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

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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). 

\[
LF = \exp\{m[(RC)_T - 60]\}
\]

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:

\[
(RC)_T = (RC)_{RT} - \alpha \Delta T^\beta
\]

where:

- \((RC)_T\) is the Rockwell C hardness at operating temperature; \((RC)_{RT}\) is the Rockwell C hardness at room temperature; \(\Delta T\) is the difference between operating temperature and room temperature; \(\alpha\) is a material constant, and \(\beta\) is a material exponent. Values of \(\alpha\) and \(\beta\) 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:

\[
LF = \exp\{0.1[(RC)_{RT} - 60] - a(T_l - T_{RT})^b]\}
\]

where:

- \(T_{RT}\) is 22°C (70°F). Equation 7 is benchmarked to a Rockwell C hardness equal 60
- \(L_l = 1\).

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 shear stress \(\tau_{max}\) for a given contact stress is decreased by the presence of a compressive residual stress \(\sigma_c\). This results in the following life factor due to residual stresses alone:

\[
LF = \left[\frac{\tau_{max}}{\tau_{\text{max}} - \frac{1}{2}c\sigma_c}\right]^{L_l}
\]

where:

- exponent \(c\) is typically 9.

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

From Figure 6, assume AISI 9310 as the bearing steel; the compressive residual stress \(\sigma_c\) is 200 MPa (29 ksi); from
Equation 8, for a lightly loaded bearing, 
\( LF = 12 \); for a heavily loaded bearing, 
\( LF = 3.8 \). 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 lim-
it” (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 bear-
ing 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 par-
ticular application (Refs. 41 and 42).

There are two problems associated 
with the use of a fatigue limit for bear-
ing 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-hard-
ened bearing steels such as AISI 52100 
and AISI M-50 (Refs. 41 and 42).

In 2007 Sakai (Refs. 44 and 45) pre-
sented stress/life rotating bending 
fatigue data from six different labora-
tories 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 \( \tau_{\text{max}} \) as low as 350 MPa (51 ksi) 
without an apparent fatigue limit.

In 2008, Tosha et al. (Ref. 46) 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 el-
ement bearing life prediction (Ref. 42). 
The results of these tests at maximum 
shearing stresses \( \tau_{\text{max}} \) as low as 500 MPa 
(76 ksi) produced fatigue lives in excess 
of 10 million (>107) stress cycles with-
out a fatigue limit. Shimizu, et al. (Ref. 
47) reported that the resultant 
fatigue life was inversely relat-
ed 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 speci-
ﬁed for the engine shaft diam-
eter (in a personal communica-
tion 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 mi-
crostructure 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 in-
stances, be uncontrolled. Expe-
rience 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 communi-
cation, 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 mate-
rial while at room temperature 
due to transformation of the retained 
austenite. The lost material had the 
appearance of a “skullcap” and the 
phe-nomenon 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-hard-
ened material, the amount of retained 
austenite increases with increasing 
material hardness. Experience has also
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 coarser 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 strength.
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.

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, $LF = 12$; for a heavily loaded bearing, $LF = 3.8$.

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 coarser 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.

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).


While Ervin V. Zaretsky, PE, is retired from his post as chief engineer/materials and structures, at the NASA Glenn Research Center, he remains a notated speaker, educator of the 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 has received 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.