 9.5 mm in diameter and about 75 mm long. The curved outer diameter surface is polished to a bearing raceway quality finish. The rod is held vertically in a precision collet that is connected directly to an electric motor set to rotate at 3,600 rpm. The polished outer surface of the test rod is contacted by three standard steel bearing balls sandwiched between a pair of opposing tapered steel raceways. A spring pack is used to apply a test load between the balls and the rod, and oil is used for lubrication. Tests are generally run until a predetermined time period (typically 800 h) has passed indicating no failure or until an accelerometer detects surface damage such as a fatigue pit or spall.

The advantage of this set up is that only a simple rod of test material is needed to conduct a material evaluation. This circumvents the time and expense needed to make dimensionally precise bearing races that can require extensive development efforts especially for hard to process materials like ceramics. To accelerate data collection, higher than normal contact stresses are typically used. Another test acceleration method is to use steel loading balls with intentionally roughened surfaces. This ensures boundary lubrication conditions despite the high rolling speed. In addition, the generation of statistically meaningful data sets is enhanced by using multiple RCF specimen test stations engineered into a single, compact test machine [3].

The ball-on-rod RCF machine was used throughout the 1980s and 1990s during the period in which hybrid ceramic bearings (steel races with silicon nitride balls) were under development. However, over the last decade or two, such machines have seen little use because databases that link the microstructure and physical properties of ceramics and advanced tool steels to bearing fatigue life have matured. Further, since these and other advanced materials are now in widespread production, full-scale bearing tests are routinely employed or well-benchmarked models and relations are used for design and application engineering purposes. Hence, simplistic tests like the ball-on-rod RCF test are no longer commonly used. Recently, however, a new class of materials, based upon Nickel-Titanium, is under consideration as a candidate bearing material [5–7]. While it has been recently shown that NiTi-based alloys can be made into operating bearings, alloy and processing development efforts are still underway and it is not yet in widespread bearing production. This has renewed interest in using the RCF test to aid development.

Nickel-Titanium-based materials are not new. W.J. Buehler [8] and his colleagues at the Naval Ordnance Laboratory first investigated them in the late 1950s. Among Buehler's early compositions, 60NiTi (60 wt% nickel and 40 wt% 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 with 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]. As a brief recap, the elastic modulus of 60NiTi is one-half that of steel and one-third that of the ceramic silicon nitride. Thus, in concentrated contacts such as a steel ball-on-60NiTi RCF rod, higher test loads are required to achieve a given stress level. As an example, for a steel ball-on-60NiTi rod, a load of 238N (53.5 lb) results in a peak stress level of 2.5 GPa (356Ksi), while the same load for steel-on-steel gives a peak stress of 3.3 GPa (480Ksi). Another way to look at the effect of the reduced modulus of 60NiTi is that for a given peak stress level, contact loads for steel-on 60NiTi must be about 2.5 times higher than steel-on-steel to reach an equivalent stress condition. Thus, the use of 60NiTi in place of steel or ceramics provides a potential avenue for machine elements with extremely high load capacity.

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 (<1.7 GPa), was erratic. Some specimens failed (surface spalls) after just a few hours, while others survived the test conditions for over 800 h 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 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.

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.

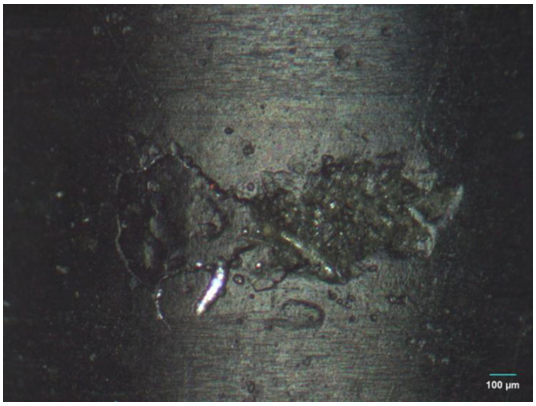

Fig. 1 Spall damage on a hardened 60NiTi rod surface following testing at 3.0 GPa

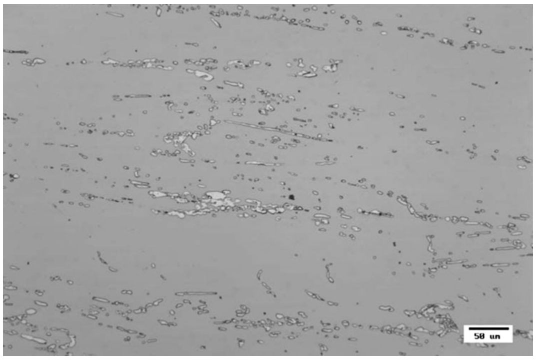

Fig. 2 Cross-sectional optical micrograph of a cast and rolled 60NiTi RCF rod showing voids and second-phase precipitates

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 50-mm 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 wt%, 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.

2 Materials and Specimens

60NiTi (60Ni and 40Ti by wt%) 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 1.

Table 1 Thermophysical and mechanical properties of 60NiTi and other bearing materials

Property	60NiTi	440C	Si_3N_4	M-50
Density (g/cc)	6.7	7.7	3.2	8.0
Hardness	56–62 Rc	58–62 Rc	1,300–1,500 Hv*	60–65 Rc
Thermal cond. (W/m °K)	~9–14	24	33	~36
Thermal expansion (/°C)	$\sim 11.2 \times 10^{-6}$	10×10^{-6}	2.6×10^{-6}	$\sim 11 \times 10^{-6}$
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Acceptable (in acids)	Marginal	Acceptable	Poor
Tensile/flexural strength (MPa)	~1,000/1,500	1,900	600–1,200 (bend strength)	2,500
Young's modulus (GPa)	~90–115	200	310	210
Poisson's ratio	~0.34	0.30	0.27	0.30
Fracture toughness (MPa/$\sqrt{}$m)	~20	22	5–7	20–23
Max. use temp (°C)	~400	~400	~1,100	~400
Elect. resistivity (Ω m)	$\sim 1.04 \times 10^{-6}$	$\sim 0.60 \times 10^{-6}$	Insulator	$\sim 0.18 \times 10^{-6}$

* 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 Fig. 3 and more fully described in the literature [18, 19].

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 isostatic 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.

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 (Fig. 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.

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 multistep 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 1,000 °C in vacuum or inert gas atmosphere for 1 h followed by a rapid quench in water. The solution treating dissolves precipitate phases like Ni_4Ti_3 and Ni_3Ti 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 µm Ra.

The balls used for the fatigue tests are grade-ten, standard 12.7mm (1/2 in.) diameter bearing balls made from hardened (HRC58062) 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.

3 Procedures

The three ball-on-rod test is used to evaluate the 60NiTi RCF behavior. Using this test, depicted in Fig. 7, three steel bearing balls are loaded against a polished, NiTi rod rotated at 3,600 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.

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

Fig. 3 PM processing route for 60NiTi

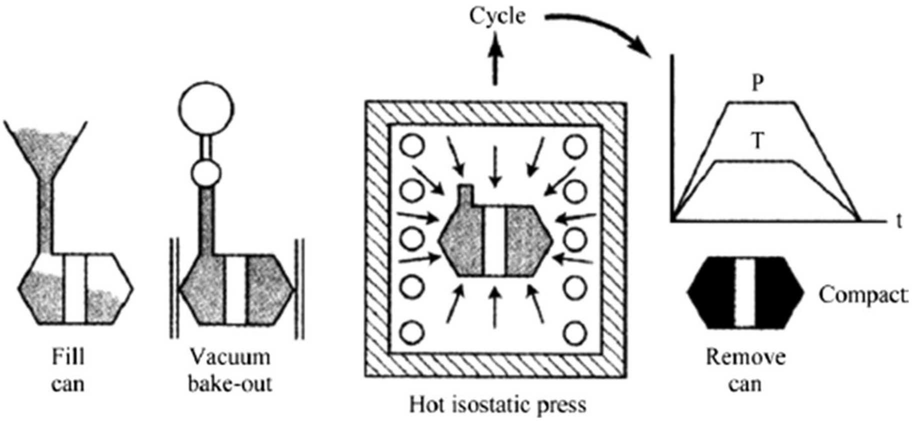

Fig. 4 60NiTi ingots and blanks produced by PM process

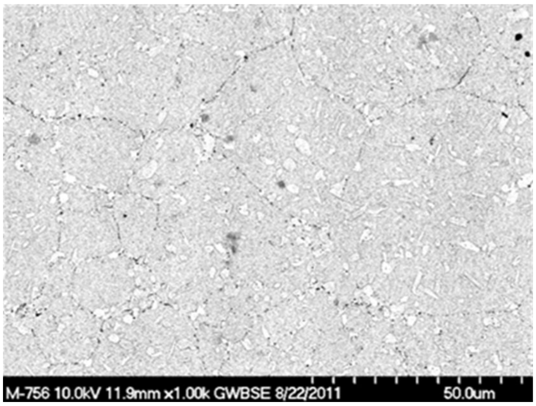

Fig. 5 Metallurgical cross sections of PM-processed 60NiTi backscattered electron image

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,

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Mitutoyo  SurftestSJ-400
DATE      10-11-2011
TIME        15:00:29
R-PROFILE
EVA-L         0.03in
λc          0.03inX1
Ra            1.3μin
Rz             13μin
Rq            1.6μin
R-PROFILE
EVA-L         0.03in
λc=0.03inX1
       ×100K
  ×200
Ver.  10.000μin/in
Hor.   0.005in
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Fig. 6 Polished 60NiTi RCF rods

however, for an emerging material like NiTi, no such full-scale bearing life versus stress database exists. Thus, the interpretation of the results can be difficult.

To partially mitigate this uncertainty, a stepwise loading method was used. Under this scheme, the lowest practical stress levels were tested first. If a sample rod achieved the predetermined cut-off period of 800 h ($\sim$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 <800 h, 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

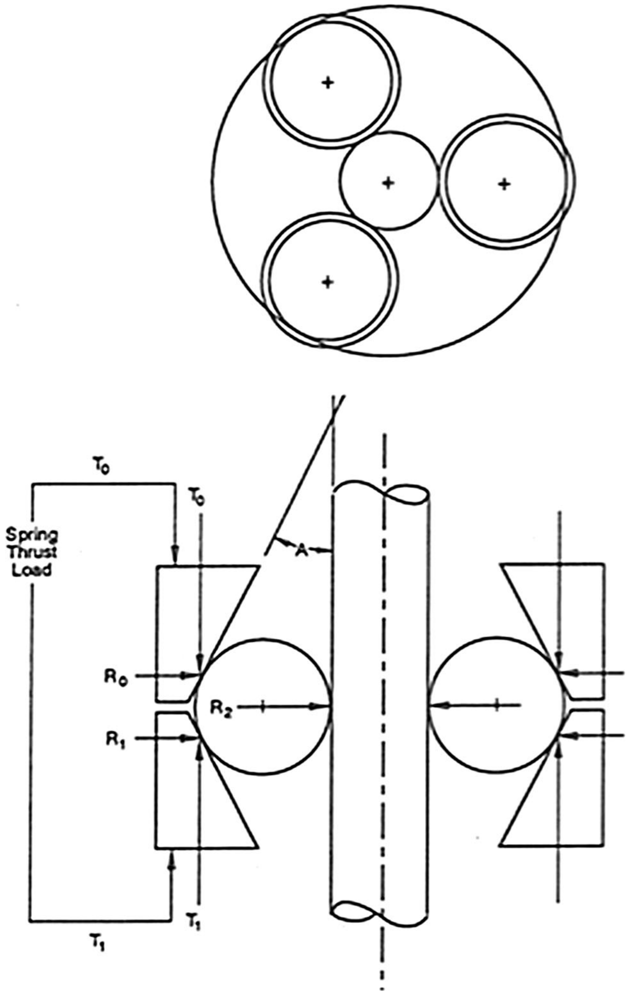

Fig. 7 Specimen configuration for the *three ball-on-rod* RCF test

Table 2 Three ball-on-rod RCF preliminary results (test duration to first detected surface damage or when 800 test hours reached)

Rod specimen	Peak contact stress (GPa)			
	1.7 GPa	2.5 GPa	3.3 GPa	4.1 GPa
PM-60NiTi (baseline)				
Average (h)	[a]> 800	291	3.6	
Max/min	N/A	>800/∼1	15.4/∼1	
Number of tests	4	31	9	
PM-60NiTi (with inclusions)				
Average (h)	192	220	47	
Max/min	240/∼1	>800/∼1	218/∼1	
Number of tests	8	11	11	
58Ni39Ti-3Hf (cast)				
Average (h)	>800	>800	262	0.1
Max/min	N/A	N/A	>800/∼1	0.2/0.2
Number of tests	1	4	7	3
58Ni39Ti-3Hf (cast and extruded)				
Average (h)	>800	528	16.4	
Max/min	N/A	>800/∼1	132/∼1	
Number of tests	1	16	9	

3,600 rpm, steel balls, NiTi rods, oil drip lubrication, 1 h equals 0.51 million stress cycles

[a] These tests are ongoing. Several specimens logged more than 6,000 h at time of writing in January 2014

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).

4 Results and Discussion

Table 2 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 h of testing is reached without failure indicating infinite life. Of course, successful operation for just 800 h does not preclude failure at 900, 1,000 or even 2,000 h. To increase confidence that test suspension after 800 h indicates essentially unlimited life, several long duration test runs are done as well and are reported alongside the data as footnotes.

Figures 8, 9, 10 and 11 show cross section and surface micrographs of the rod wear tracks inside and in the vicinity of the failure sites. The cross-sectional image (Fig. 8) reveals that the damaged surface at the bottom of the fatigue pit includes grain boundary and grain interior regions. This suggests that, once initiated, the fatigue cracks propagate both along grain boundaries (intergranular) and through the grains (intragranular).

As shown in Fig. 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 the 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 [20]. 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

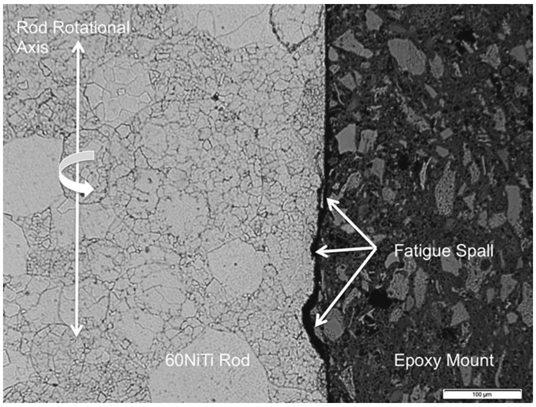

Fig. 8 PM-60NiTi RCF rod cross section showing typical damage site

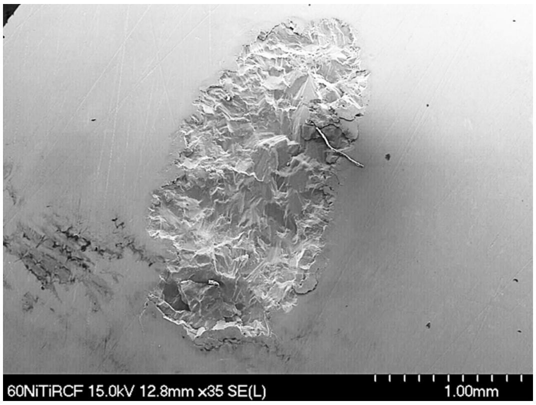

Fig. 9 PM-60NiTi RCF rod surface view (SEM) of fatigue spall

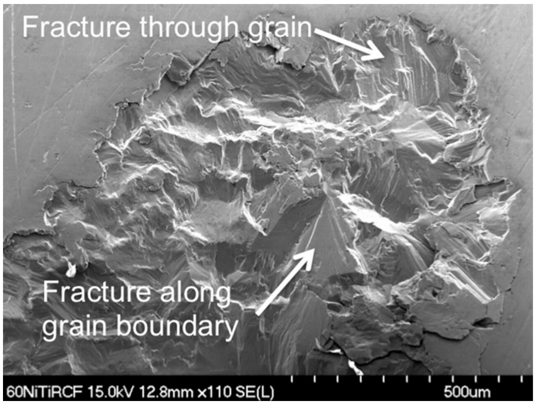

Fig. 10 PM-60NiTi RCF rod close-up surface view (SEM) of initiation damage area of fatigue spall

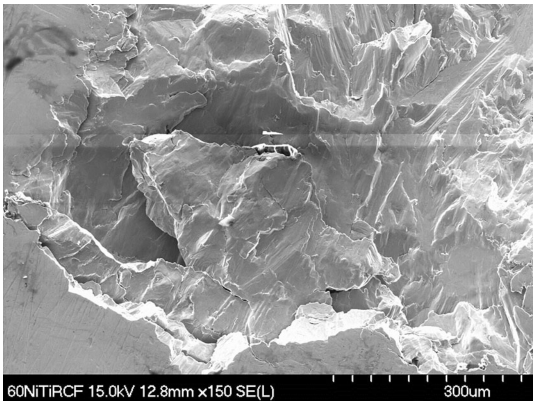

Fig. 11 PM-60NiTi RCF rod close-up surface view (SEM) of propagating edge of fatigue spall

been hardened through heat treatment they show evidence of mixed fracture modes.

Examination of the numerical data in Table 2 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. Weibull statistical analyses were applied to the test data but the interpretation of the plots was impeded by the immature nature of the material and the limited number of repeat experiments performed. It is expected that future tests using specimens from more highly controlled production batches of materials will benefit from such statistical analyses.

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 (3–5 GPa) 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 (Figs. 1, 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

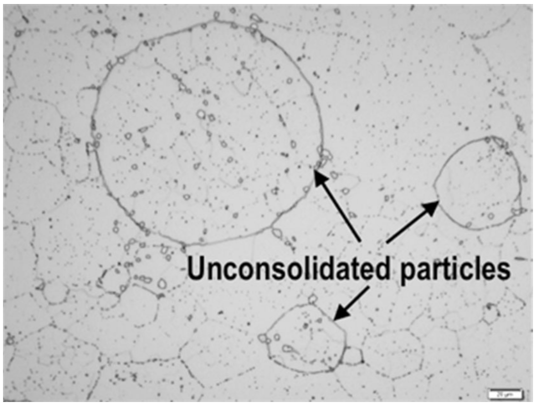

Fig. 12 PM-60NiTi RCF rod specimen cross section showing unconsolidated particle flaw

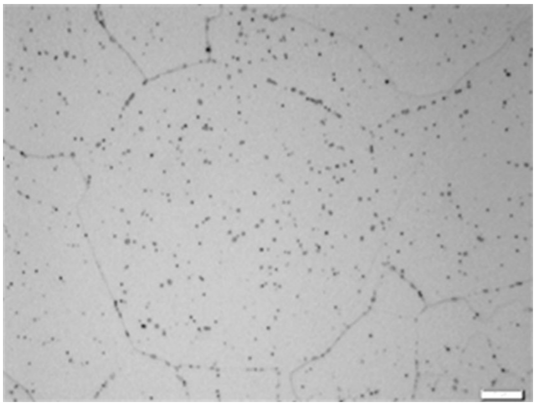

Fig. 13 PM-60NiTi RCF rod specimen cross section showing properly consolidated microstructure

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 (1.7 GPa). 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 (Fig. 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-sectional micrograph of a properly formed PM-60NiTi microstructure at a magnification level comparable to the image in the previous figure.

Based upon post-test cross-sectional 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 show that when the PM-60NiTi rods are considered based upon the cleanliness of their microstructure the data is more consistent. Baseline 60NiTi can withstand 1.7 GPa stress and only begins to sporadically fail at 2.5 GPa and above. Flawed PM-60NiTi sporadically fails at even the lowest stress level, 1.7 GPa.

The data also show 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 2. 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.

Compared with conventionally cast 60NiTi (upper portion of Fig. 14), the microstructures of the alloy (lower portion of Fig. 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 (~1.7 GPa) 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 do 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 <1 GPa) and fatigue is rarely a concern.

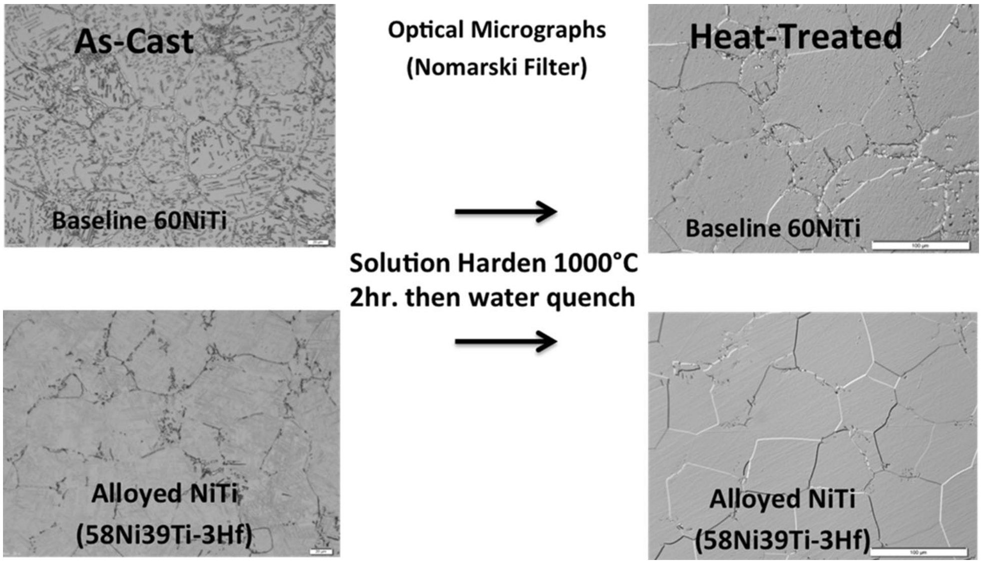

Fig. 14 Comparison of microstructures of 60NiTi (*upper images*) to Hf containing alloyed NiTi (*lower images*) before and after heat treatment

5 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 1.7 GPa). Compared with 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 3.5 GPa) 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 1.7 GPa. 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 NiTi 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.

Acknowledgments The authors wish to thank Walt Wozniak, Olivia Leak and Joy Buehler of NASA Glenn Research Center for their invaluable assistance in preparing rod specimens and in the post-test examinations of the fatigue failures. The support provided by the NASA International Space Station Program, the NASA Engineering and Safety Center (NESC) and the Aerosciences Project within the NASA Fundamental Aeronautics Program are greatly appreciated.

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