Rolling Bearing Steels—A Technical and Historical Perspective, Part II

Erwin V. Zaretsky

This paper summarizes the chemical, metallurgical and physical aspects of bearing steels and their effect on rolling bearing life and reliability.

Heat Treatment

Steel hardness. Hardness is an influential heat treatment-induced variable. For most rolling bearing applications it is required that the Rockwell *C* hardness at operating temperature be 58 or higher. In general, the higher the hardness of the bearing steel at operating temperature, the longer the life. A relationship that approximates the effect of bearing material hardness on fatigue life has been developed (Refs. 20 and 31).

$$LF = \exp\{m[(\mathrm{RC})_T - 60]\} \qquad (5)$$

where:

m is an exponent relating material hardness and life (typically $m = 0.1$) and $(RC)_T$ is the Rockwell *C* hardness at operating temperature. It was assumed for the purpose of this relationship, which was obtained for AISI 52100, that all components in the rolling element bearing (i.e., the rolling elements and the races) are of the same hardness. It was further assumed that this equation can be extended to other bearing steels. A 3 point increase in hardness can result in a 35 percent increase in bearing life. With the exception of AISI 52100 and other low-tempering-temperature bearing steels, most bearing steels can be expected to maintain their room-temperature hardness after soaking at elevated temperatures.

As was discussed for through-hardened steels, the bearing industry also assumed that materials with higher alloy content would have better hardness retention at elevated temperatures. A study to verify this assumption was undertaken at NASA Lewis Research Center (Refs. 32 to 34). Short-term, hot-hardness measurements were made for groups of through-hardened specimens of AISI 52100, M–1, M–50, 440C, Halmo, WB–49, WD65, and Matrix II. Measurements were also made of specimens of Super Nitralloy (5Ni-2A1) and case-carburized AISI 8620, CBS 600, CBS 1000, and Vasco X–2. The results for the AISI 52100 and the other through-hardened steels were normalized and are shown in Figure 5. These normalized data show that regardless of the initial hardness, the hot hardness of individual materials shows the same functional dependence. These results completely changed previously held assumptions (Ref. 20). These data can be represented by a straight line having the form:

$$(RC)_T = (RC)_{RT} - \alpha\,\Delta T^{\beta} \qquad (6)$$

where:

$(RC)_T$ is the Rockwell *C* hardness at operating temperature; $(RC)_{RT}$ is the Rockwell *C* hardness at room temperature; ΔT is the difference between operating temperature and room temperature, α is a material constant, and β is a material exponent. Values of α and β for various bearing steels are given in Table 4.

To determine hardness effects at the bearing operating temperature (Eqs. 2 and 3) can be combined to obtain a life factor as follows:

$$LF = \exp\Big(0.1\big\{[(\mathrm{RC})_{RT} - 60] - \alpha(T_T - T_{RT})^{\beta}\big\}\Big) \qquad (7)$$

where:

T_{RT} is 22°C (70°F). Equation 7 is benchmarked to a Rockwell *C* hardness equal 60

where:

$L_F = 1.$

Compressive Residual Stresses

From the late 1920s through to the 1960s, Almen (Ref. 35) and his colleagues (Refs. 36 to 38) at the General Motors Research Laboratories pioneered the study of residual stresses in rotating steel components that included rolling element bearings. These residual stresses can either be tensile or compressive. They can be induced by producing microscopic and macroscopic deformations and by transformations in the microstructure of the steel. Residual stresses can also be induced by heat treating, rolling, shot peening, diamond burnishing, and severe grinding. Each of these methods (except heat treating) is a separate mechanical process that is performed after heat treating (Ref. 15).

They found that compressive residual stresses induced beneath the surface of ball bearing race grooves increase rolling element fatigue life. According to Gentile and Martin (Ref. 37) ball bearing lives were doubled when metallurgically induced ("pre-nitrided") compressive residual stresses were present in the inner races. Scott et al. (Ref. 38) found that compressive residual stresses induced by unidentified "mechanical processing" extend the fatigue life of ball bearings (Ref. 15).

Figure 6 shows representative residual stresses as a function of depth below the surface for three heat treated bearing steels. In general, most—if not all—carburized bearing steels have induced compressive residual stresses represented by those shown for AISI 9310 steel (Fig. 6). These stresses are induced by the carburization process.

In 1965 E.V. Zaretsky (Refs. 15 and 39) and his colleagues at the NASA Lewis (now Glenn) Research Center published an equation relating rolling element fatigue life to these compressive residual stresses. The maximum shearing stress τmax for a given contact stress is decreased by the presence of a compressive residual stress σ_r. This results in the following life factor due to residual stresses alone:

$$LF = \left[\frac{\tau_{max}}{\tau_{max} - \tfrac{1}{2}\sigma_r}\right] \qquad (8)$$

where:

exponent *c* is typically 9.

For light-to-moderately loaded bearings, a typical value of τ_{max} is 414 MPa (60 ksi). For heavily loaded bearings a typical value of τ_{max} is 724 MPa (105 ksi).

From Figure 6, assume AISI 9310 as the bearing steel; the compressive residual stress σ_r is 200 MPa (29 ksi); from

Equation 8, for a lightly loaded bearing, $LF \approx 12$; for a heavily loaded bearing, $LF \approx 3.8$. These life factors can be applied in Equation 1 together with the other life factors discussed. However, when bearing life results are analyzed independent of these residual stresses, the load-life exponent p appears to increase from their accepted values (Ref. 40).

Investigators have misinterpreted these results caused by the presence of residual stresses as a "fatigue limit" (Ref. 41). They have incorporated them into bearing life predictions and in some cases bearing manufacturer catalogues (Ref. 42). The concept of a fatigue limit has also been incorporated into an ISO standard (Ref. 43) for bearing life prediction for AISI 52100 steel where there are no residual stresses in the as-heat treated steel (Ref. 42). This can result in bearing life over prediction and/or undersizing a bearing for a particular application (Refs. 41 and 42).

There are two problems associated with the use of a fatigue limit for bearing steels: 1) the form of the equation as expressed in the ISO standard (Ref. 43) may not reflect a fatigue limit, but the presence of a compressive residual stress; and 2) there are no data in the open literature that would justify the use of a fatigue limit for through-hardened bearing steels such as AISI 52100 and AISI M-50 (Refs. 41 and 42).

In 2007 Sakai (Refs. 44 and 45) presented stress/life rotating bending fatigue data from six different laboratories in Japan for AISI 52100 steel. He also presented stress/life fatigue data for axial loading. The resultant lives were in excess of one billion (>109) stress cycles at a maximum shearing stress τ_{max} as low as 350 MPa (51 ksi) without an apparent fatigue limit.

In 2008, Tosha et al. (Ref. 46) of Meiji University in Japan reported rotating bending stress life fatigue tests for through-hardened bearing steels having Rockwell C hardness above 58. The results of these tests at maximum shearing stresses τ_{max} as low as 480 MPa (70 ksi) produced fatigue lives in excess of 100 million (>108) stress cycles without the manifestation of a fatigue limit.

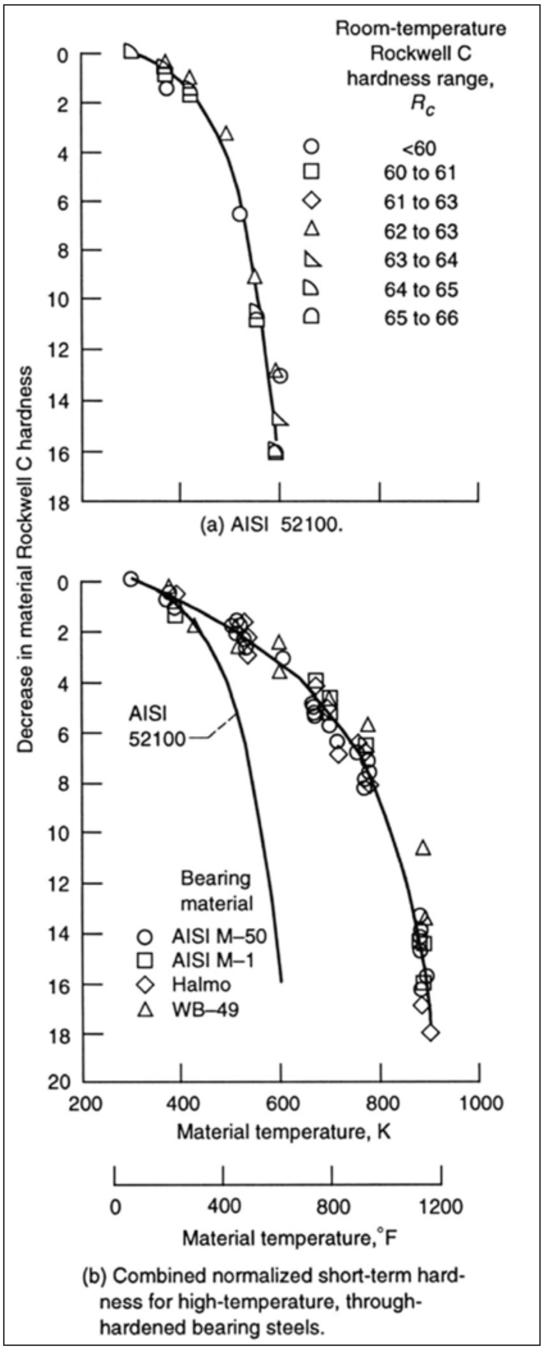
In 2009, in order to verify the Sakai results (Refs. 44 and 45) and Tosha, et al. (Ref. 46), Shimizu, et al. (Ref. 47), also of Meiji University, published the results from six groups of AISI 52100 bearing steel specimens using four alternating torsion fatigue tests rigs to determine whether a fatigue limit exists or not, and to compare the resultant shear stress life relation with that used for rolling element bearing life prediction (Ref. 42). The results of these tests at maximum shearing stresses τ_{max} as low as 500 MPa (76 ksi) produced fatigue lives in excess of 10 million (>107) stress cycles without a fatigue limit. Shimizu, et al. (Ref. 47) reported that the resultant fatigue life was inversely related to the shearing stress to the 10.34 power (Ref. 42).

Retained Austenite

In the early 1960s a major U.S. aircraft engine company had to discard unused rolling element bearings made from AISI M-50 because their bore diameter had increased from that specified for the engine shaft diameter (in a personal communication with E.N. Bamberger, General Electric Company, February 1963). This expansion in bore size was attributed to the presence of large amounts of retained austenite in the microstructure of the steel. The retained austenite transformed to martensite and bainite on the shelf at room temperature. As a result, for most critical aerospace applications, the retained austenite is limited to 2 to 5 percent. However, for noncritical applications, higher amounts of retained austenite are allowed or may, in some instances, be uncontrolled. Experience has suggested that lower values of retained austenite are preferable for reliable bearing operation (Ref. 15).

L.R. Waldmiller, of Frost, Inc. (in a personal communication, December 1994) described un-run, carburized, 12.7-mm (0.5-in.) diameter AISI 1022 balls having 40 to 50 percent retained austenite. The balls lost a portion of the case material while at room temperature due to transformation of the retained austenite. The lost material had the appearance of a "skullcap" and the phenomenon was referred to as "capping." He reported that the phenomenon also occurs during bearing operation. The same material with a lower amount of retained austenite did not experience capping (Ref. 15).

In general, for a given through-hardened material, the amount of retained austenite increases with increasing material hardness. Experience has also



(b) Combined normalized short-term hardness for high-temperature, through-hardened bearing steels.

Figure 5 Summary of short-term, hot-hardness, through-hardened bearing steel data (Ref. 20).

shown that test rollers made from AISI 52100 of Rockwell C hardness greater than 63 will have sufficient austenite-to-martensite transformation during rolling contact to alter the surface waviness and cause early surface spalling (Ref. 15).

Johnston et al. (Ref. 48) studied the effect of the decomposition of retained austenite and the inducement of compressive residual stress as a result of bearing operation. What is unique for their data is that the magnitudes of the compressive residual stresses are directly proportional to the decomposition of retained austenite (Ref. 15).

Changes in microstructure (phase transformations) have been reported to occur in the same areas as the maximum induced residual stress (Refs. 36 and 49). Under some conditions of extremely high contact stresses, nonmicrostructural alteration was apparent after significant residual stresses had been induced in a few cycles (Ref. 49). Muro and Tsushima (Ref. 50) proposed that the induced residual stresses and the microstructural alterations are independent phenomena (Ref. 15).

Research performed by Zhu et al. (Ref. 51) in 1985 on carburized rollers suggested that the structural change in the zone of maximum resolved shearing stresses observed by Jones (Ref. 52) in 1947 and later by Carter (Ref. 53) in 1960, as well as others is a manifestation of retained austenite transforming to martensite under cyclic Hertzian stress conditions. A combination of thermal and strain energy and time is believed to cause this change (Ref. 15).

Grain Size

It is generally accepted in the bearing industry that prior austenite grain size should be ASTM No. 8—or finer—and that individual grains should not exceed ASTM No. 5 (Ref. 54). The higher the ASTM number, the finer the grain size. The 1960 work of R.A. Baughman (Ref. 55) suggested that rolling element fatigue life increases with finer grain sizes (Ref. 20). A recent analysis of grain size and orientation on rolling element fatigue life was performed by N. Weinzapfel, et al. (Ref. 56).

Carbides

Residual carbides are those carbides that do not go completely into solution during austenitizing and are a function of the alloying elements and raw material processing. In contrast, hardening carbides precipitate upon aging at the tempering temperature. The carbides referred to in the following paragraphs are the residual carbides.

Carbide composition has been found to vary among steel producers. Heat treating steel ingots creates large, extremely hard metal carbides (MC), considered to be essentially a vanadium carbide that can act as asperities in the bearing surface (Ref. 57). J.E. Bridge, et al. (Ref. 58) identified the primary carbides in AISI M–50 as MC and M2C. Pearson and Dickinson (Ref. 57) found that the M2C carbides contain a high percentage of molybdenum, and that in a bearing ball under thin film elastohydrodynamic (EHD) lubrication conditions, they can cause distress or peeling of the bearing race surfaces. The carbide "stick out" has been attributed in whole or in part to an excessive rate of grinding in the manufacture of bearing balls made from AISI M-50 steel.

Parker et al. (Refs. 17, 59 and 60) have shown an interrelation among steel alloy content; median residual carbide size; number of residual carbide particles-per-unit area; percentage of residual carbide area in through-hardened bearing steels; and rolling element fatigue life. As the percentage of alloying elements increases in a steel, the number and size of the carbides increase (Refs. 61 and 62). Subsequent research by Parker and Bamberger (Ref. 63) for AMS 5749 steel further substantiated the negative effect of large-carbide-size and banded-carbide distribution on rolling element fatigue life.

Pearson and Dickinson (Ref. 57) verified the observations of Butterfield and T.R. McNelley (Ref. 64), who reported voids of the order of 1 μm (40 μin.) adjacent to carbides of AISI M–50 steel. This work (Ref. 64) suggested that these voids form during bearing operation at the site of the carbide tip and can act as a nucleus for crack initiation in the subsurface zone of maximum shear stresses. The large carbides act as stress raisers to initiate an incipient crack that results in a rolling element fatigue spall. The effect of carbides on rolling element fatigue life is reflected in the life factors displayed in Table 1 (Ref. 15).

In general, case-carburized bearing steels, with the exception of M50 NiL, have a courser and larger carbide structure when compared to through-hardened bearing steels such as AISI 52100 or AISI M-50. However, this disadvantage is more than offset by the compressive

Table 4 Temperature proportionality factors α and e × ponents β for bearings steels $(RC)_T = (RC)_{RT} - \alpha \Delta T_\beta$; (Ref. 20).

Material	Temperature range, °C (°F)	α		β	
		°C	°F	°C	°F
AISI 8620	21 to 316 (70 to 600)	73×10^{-5}	26×10^{-5}	1.7	1.7
CBS 600	21 to 316 (70 to 600)	$.75 \times 10^{-5}$	$.18 \times 10^{-5}$	2.4	2.4
Vasco × -2	21 to 538 (70 to 1000)	1.4×10^{-5}	$.38 \times 10^{-5}$	2.2	2.2
CBS 1000	21 to 538 (70 to 1000)	93×10^{-5}	38×10^{-5}	1.5	1.5
CBS 1000M	21 to 538 (70 to 1000)	340×10^{-5}	160×10^{-5}	1.3	1.3
Super Nitralloy	21 to 327 (70 to 620)	1.3×10^{-5}	$.33 \times 10^{-5}$	2.3	2.3
AISI 52100	21 to 260 (70 to 500)	92×10^{-5}	34×10^{-5}	1.6	1.6
AISI M-50	21 to 538 (70 to 1000)	133×10^{-5}	54×10^{-5}	1.4	1.4
AISI M-1	↓	↓	↓	↓	↓
AISI M-2					
AISI M-10					
AISI M-42					
AISI T-1 (18-4-1)					
Halmo					
WB-49					
WD-65					
Matri × II					
AISI 440C					
AMS 5749 (BG42)					
AMS 6278 (M50 NiL)					

residual stresses induced into the case by the carburization process.

Summary

In order to assure long rolling element bearing life and reliability for commercial, industrial and aerospace applications, materials, lubricants and design variables must be carefully considered and specified. The catalyst to quantum advances in high-performance rolling element bearing steels was the advent of the aircraft gas turbine engine. The reliability of these bearings became a major consideration because of system and mission complexities and because of the high costs involved. With improved bearing manufacturing and steel processing together with advanced lubrication technology, the potential improvements in bearing life can be as much as 80 times that attainable in the late 1950s or as much as 400 times that attainable in 1940. The following summarizes the chemical, metallurgical and physical aspects of bearing steels and their effect on rolling bearing life and reliability:

For temperatures less than 149° C (300° F) the bearing steels of choice are: through-hardened, AISI 52100; case-carburized, AISI 8620 and AISI 9310; and corrosion-resistant, AISI 440C. For temperatures greater than 149° C (300° F) the bearing steels of choice are: through-hardened, AISI M-50; case-carburized, M50 Nil; and corrosion-resistant, BG-42.

Vacuum processing of bearing steel reduces or eliminates the amount of nonmetallic inclusions, entrapped gases and trace elements in structural alloys, resulting in substantially cleaner material and significantly longer bearing life.

For a post-1960 vacuum-processed bearing steels such as AISI 52100 and AISI M-50, the values for the load life-exponent p, where life is inversely proportional to load to the exponent p, increased from three and four for ball and roller bearings, respectively, to four and five.

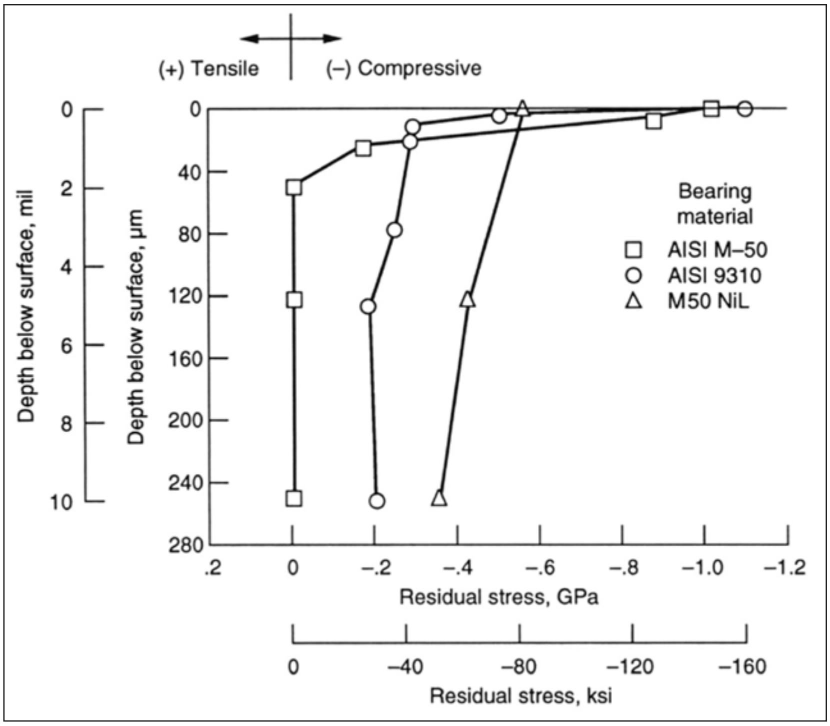


Figure 6 Representative principal residual stress as a function of depth below surface for heat-treated AISI M–50, AISI 9310 and M50 NiL (AMS 6278) (Ref. 3).

Minimum hardness for bearing steel at operating temperature should not be less than Rockwell C 58. Bearing life increases with increasing steel hardness at operating temperature. A three-point increase in hardness can result in a 35 percent increase in bearing life. For M-Series bearing steels, the change in hardness with temperature is independent of alloy content.

Bearing steels with high chromium content, greater than 12 percent, such as AISI 440° C are considered corrosion-resistant. Although the chromium forms a passive, chromium oxide layer at the surface that provides substantial protection, it is not inert and these alloys will corrode in hostile environments.

Compressive residual stresses induced or present from heat treatment beneath the surface of bearing steel components increase rolling element fatigue life and can alter the Hertzian stress-life relation. A compressive residual stress of 200 MPa (29 ksi) can increase bearing life for a lightly loaded bearing by a life factor, $LF \approx 12$; for a heavily loaded bearing, $LF \approx 3.8$.

For most critical aerospace applications, retained austenite is limited to two-to-five percent. However, for non-critical applications, higher amounts of retained austenite are allowed or may, in some instances, be uncontrolled. Experience has suggested that lower values of retained austenite are preferable for reliable bearing operation.

Rolling element fatigue life increases with finer grain sizes. Prior austenite grain size should be ASTM No. 8 or finer, and that individual grains should not exceed ASTM No. 5. The higher the ASTM number, the smaller the grain size.

There is an interrelation among steel alloy content, median residual carbide size, number of residual carbide particles per-unit-area, percentage of residual carbide area, and rolling element fatigue life. The large carbides act as stress raisers to initiate an incipient crack that results in a rolling element fatigue spall. As the percentage of alloying elements increases in through-hardened bearing steel, the number and size of the carbides increase.

Case-carburized bearing steels, with the exception of M50 NiL, have a courser and larger carbide structure when compared to through-hardened bearing steels such as AISI 52100 or AISI M-50. However, this disadvantage is more than offset by the compressive residual stresses induced into the case by the carburization process. **PTE**

References

31. Zaretsky, E.V., R.J. Parker and W.J. Anderson. “Effect of Component Differential Hardness on Rolling Contact Fatigue and Load Capacity,” NASA TN D–2640, National Aeronautics and Space Administration, 1965, Washington, D.C.
32. Chevalier, J.L., M.W. Dietrich and E.V. Zaretsky. “Short-Term Hot/Hardness Characteristics of Rolling Element Steels,” NASA TN D–6632, National Aeronautics and Space Administration, 1972, Washington, D.C.
33. Chevalier, J.L., M.W. Dietrich and E.V. Zaretsky. (1973), “Hot/Hardness Characteristics of Ausformed AISI M–50, Matrix II, WD–65, Modified AISI 440–C and Super Nitralloy,” NASA TN D–7244, National Aeronautics and Space Administration, 1973, Washington, D.C.
34. Anderson, N.E. and E.V. Zaretsky. (1975), “Short-Term Hot-Hardness Characteristics of Five Case-Hardened Steels,” NASA TN D–8031, National Aeronautics and Space Administration, 1975, Washington, D.C.
35. Almen, J. O., “Effects of Residual Stress on Rolling Bodies,” *Rolling Contact Phenomena,* J. B. Bidwell, Ed., Elsevier, New York, 1962, pp. 400–431.
36. Gentile, A.J., E.F. Jordan and A.D. Martin. “Phase Transformations in High-Carbon, High-Hardness Steels Under Contact Loads,” *AIME Transactions, Vol. 233, No. 6*, 1965, pp. 1085–1093.
37. Gentile, A.J. and A.D. Martin. “The Effect of Prior Metallurgically Induced Compressive Residual Stress on the Metallurgical and Endurance Properties of Overload-Tested Ball Bearings,” 1965, ASME Paper 65–WA/CF–7.
38. Scott, R.L., R.K. Kepple and M.H. Miller. “The Effect of Processing-Induced Near-Surface Residual Stress on Ball Bearing Fatigue,” *Rolling Contact Phenomena*, J.B. Bidwell, Ed., Elsevier, 1962, pp. 301–316.
39. Zaretsky, E.V., R.J. Parker, W.J. Anderson and S.T. Miller. (1965), “Effect on Component Differential Hardness on Residual Stress and Rolling Contact Fatigue,” NASA TN D–3101, National Aeronautics and Space Administration, Washington, D.C.
40. Oswald, F.B., E.V. Zaretsky and J.V. Poplawski. “Relation Between Residual and Hoop Stresses and Rolling Bearing Fatigue Life,” Presented at the 2011 STLE Annual Meeting, May 15–Zaretsky, E.V., Poplawski, J.V., and Peters, S.M., (1996), “Comparison of Life Theories for Rolling element Bearings,” *STLE Tribology Trans.*, 39, 2, 2011, pp. 237–247, Discussion by E. Ioannides and T.A. Harris, pp.247–248; Authors’ reply, pp. 501–503.
41. Zaretsky, E.V., J.V. Poplawski and S.M. Peters. “Comparison of Life Theories for Rolling Element Bearings,” *STLE Tribology Trans.*, 39, *2*, 1996, pp. 237–247, Discussion by E. Ioannides and T.A. Harris, pp.247–248; Authors’ reply, pp. 501–503.
42. Zaretsky, E.V. “In Search of a Fatigue Limit: A Critique of ISO Standard 281:2007,” *Tribology & Lubrication Technology*, STLE, 66, 8, Aug. 2010, 2010, pp. 30–40.
43. ISO 281:2007. “Rolling Bearings: Dynamic Load Ratings and Rating Life,” International Organization for Standardization, 2007, Geneva.
44. Sakai, T. “Review and Prospects for Current Studies on Very-High-Cycle Fatigue of Metallic Materials for Machine Structure Use,” *Proc. 4th International Conference on Very High Cycle Fatigue (VHCF–4)*, TMS (The Minerals, Metals & Materials Society), 2007, pp. 3–12.
45. Sakai, T., M. Takeda, K. Shiozawa, Y., Ochi, M. Nakajima, T. Nakamura and Y. Oguma. “Experimental Reconfirmation of Characteristic S-N Property for High-Carbon- Bearing Steel in Wide Life Region in Rotating Bending,” *J. Soc. Mat. Sci.,* Japan, 49, 7, 2000, pp. 779–785 (in Japanese).
46. Tosha, K., D. Ueda, H. Shimoda and S. Shimizu. “A Study on P-S-N Curve for Rotating Bending Fatigue Test for Bearing Steel,” *STLE Tribology Trans.*, 51, 2, 2008, pp. 166–172.
47. Shimizu, S., K. Tsuchiya and K. Tosha. “Probabilistic Stress-Life (P-S-N) Study on Bearing Steel Using Alternating Torsion Life Test,” *STLE Tribology, Trans.*, 52, 6, pp. 807–816.
48. Johnston, G.B., T. Anderson, E.V. Amerongen and A. Voskamp. “Experience of Element and Full-Bearing Testing of Materials over Several Years,” *Rolling Contact Fatigue Testing of Bearing Steels*, ASTM STP–771, J.J.C. Hoo, Ed., American Society for Testing and Materials, Philadelphia, PA,1982, pp. 190–195.
49. Bush, J.J., W.L. Grube and G.H. Robinson. “Microstructural and Residual Stress Changes in Hardened Steel due to Rolling Contact,” *Rolling Contact Phenomena*, J.B. Bidwell, Ed., Elsevier, New York, 1962, pp. 365–399.
50. Muro, H. and N. Tsushima. “Microstructural Microhardness and Residual Stress Changes Due to Rolling Contact,” *Wear*, 15, 1970, pp. 309–330.
51. Zhu, D., F. Wang, Q. Cai, M. Zheng and Y. Cheng. “Effect of Retained Austenite on Rolling Element Fatigue and Its Mechanism,” *Wear*, 105, 1985, pp. 223–234.
52. Jones, A.B. “Metallographic Observations of Ball Bearing Fatigue Phenomena,” *Symposium on Testing of Bearings*, American Society for Testing and Materials, Philadelphia, PA, 1947, pp. 35–52.
53. Carter, T.L. “A Study of Some Factors Affecting Rolling Contact Fatigue Life,” NASA TR R–60, National Aeronautics and Space Administration, 1960, Washington, D.C.
54. Irwin, A.S., W.J. Anderson and W.J. and W.J. Derner. “Review and Critical Analysis: Rolling Element Bearings for System Life and Reliability,” NASA CR–174710, National Aeronautics and Space Administration, 1985, Washington, D.C.
55. Baughman, R.A. “Effect of Hardness, Surface Finish and Grain Size on Rolling Contact Fatigue Life of M–50 Bearing Steel,” *Jour. of Basic Engineering, ASME Trans.*, 82, 2, 1960, pp. 287–294.
56. Weinzapfel, N., F. Sadeghi and V. Bakolas. “An Approach for Modeling Material Grain Structure in Investigations of Hertzian Subsurface Stresses and Rolling Contact Fatigue,” *Jour. Of Tribology, Trans. ASME, 132*, Oct., 2010, pp. 041404–1–041404–12.
57. Pearson, P.K. and T.W. Dickinson. “The Role of Carbides in Performance of High-Alloy Bearing Steels,” *Effect of Steel Manufacturing Processes on the Quality of Bearing Steels*, ASTM STP–987, J.J.C. Hoo, Ed., American Society for Testing and Materials, Philadelphia, PA, 1988, pp. 113–131.
58. Bridge, J.E., G.N. Maniar and T.V. Philip. “Carbides in M–50 High-Speed Steel,” *Metallurgical Transactions*, 2, 1971, pp. 2209–2214.
59. Parker, R.J., E.V. Zaretsky and M.W. Dietrich. “Rolling Element Fatigue Lives of Four M Series Steels and AISI 52100 at 150° F,” NASA TN D–7033, National Aeronautics and Space Administration, 1971, Washington, D.C.
60. Parker, R.J., Zaretsky, E.V. and M.W. Dietrich. “Rolling Element Fatigue Lives of AISI T–1, AISI M-42, AISI 52100 and Halmo at 150° F,” NASA TN D–6179, National Aeronautics and Space Administration, 1971, Washington, D.C.
61. Chevalier, J.L. and E.V. Zaretsky. “Effect of Carbide Size, Area and Density on Rolling Element Fatigue,” NASA TN D–6835, National Aeronautics and Space Administration, 1972, Washington, D.C.
62. Chevalier, J.L., E.V. Zaretsky and R.J. Parker. “A New Criterion for Predicting Rolling Element Fatigue Lives of Through-Hardened Steels,” *Journal of Lubrication Technology*, 95, 3, 1973, pp. 287–297.
63. Parker, R.J, and E.N. Bamberger. “Effect of Carbide Distribution on Rolling Element Fatigue Life of AMS 5749,” NASA TP–2189, National Aeronautics and Space Administration, 1983, Washington, D.C.
64. Butterfield, S.A. and T.R. McNelley. “Porosity Associated with Insoluble Carbides in VIM–VAR AISI M–50 Steel and Its Effect on Rolling element Fatigue,” *Journal of Tribology*, 108, 3, 1986, pp. 352–358.

While **Erwin V. Zaretsky, PE,** is retired from his post as chief engineer/materials and structures, at the NASA Glenn Research Center, he remains a noted speaker, educator (Case Western Reserve University, University of Wisconsin/Milwaukee and Cleveland State University), writer (at least 180 technical papers and two books) and consultant to both government and industry. A 1957 graduate of the Illinois Institute of Technology in Chicago—and with a 1963 doctorate from Cleveland State University—Zaretsky is also a former head of the NASA Bearing, Gearing and Transmission Section, where he was responsible for most of the NASA mechanical component research for air-breathing engines and helicopter transmissions. With approximately a half-century of experience in mechanical engineering related to rotating machinery and tribology, Zaretsky has performed pioneering research in rolling-element fatigue, lubrication and probabilistic life prediction; his work resulted in the first successful 3 million DN bearing. Zaretsky is an adjunct professor at Case-Western Reserve University and is a member of the executive advisory board of the Northern Illinois University College of Engineering. In 1992 he edited and co-authored the STLE (Society of Tribologists and Lubrication Engineers) book, Life Factors for Rolling Bearings, as he had done previously, in 1997—Tribology for Aerospace Applications. Zaretsky is the recipient of numerous NASA awards for his contributions to the Space Program, among which are the NASA Medal for Exceptional Engineering Achievement, the NESC Director’s Award and the astronauts’ Silver Snoopy Award. In 1999 the STLE honored him with the Wilber E. Deutsch Memorial Award; he has also received four IR-100 awards. Zaretsky is a Life Fellow of the ASME and a Fellow of STLE.