Rolling Bearing Steels—A Technical and Historical Perspective - Part I

Erwin V. Zaretsky

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

Introduction

Jacob Rowe applied for a British patent in 1734 for a rolling element bearing. In his patent he defined the advantages of such a bearing:

(With the adoption of such bearings to) "...wheel carriages, one horse now will do the labor of two. And I will suppose that there will be occasion to employ only 20,000 horses ... instead of the 40,000 existing in the United Kingdom at an annual savings of 1,095,000 pounds per year."

B.W. Kelly (Ref. 1), in writing about Rowe, said that he "was not able to find historical records that reported such sudden prosperity had occurred. As a result, he concluded that that the cost for keeping a horse that was not working was as much as it was for one that was in fact working."

Things really have not changed in over 275 years.

The rolling bearing materials used in Rowe's era would have been wood, bronze and iron. Modern steel and metallurgy do not begin until about 1856 with the Bessemer process. In this process air is blown through molten pig iron to produce a relatively high grade of steel. This was followed 10 years later by the invention of open-hearth melting, which further improved quality and made steel far more accessible to industry. However, because heat treatment of steel was still an art known only to a few, most rolling-element bearings were probably made of unhardened steel. In 1879, British patent 869 was issued to J. Harrington and H. Brent for a hardened steel bushing—or inner shaft—fitted with a groove for balls. About the same time, Englishman W. Hillman constructed a machine for cutting balls from steel wire (Refs. 2 and 3).

In 1900, according to Stribeck (Ref. 4), the use of carbon and chromium steels for bearings gradually increased during the last quarter of the 19th century, as the need for bearings capable of reliably supporting heavy loads increased. He reported that water-hardened steel gave higher elastic limits and greater capacity than oil-hardened steel. In a discussion of the Stribeck paper, Hess (Ref. 4) presented chemical analyses of four bearing steels then in use. Hess stated that these bearing steels "harden throughout and (are) uniformly hard and tough where durability and long life are wanted." The chemistry of one of the French steels, No. 88, listed in the table, closely matches that of AISI 52100. This steel was first specified about 1920 and remains the most used bearing steel today (Refs. 2 and 3).

Starting about 1920 it becomes easier to track the growth of bearing materials technology. Until 1955, with few exceptions, comparatively little progress was made in this area. AISI 52100 and some carburizing grades (AISI 4320, AISI 9310) were adequate for most applications. Materials such as AISI 440 were available in those cases where improved corrosion resistance was required (Ref. 3). In one of the classic textbooks on bearing analysis, by Shaw and Macks (Ref. 5) in 1949, the only rolling element bearing steel discussed was AISI 52100. Even as recently as 1957, in another authoritative text written by Wilcock and Booser (Ref. 6), the authors made only incidental note of the fact that AISI 52100 is not useful over 177°C (350°F). And, according to Wilcock and Booser (Ref. 6), "For temperatures above 177°C (350°F), bearing manufacturers have made small lots of bearings of AISI M–l and AISI M–10 tool steels. These steels retain their hardness to temperatures approaching 538°C (1,000°F). Evidence available to date indicates that they operate satisfactorily, provided lubrication can be maintained."

As discussed by Bamberger (Ref. 2) of General Electric Company Engine Division, Cincinnati, Ohio, the catalyst to quantum advances in all high-performance materials, including those steels used for bearings, was the advent of the aircraft gas turbine engine. The impact of the gas turbine engine on the growth of the aircraft industry after the Second World War created unprecedented needs for better materials and designs for rolling element bearings. These needs included bearings for higher temperatures, higher speeds and greater loads. The continuously increasing thrust-to-weight ratio for the aircraft jet engines required the use of smaller and lighter bearings. The reliability of these bearings became a major consideration because of system and mission complexities, and because of the high costs involved (Refs. 2 and 3).

In order to assure long rolling bearing life and reliability for commercial, industrial and aerospace applications, the materials, lubricants and design variables must be carefully con-

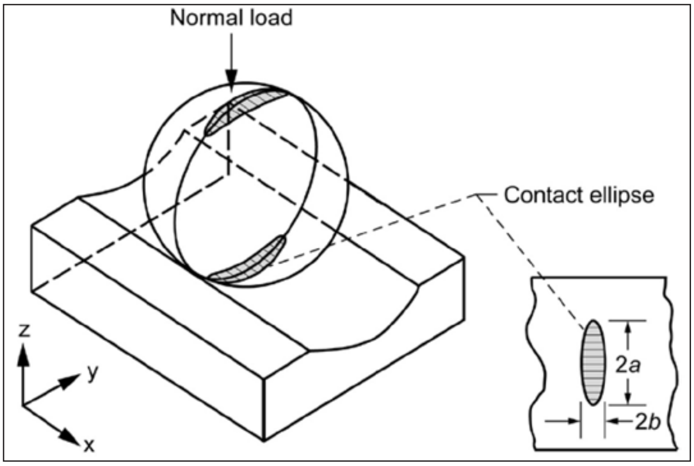


Figure 1 **Schematic of contact profile of ball on raceway; a and b = semi-widths of major and minor axes of Hertzian contact area, respectively.**

sidered and specified. The treatment of an alloy—from ore to finished bearing—can have a very significant effect on bearing performance, life and reliability. Experience has shown that different heats of the same material and process can produce life differences in the range of 2 to 1. It is therefore the objective of this paper to bring together and discuss—from both a technical and historical perspective—the chemical, metallurgical and physical aspects of bearing steels and their effect on rolling bearing life and reliability.

Bearing Life

Figure 1 is a schematic of the contact profile of a ball on a bearing race. Figure 2a shows the surface (Hertzian) stress distribution under the ball and the principal stresses at *z*—a critical location below the surface. Figure 2b shows the stress distribution below the surface. From these principal stresses the shearing stresses can be calculated.

Three shearing stresses can be applied to bearing life analysis: 1) orthogonal shearing stress—τ_o; 2) octahedral shearing stress— τ_{oct}; and 3) the maximum shearing stress—τ_{max}. The von Mises stress—which is not a shearing stress—has been inappropriately used by some investigators as a substitute for octahedral shearing stress τ_{oct}. All of these shearing stresses are a function of the maximum Hertz stress where:

$$\tau = k_1 S_{\max} \tag{1}$$

The proportionality constant k_1 is a variable related to the specific shearing stress, and the maximum Hertzian stress is the maximum value of the Hertzian stress distribution shown in Figure 2a. For ball bearings (point contact), $k_1 = 0.25$, 0.28 and 0.32 for orthogonal shearing stress τ_o; octahedral shearing stress τ_{oct}; and maximum shearing stress τ_{max}, respectively. For roller bearings (line contact), $k_1 = 0.25$, 0.29 and 0.30 for orthogonal shearing stress τ_o; octahedral shearing stress τ_{oct}; and maximum shearing stress τ_{max}, respectively.

For the analysis reported herein, only the maximum shearing stress is considered. The maximum shearing stress is one-half the maximum difference between the principal stresses:

$$\tau_{max} = \frac{\sigma_z - \sigma_x}{2} \tag{2}$$

Moyer and Zaretsky (Ref. 7) discuss in detail "failure modes related to bearing life." The ultimate failure mode limiting bearing life is classical rolling element fatigue of either a bearing race or rolling element. The failure manifests itself as a spall limited to the width of the running track and the depth of the maximum shearing stresses—a distance *z* below the contact surface where:

$$z = k_1 b \tag{3}$$

The proportionality constant k_2 is a variable related to the specific shearing stress, and *b* is the semi minor axis of the contact ellipse (Fig. 2). For ball bearings (point contact), $k_2 = 0.50$, 0.76 and 0.76 for orthogonal shearing stress τ_o; octahedral shearing stress τ_{oct}; and maximum shearing stress τ_{max}, respectively. For roller bearings (line contact), $k_2 = 0.50$, 0.79 and 079 for the orthogonal shearing stress τ_o; octahedral shearing stress τ_{oct}; and maximum shearing stress τ_{max}, respectively. The region or zone of maximum shearing stresses can be defined as the stressed volume beneath the Hertzian contact, ranging from a 0.50b to 0.79b depth below the stressed surface.

Generally, the spall begins in the region of maximum shearing stresses and propagates into a crack network. Most bearings, however, fail for other reasons. Failures other than those caused by classical rolling element fatigue are consid-

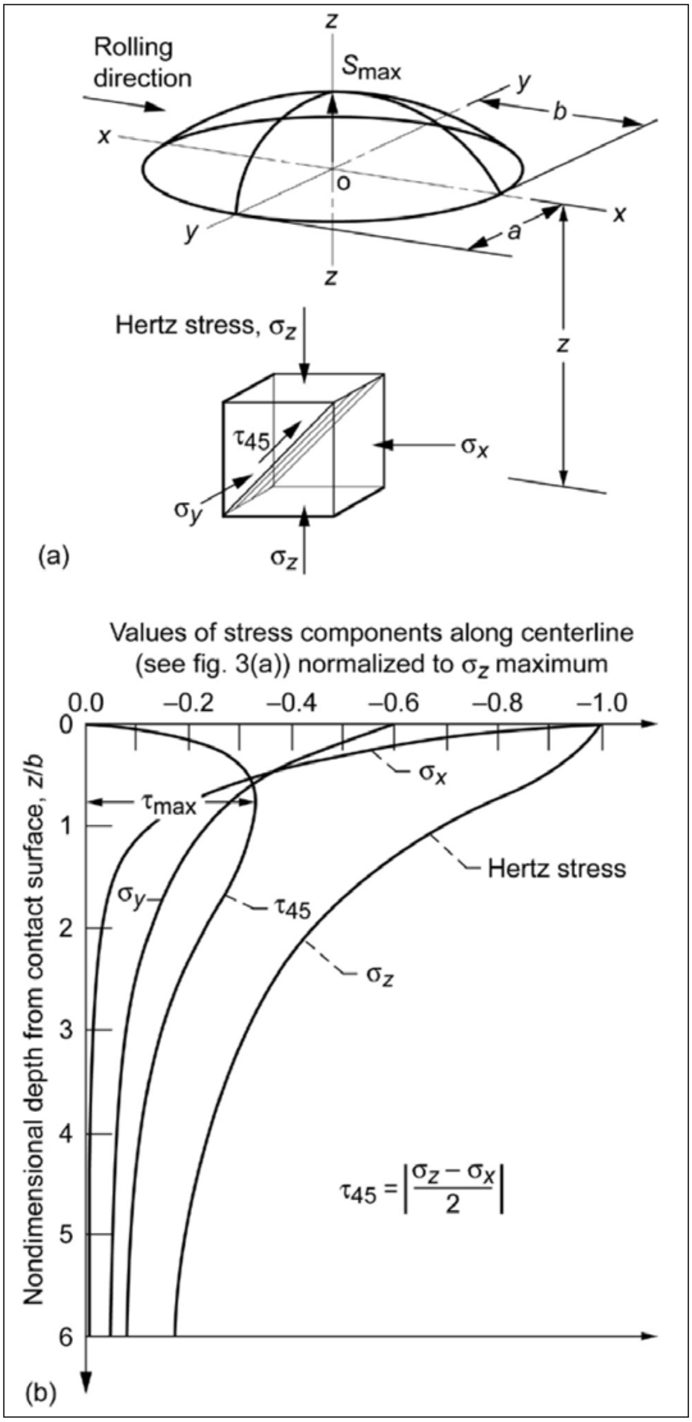
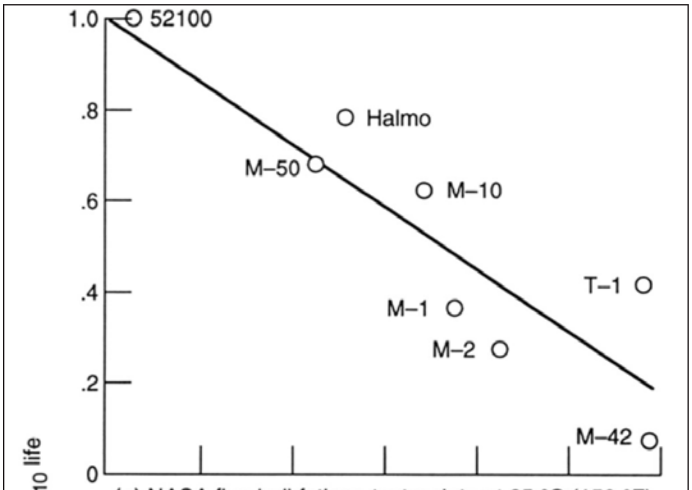


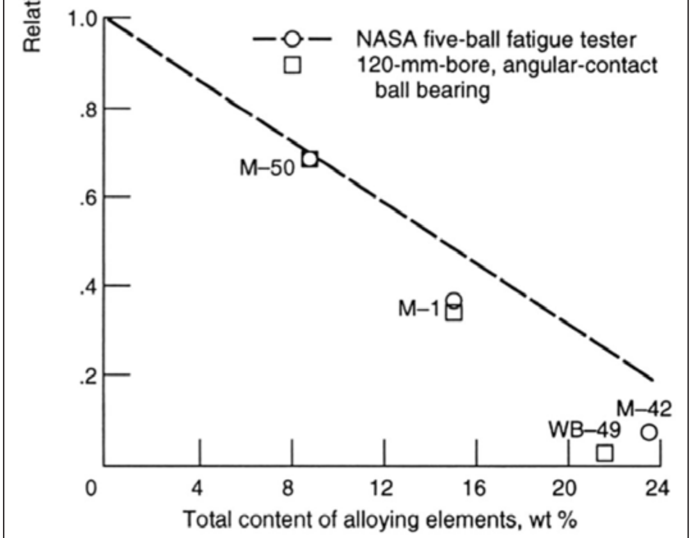
Figure 2 Sub-surface stress field under point contact. (a) Hertz stress distribution for ball on raceway showing principal stresses (σ = stress; τ = shear stress; and S_{max}, = maximum Hertz stress) at depth z below surface. (b) Distribution of principal and shearing stress as function of depth z/b below surface.

Table 1 Life factors for bearing steels (Ref. 3)

Material	Life factor, LF
Through-hardened steels	
AISI 52100	3
AISI M-10	2
AISI M-50	2
AISI T-1 (18-4-1)	2
Halmo	2
AISI M-1	.6
AISI M-2	.6
Corrosion-resistant steels	
AMS 5749 (BG-42)	2
AMS 5900 (CRB7)	2
AISI 440C	.6
Case-carburized steels	
AMS 6278 (VIM–VAR M50 NiL)	4
AISI 4620	3
AISI 8620	2
AISI 9310	2
CBS 600	2
Vasco X-2	2
CBS 1000	2
AISI 8720	1.5



(a) NASA five-ball fatigue tester data at 65 °C (150 °F).



(b) 120-mm-bore, angular-contact ball bearings at 315 °C (600 °F).

Figure 3 Rolling-element fatigue life as a function of total content of alloying elements tungsten, chromium, vanadium, molybdenum and cobalt (Ref. 17).

ered avoidable if the bearing is properly designed, handled, installed and lubricated and is not overloaded (Ref. 7).

Rolling element fatigue is extremely variable but is statistically predictable, depending on the steel type, steel processing, heat treatment, bearing manufacturing and type, and operating conditions. Sadeghi, et al. (Ref. 8) provide an excellent review of this failure mode.

Alley and Neu (Ref. 9) provide a recent attempt at modeling rolling element fatigue. With improved bearing manufacturing and steel processing, together with 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 (Ref. 3).

Based on the 1947 work by Lundberg and Palmgren (Refs. 10 and 11), who use the orthogonal shearing stress τ_o for their analysis, the life of a ball or roller bearing based on rolling element fatigue can be expressed in its most simplistic form as follows:

$$L_{10} = LF\left(\frac{C}{P}\right)^{p} \qquad (4)$$

Equation 4 is benchmarked to pre-1940 air melt AISI 52100 steel where $LF = 1$.

The L_{10} life, in millions of inner race revolutions, is the theoretical life that 90 percent of a bearing population should equal or exceed without failure at their operating load P. C is defined as the theoretical load that a bearing can carry for a life of one million inner-race revolutions with a 90 percent probability of survival. The load-life exponent is p. And, L_F is a life factor dependent on the bearing steel and its processing (Ref. 11).

Lundberg and Palmgren (Ref. 10) derive the load-life exponent p to be three for ball bearings and four for roller bearings. However, in their 1952 paper (Ref. 12), Lundberg and Palmgren modified their value of the load-life exponent p for roller bearings from four to 10/3. Their rationale for doing so was that various roller bearing types had one contact that is line contact and another that is point contact. They state that "as a rule the contacts between the roller and the raceways transform from a point to a line for some certain load, so that the life exponent varies from three-to-four for differing loading intervals within the same bearing." The ANSI/ABMA (Ref. 13) and ISO (Ref. 14) standards incorporate $p = 10/3$ for roller bearings. Computer codes for rolling element bearings incorporate $p = 4$ for roller bearings and $p = 3$ for ball bearings (Ref. 11).

Bearing lives determined by using Equation 4 with the values of C given in bearing manufacturers' catalogues are based on the "first evidence of fatigue." This can be a tiny spall that may not significantly impair the function of the bearing; thus, the actual useful life can be much longer. Society of Tribologists and Lubrication Engineers (STLE) life factors L_F for various bearing steels are given in Table 1 (Ref. 3). It can be reasonably assumed that these life factors are benchmarked to air melt AISI 52100 steel at a maximum Hertzian (contact) stress of 1.723 GPa (250 ksi). Table 2 provides the designation and chemistry of these and other representative bearing steels (Ref. 15).

Steel Chemistry

Through-hardened steels. In the 1950s and through the 1960s the bearing industry assumed that materials with higher alloy content would have better hardness retention at elevated temperatures. It was reasoned that this would also result in higher ambient-temperature hardness as well as longer bearing life. Based on this assumption steel companies and research laboratories within the United States began to develop bearing steels with higher alloy content.

It is necessary to compare these steel and processing variables in rolling-element fatigue tests and/or actual bearing tests. Standard mechanical tests, such as tension and compression tests or rotating-beam tests, could not be correlated with rolling-element fatigue results (Ref. 16). Accordingly, a series of studies to verify the effect of increased alloying elements on rolling-element fatigue life was undertaken by the author and his colleagues at the NASA Lewis Research Center (now NASA Glenn Research Center), Cleveland, Ohio (Refs. 17 and 18).

Figure 3a summarizes the results of rolling-element fatigue tests conducted in the NASA five-ball fatigue tester (Ref. 17). Previous studies by others did not maintain the close control of operating and processing variables, such as material hardness, melting technique, and lubricant type and batch—required for a completely unbiased material comparison (Ref. 18). These tests comprised three groups each of eight through-hardened bearing steels. There were a total of 720 tests. All of the specimens for the specified steel came from the same heat of material and were manufactured and heat treated to the same hardness at the same time; all other variables were also carefully controlled. Contrary to expectation, rolling-element fatigue life decreases with increasing total content of alloying element in the steel. When present in high percentages these alloying elements appear to significantly decrease rolling element fatigue life.

Additional work (Fig. 3b) was performed with 120-mm-bore, angular-contact ball bearings made from VAR AISI M–I, AISI M–42, AISI M–50, and WB–49 steels to verify the results in the NASA five-ball fatigue tester (Refs. 17 and 19). Bearings were tested at an outer-race temperature of 316°C (600°F). These four test series comprised a total of 120 bearings—or 30 for each steel. The magnitudes of the differences seen in these bearing tests at 316°C (600°F) correlate well with the results of five-ball fatigue tests that are also shown in Figure 3a. Using the AISI M–50 L_{10} life as a comparison, the AISI M–1 data from the five-ball fatigue tests and from the bearing tests agree remarkably well. WB–49 in the bearing tests and AISI M–42 in the five-ball fatigue tests, both of which alloys contain relatively high percentages of cobalt and have similar microstructures, show reasonably good agreement (Ref. 20).

These results completely changed previously held assumptions regarding the effect of bearing steel alloying elements on rolling-element fatigue life. As a result, by the mid-1980s AISI M-50 steel became the steel of choice for most high-temperature bearing applications over 149°C (300°F). For bearing temperatures less than 149°C (300°F), AISI 52100 steel with the lowest alloying content has a longer fatigue life and is probably the most widely used bearing steel throughout the world. These steels are usually heat treated to Rockwell C hardness at room temperature of not less than 60. At operating temperature, it is a general requirement that the operating hot hardness be greater than Rockwell C 58.

Carburizing-grade steels. Bearings are required to tolerate substantial damage progression without catastrophic fracture during the interval between the onset of a problem and when routine maintenance identifies the need for repair (Refs. 21 and 22). Material toughness provides this capability. Fracture toughness is the material property that defines the stress required to initiate rapid fracture in the presence of a local defect (e.g., a fatigue spall). Initial defect size substantially affects fracture characteristics, but is beyond the control of the designer. Tensile stresses, either application-induced or residual, are necessary for rapid fracture to occur. These are somewhat controllable by the designer, but advanced applications will require tolerance to increased stress (Ref. 3).

Table 2 Representative bearing and gear steels (Ref. 15)

Material			Alloying element, percent by weight (balance Fe)												
Common designation	**Description**	**Reference specifications**	**C**	**P (max)**	**S (max)**	**Mn**	**Si**	**Cr**	**V**	**W**	**Mo**	**Co**	**Nb**	**Ni**	**Other**
50100	Cr alloy steel	UNS G 50986; AISI E 50100; AMS 6442	1.00	0.025	0.025	0.35	0.25	0.50							
51100	Cr alloy steel	UNS G 51986; AISI E 51100; AMS 6440, 6444, 6447	1.00	.025	.025	.35	.25	1.00							
52100	Cr alloy steel	UNS G 52986; AISI E 52100; AMS 6440, 6444, 6447	1.00	.025	.025	.35	.39		1.45						
MHT	Al-modified bearing steel		1.03	.025	.025	.35	.35	1.50							1.36 A1
Halmo	Bearing steel		.56	.003	.008	.36	1.12	4.84	0.53		5.18				
M-1	High-speed tool steel	UNS T 11301; AISI M-1	.80	.030	.030	.30	.30	4.00	1.00	1.50	8.00				
M-2	High-speed tool steel	TINT 11302; AISI M-2	.83	.030	.030	.30	.30	3.85	1.90	6.15	5.00				
M-10	High-speed tool steel	UNS T 11310; AISI M-10	.85	.030	.030	.25	.30	4.00	2.00		8.00				
M-42	High-speed tool steel	UN S42T 11342; AISI M-	1.10	.012	.007	.15	.17	3.77	1.15	1.66	9.51	7.99			
M-50	High-speed tool steel	UNS T 11350; AISI M-50; AMS 6490, 6491	.80	.030	.030	.30	.25	4.00	1.00		4.25				
M50 NiL[a]	Carburized steel	AMS 6278	.13	.030	.030	.30	.25	4.00	1.20	4.25				3.50	
T-1(18-4-1)	High-speed tool steel	UNS T 12001; AISI T-1; AMS 5626	.70	.030	.030	.30	.25	4.00	1.00	18.0					
T-15	High-speed tool steel	UNS T 12015; AISI T-15	1.52	.030	.030	.26	.25	4.70	4.90	12.5	‘1.0	5.10			
440C	Hardenable Cr stainless steel	UNS S 44004; AISI 440C; AMS 5618, 5630, 5880, 7445	1.03	.018	.014	[b]1.0	.41	17.3	.14			.75			
AMS 5749	Martensitic stainless steel	UNS S 42700; AMS5749	1.15	.015	.010	.50	.30	14.5	1.20		4.00				[b].35 Cu
Vasco matrix II	Gear steel		.53	.014	.013	.12	.21	4.13	1.08	1.40	4.80	7.81		.10	
CRB-7	Bearing steel		1.10	.016	.003	.43	.31	14.0	1.03		2.02		.32		
AMS 5900	Martensitic stainless steel	UNS S 42800; AMS5900	1.10	.015	.010	.40	.30	14.0	1.00	2.00				[b].35	.25 Nb
9310[a]	Ni-Cr-Mo alloy steel	UNS G 93106; AISI 9310; AMS 6260, 6265, 6267	.10	.025	.025	.54	.28	1.18			.11			3.15	
CBS 600[a]	Alloy steel	UNS K 21940; AMS6255	.19	.010	.010	.61	1.05	1.50			.94			.18	.07 Al
CBS 1000[a]	Alloy steel		.14	.018	.019	.48	.43	1.12			4.77			2.94	
Vasco X-2[a]	Gear steel		.14	.011	.011	.24	.94	4.76	.45	1.40	1.40	.03		.10	
8620[a]	Ni-Cr-Mo alloy steel	UHS G 86200; AISI 8620; AMS 6274, 6276, 6277	.21	.035	.040	.80	.25	.50			.20			.55	
EX-53[a]	Gear steel		.10	.009	.006	.37	.98	1.05	.12	2.13	3.30				2.07 Cu
3310[a]	Alloy steel	UNS G 33106; AISI 3310	.11	.025	.040	.52	.22	1.58						3.50	
4320[a]	Ni-Cr-Mo alloy steel	UNS G 43200; AISI 4320	.20	.035	.040	.55	.25	.50			.25			1.82	
4620[a]	Ni-Mo alloy steel	UNS G 46200; AISI 4620; AMS 6294	.20	.035	.040	.55	.25				.25			1.82	
4720[a]	Ni-Cr-Ni alloy steel	AISI . UNS G 47200; 4720	.20	.035	.040	.55	.25	.45			.20			1.05	
Pyrowear 675	Carburized stainless steel		.07	.005	.003	.65	.40	13.0	.60		1.80	5.40		2.60	

[a] Carburized grades., [b] Maximum.

Through-hardened materials, heat treated to Rockwell C 60 hardness, as is typical with bearing components, have limited fracture toughness. The KIC is usually less than 24 MPa $m^{1/2}$ (22 ksi $in.^{1/2}$), depending upon heat treatment (Ref. 23). Materials with fracture toughness this low have limited bulk tensile stress capability if rapid fracture is to be avoided. A conservatively safe limit is 172.4 MPa (25 ksi). Applications requiring higher toughness will have to be made from a carburizing-grade steel (Ref. 3).

Carburizing-grade steels have reduced carbon content so that heat treatment normally results in moderate hardness and high toughness. High surface hardness, required for rolling-element bearing performance, is achieved by diffusing carbon into the surface, a process called carburizing, prior to heat treatment. Locally the steel is then a high-carbon alloy and is heat treatable to full hardness. The resulting structure has a surface layer with mechanical properties that are equivalent to those of traditional through-hardened bearing steels and a core that remains at low hardness, with corresponding high ductility and high fracture toughness. Surface-initiated defects (e.g., a spall) propagate cracks into the tough core before they reach critical size. The tough core prevents rapid and catastrophic fracture (Ref. 3).

Fracture toughness of a material is inversely proportional to its carbon content and hardness. The carbon content also determines hardness. Fracture toughness can be improved without affecting hardness by adding nickel. When present in high-chromium, low-carbon steels, nickel causes the steel to become fully austenitic above 875°C (1,605°F) where the steel is heat treated or carburized. Adding nickel also influences carbide size and distribution within the steel, which affects fatigue life. Recognizing this, Bamberger (Ref. 24) modified the chemistry of AISI M–50 steel by decreasing the amount of carbon and increasing the amount of nickel. He called this modified AISI M-50 steel M50 NiL (the "Ni" referring to increased nickel and the "L" to low carbon). The steel is also designated as Aerospace Material Specification (AMS) 6268.

M50 NiL, which is case carburized, has a core with a high fracture toughness KIC (over 60 MPa -$m^{1/2}$; 50 ksi-$in.^{1/2}$) than through-hardened AISI M-50 (29 MPa -$m^{1/2}$; 20 ksi-$in.^{1/2}$). The M50 NiL core hardness is Rockwell C 43 to 45. M50 NiL has finer carbides (compounds of carbon and various alloying elements) dispersed more evenly within its microstructure than standard AISI M–50. Compressive residual stresses in excess of 210 MPa (30 ksi) are induced in the zone of maximum resolved shear stresses during carburization of M50 NiL. These residual stresses combined with the fine carbide structure will increase its rolling-element fatigue life over that of conventional AISI M–50 (Ref. 25).

Many carburized gear steels are also used as bearing steels. These carburized steels are primarily used for tapered roller bearings or other bearings such as cylindrical roller bearings where tight interference fits are required between the bearing bore and shaft. A tight interference fit will induce large tensile (hoop) stresses in the bearing inner ring that can cause catastrophic fracture failure of the ring and the bearing. As with AISI 52100 steel, for temperatures less than 149°C (300°F), AISI 9310 and AISI 8620 are usually the materials of choice. However, for bearing operating temperatures greater than 149°C (300°F), M50 NiL is the steel of choice.

Corrosion-resistant steels. Although not normally a functional requirement, corrosion resistance is highly desirable because of its potentially large effect on life-cycle cost. Alloy steels with high chromium content, greater than 12 percent, are considered corrosion resistant. However, 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 (Ref. 3).

Available corrosion-resistant bearing alloys include AISI 440C and the high-temperature variations such as AISI 440C Mod, Aerospace Material Specification (AMS) 5749 (VIM–VAR BG-42), AMS 5900 (VIM–VAR CRB7) and Pyrowear 675. AISI 440C is widely used in instrument bearings and in bearings for food-processing equipment. In addition, AISI 440C is the traditional alloy chosen for use in cryogenic rocket engine turbo pumps such as those in the NASA Space Shuttle. AMS 5749 (VIM–VAR BG-42), AMS 5900 (VIM–VAR CRB7) and Pyrowear 675 are more recent developments (Ref. 3). For temperatures less than 149°C (300°F), AISI 440C is the corrosion-resistant steel of choice; for temperatures greater than 149°C (300°F), AMS 5749(BG-42) is the steel of choice.

Steel processing. In the early years of the bearing industry, acid- and base-refractory, air-melting methods were used to process steel. Major advances in steel producing have occurred, beginning with the 1950s by the introduction of vacuum-melting procedures. Vacuum processing reduces or eliminates the amount of nonmetallic inclusions, entrapped gases, and trace elements in structural alloys, resulting in substantially cleaner material. The two primary methods of vacuum processing are vacuum induction melting (VIM) and consumable-electrode vacuum melting (CEVM)—also called

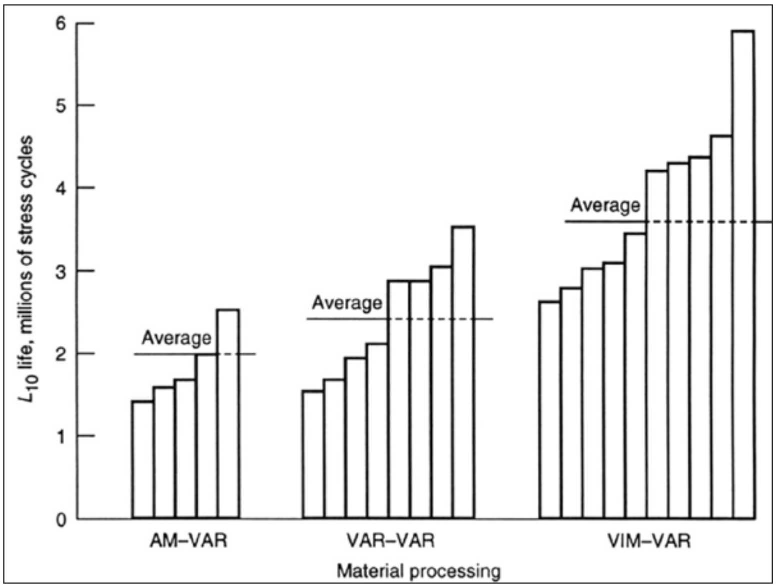


Figure 4 Rolling-element fatigue life of AISI M–50 steel in rolling-contact fatigue tester as a function of steel processing. Specimen diameter, 9.525 mm (3/8 in.); maximum Hertz stress, 4.8 GPa (700 ksi); speed, 12,500 rpm (Ref. 26).

Table 3 Life factors for melting practice (Ref. 3)

Processing	Life factor, LF
Air melting (AM)	1
Vacuum processing (VP) or carbon vacuum degrassing (CVD)	1.5
Vacuum are remelting (VAR)[a]	3
Electroflux remelting (EFR)[b]	3
Vacuum are remelting-vacuum are remelting (VAR–VAR)	4.5
Vacuum induction melting-vacuum are remelting (VIM–VAR)	6

[a] Also called consumable-electrode vacuum melting (CEVM).

[b] Also called electroslag remelting (ESR).

vacuum arc re-melting (VAR). In the early 1970s these two methods were combined, whereby the vacuum induction primary melt is vacuum arc re-melted. This method, called VIM–VAR, produces much cleaner steel than either VIM or CEVM individually (Ref. 26; Fig. 4).

Although CEVM and VIM–VAR are the primary methods used today to produce materials such as AISI M–50, other vacuum processing methods have been developed, primarily aimed at improving AISI 52100. The effect of melting practice on rolling-element fatigue life is shown by STLE life factors (*LF*) in Table 3 (Ref. 3). The product of the life factors for bearing steel from Table 1 and melting practice from Table 3 is used as a single life factor *LF* in Equation 1 to determine the bearing L_{10} life.

Vacuum processing of bearing steel increases bearing life by eliminating hard oxide inclusions that act as stress raisers to initiate incipient failure. This results in an unforeseen secondary benefit. The fatigue life of the bearing steel becomes more sensitive to a reduction in stress. That is, as contact load or (Hertzian) stress is decreased, bearing fatigue life is increased at a faster rate than with the air melted bearing steels.

As previously discussed, the load-life exponent p in Equation 1 is three for ball bearings and four for roller bearings, based on pre-1940 air melt AISI 52100 steel. However, a reevaluation of the load-life relation (Refs. 27 to 29) based on a summary of published data by R.J. Parker and E.V. Zaretsky (Ref. 30), suggests that for post-1960 vacuum processed bearing steels, the load life exponent p equals four and five for ball and roller bearings, respectively. This accounts for another significant improvement in rolling bearing life and reliability. **PTE**

(Part II of "Rolling Bearing Steels—A Technical and Historical Perspective," will appear in the April issue of *Power Transmission Engineering*.)

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