Impact of NASA-Sponsored Research on Aircraft Turbine Engine Bearing Specifications

A. H. Nahm

The current General Electric Premium Quality Bearing Materials Specifications and Design Practices for aircraft gas turbine engine bearings is the culmination of many years of R&D work and engine operational experience. The R&D investigations have been carried out as in-house work or as a cooperative approach among government agencies, academic and research communities,* and bearing and steel manufacturers. The GE bearing material specification (C50TF56), for example, requires double vacuum melting (VIM–VAR), certain hardness range, restricted grain size, forging flow conformity, precise control of chemical composition, etc.

For familiarization, a cutaway view of a typical high bypass turbofan engine is shown in figure 1. It has eight main engine bearings: two ball and six roller. The main thrust bearing runs at about 1.7×10^6 DN (168-mm bore $\times$ 10 000 rpm) with a cubic mean load of 2500 lb. (*DN* is a measure of bearing speed: the bore diameter, *D*, in millimeters, multiplied by the rotational speed in rpm.) Most main engine bearings manufactured in the U.S.A. are made with AISI M–50 material.

To present a historical background, figure 2 shows the evolutionary development of AISI M–50 as a major bearing material in aircraft gas-turbine engines. A significant improvement in bearing life has been achieved during the last two decades. The improvement may be a conservative estimate. Full-scale bearing tests indicated greater than 40 in the material life factor (ref. 1). Before the mid-1950's, AISI 52100 steel was a major bearing material in aircraft engines and is still in use today in some restricted engine applications.

The purpose of the present paper is to briefly review the advancement of the state-of-the-art in aircraft bearing materials technology. For more details on the subject, other reviews (e.g., refs. 2 and 3) are available. In the present paper, particular reference will be made to current specifications and design practices resulting from NASA-sponsored programs.

Melting Practice

One of the technical breakthroughs in materials engineering is the advent of the vacuum melting process in steel industries in the late 1950's to early 1960's. With the development of larger scale production melting furnaces, drastic improvement in micro- and macroscopic homogeneity and cleanliness was realized. This, consequently, resulted in a significant improvement in materials properties including rolling contact fatigue life. Macroscopic inhomogeneity is, for example, characterized by freckles, segregation, and casting structure. Microscopic cleanliness can be described in terms of the amount of inclusions and gas content. Carbide distribution and chemical composition can be favorably controlled by employing the vacuum melting process. Earlier studies, including those performed by NASA (refs. 4 to 7), showed that certain types and locations of inclusions strongly influence the rolling contact fatigue-life performance of bearing steels. In general, cleaner steels with less inclusions, gas elements, and trace elements will improve the fatigue life.

In fatigue life testing of 6309-size bearings, AISI 52100 bearing (ref. 8) inner races made from air melt and five successive vacuum consumable remelts of the same heat showed four times the fatigue life of those of air melted heats (fig. 3).

Currently, the bearing material for aircraft engines, AISI M–50 is being processed via a double vacuum melting process—vacuum induction melting (VIM) followed by vacuum arc remelting (VAR). Each process has its own advantages and disadvantages. It was recognized in the mid 1960's

*General Electric Company.

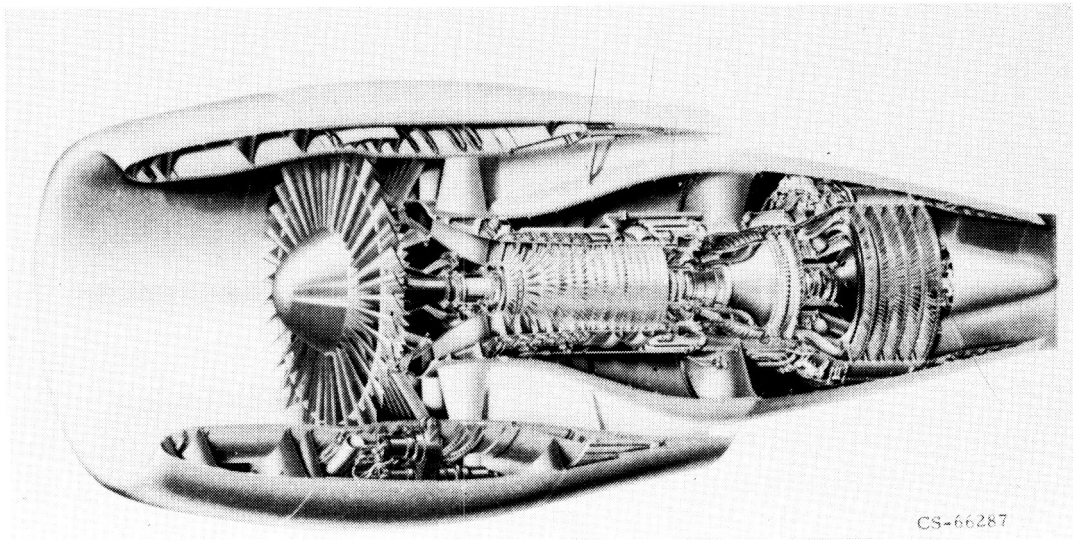

Figure 1. - Cutaway view of a typical high-bypass turbofan engine.

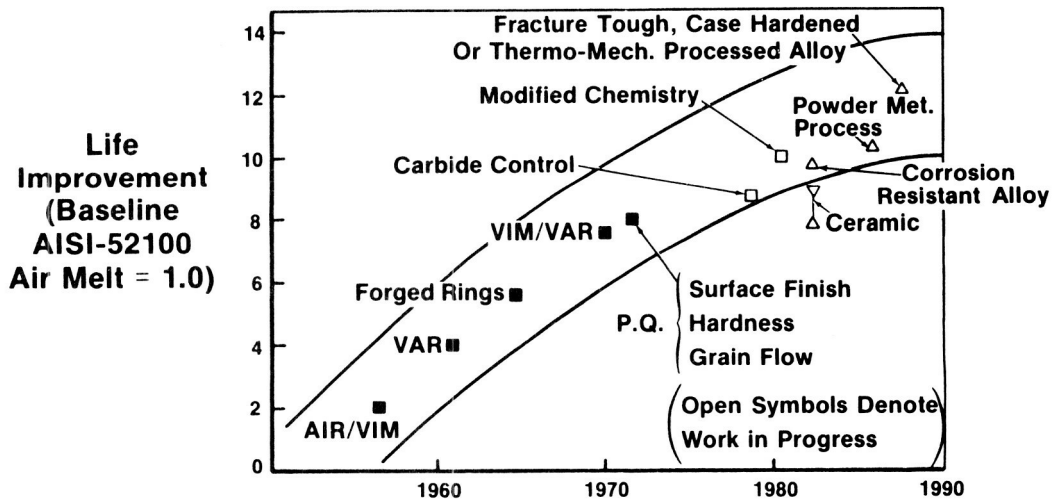

Figure 2. - Evolution of AISI M-50 bearing steel.

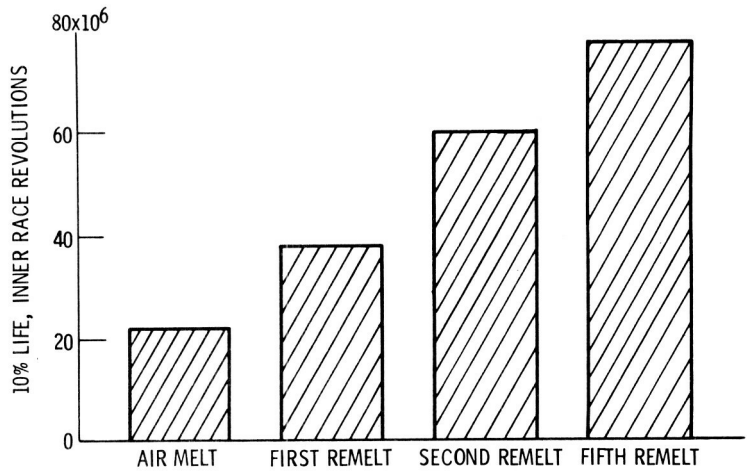

Figure 3. - Life of 6309-size bearing inner races made from air melt and successive consumable remelt of the heat AISI 52100 steel.

that the combination of these two processes produced an even better product by obtaining the advantages of both as well as eliminating the disadvantages of the first process (VIM). The two principal disadvantages of the VIM process are the reaction with crucibles and the solidification pattern developed in cast ingots. These limitations are largely eliminated in a subsequent vacuum arc remelting furnace (ref. 9). Figure 4 shows these processes.

In concurrence with the development of the large scale, commercial double vacuum melting facilities in the steel industry, General Electric, initiated an extensive evaluation of the melting processes using rolling contact (RC) fatigue rigs. Figure 5 shows a summary of the RC rig evaluation of air melted and vacuum arc remelted (AM-VAR), double vacuum arc remelted (VAR-VAR), and vacuum induction melted and vacuum arc remelted (VIM-VAR) heats. More than 20 heats of AISI M-50 were evaluated. The advantage of the VIM-VAR process in AISI M-50 is apparent in figure 5. Based on this, it was decided to standardize the VIM-VAR AISI M-50 material as the aircraft engine

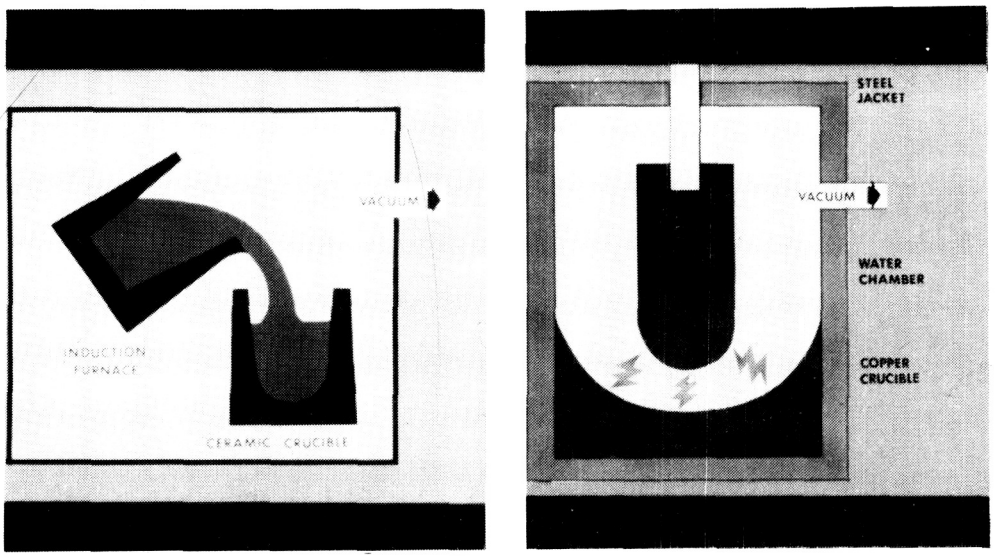

Figure 4. - Schematics of VIM (left) and VAR processes.

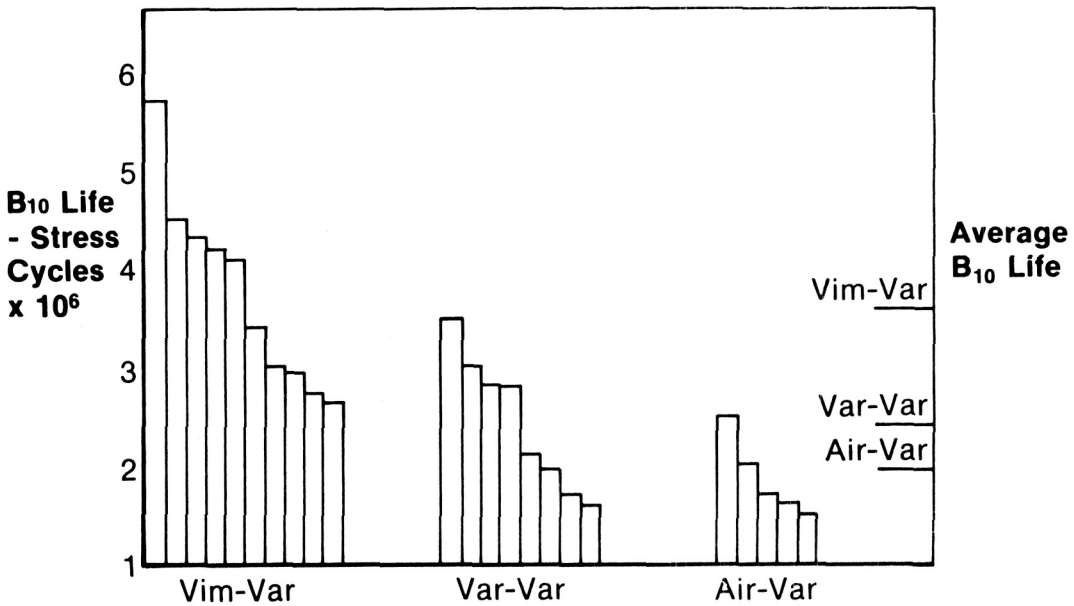

Figure 5. - RC rig evaluation of AISI M-50 melting procedures. (Each bar represents 20 tests.)

bearing material. However, full-scale bearing test data were not available to validate the advantages from the double vacuum melting process. To accomplish this, 120-mm-bore angular contact engine bearings were life tested as part of a series of NASA-GE-Industrial Tectonics, Inc., programs. The results showed that VIM-VAR AISI M-50 had at least five times the life of VAR AISI M-50 (ref. 10).

Forging Flow

One of the important variables affecting bearing life is the forging flow orientation with respect to rolling contact fatigue surfaces. Most bearing races and balls are manufactured by forging, which is known to influence the rolling contact fatigue life of bearings and gears. Figure 6 shows a view of macroetched cross sections of forged bearing races showing conforming and nonconforming grain flow.

An early experimental work by NASA performed on AISI 52100 balls using test rigs showed a significant improvement when rolling contact surfaces ran over areas other than the polar areas of forged balls (ref. 11). Another NASA work (ref. 12) was performed on AISI T-1 cylinders in test rigs to study the effect of forging flow on the rolling contact fatigue life. The cylinders, simulating bearing races, were machined from an AISI T-1 billet with the controlled forging flow orientation, 0°, 45°, and 90° to billet forging axis (see fig. 7). A trend toward increasing fatigue life was observed with transition from perpendicular to parallel forging flow.

Full scale bearing tests confirmed the above results (ref. 13). Bearings were manufactured with AISI 52100 steels having two different orientations. The bearings with side grains (parallel flow) showed at least 10 times the B-10 life when compared with the bearings with end grains (perpendicular flow). This is shown in figure 8.

Based on the findings from these investigations as well as other corroborating data from the author's in-house effort, the present GE bearing specifications require conforming forging (grain flow) for main shaft and other critical engine bearings.

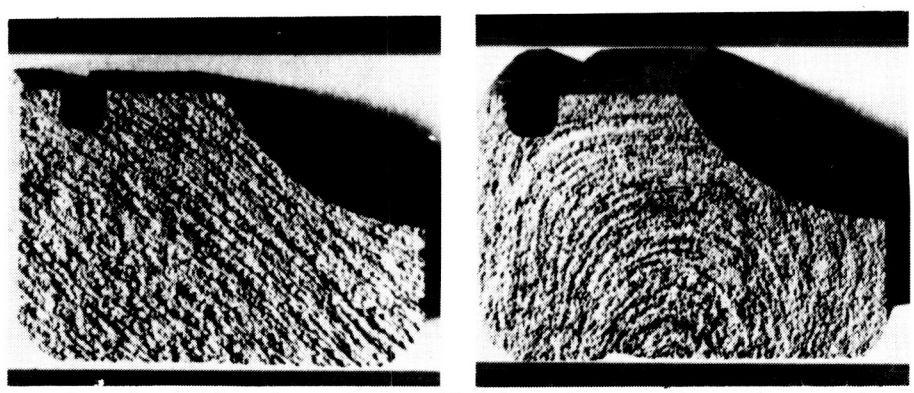

Figure 6. - Forged bearings showing (left) conforming fiber flow and (right) nonconforming fiber flow with respect to the raceway.

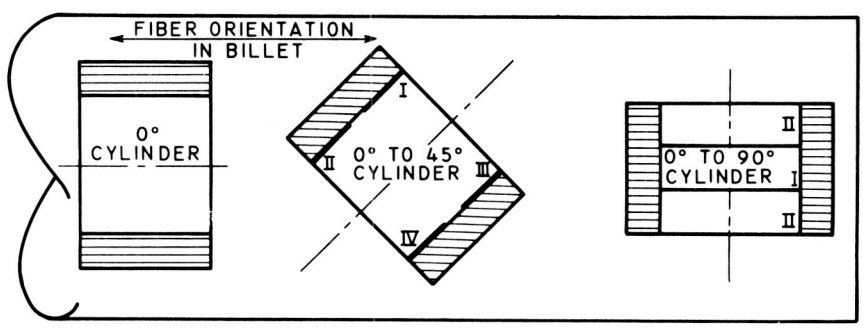

Figure 7. - T-1 tool steel cylinder orientation in billet stock.

Heat Treating Practice

Heat treating may be the most important process influencing the rolling contact fatigue life of bearing materials. Hardness, grain size, carbide morphology, retained austenite, and other microstructural features are determined mainly by heat treating.

Early studies including NASA's (refs. 4, 14 and 15) showed that hardness was the most critical variable in achieving the optimum life of bearing materials. The differential hardness concept for optimum life was also proposed in the 1960's (refs. 16 to 18). Figure 9 shows the results from 52100

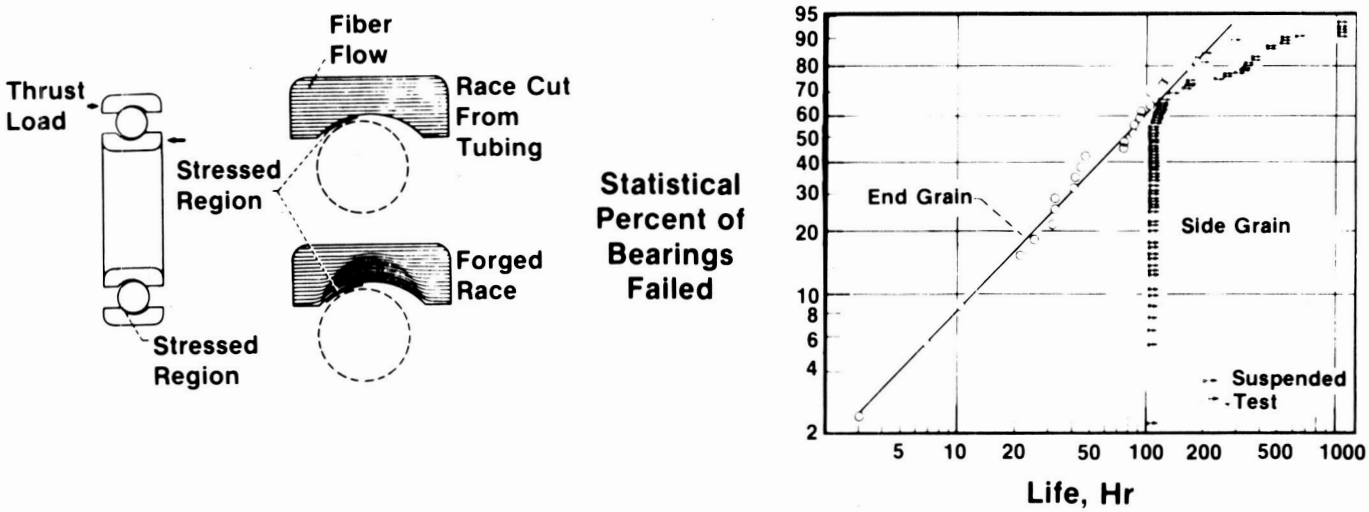

Figure 8. - Effect of end grain and side grain on bearing fatigue life for 140-mm-bore, angular-contact, ball bearing. MIL-L-7808 lubricant; thrust load 9500 lb; speed, 10 000 rpm; temperature, 250° F.

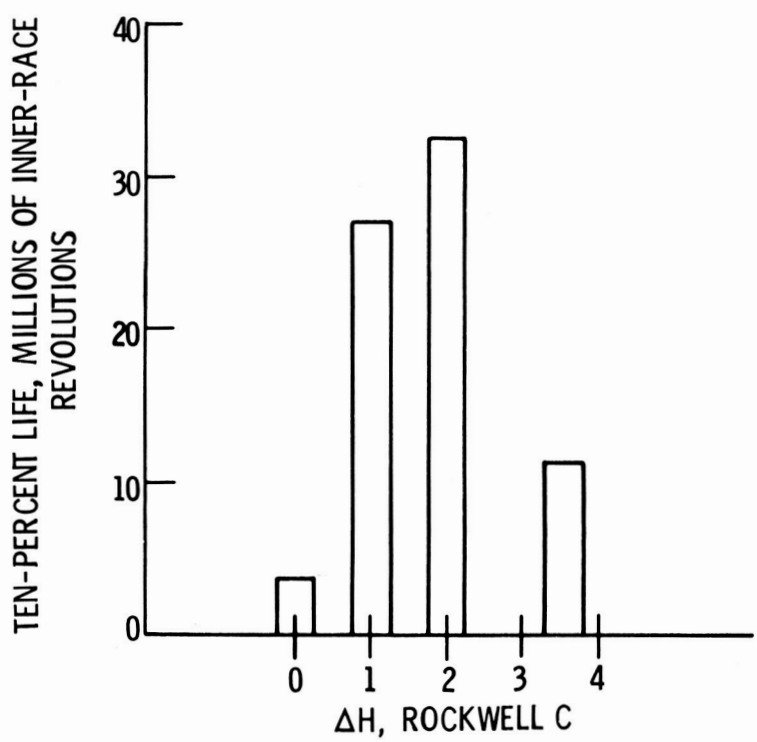

Figure 9. - 10-Percent life as function of difference in Rockwell C hardness of balls and races for AISI 52100 207-S size deep-groove ball bearings.

bearing tests (ref. 19), indicating a maximum life with a differential hardness of 1 to 2 in Rockwell C hardness (HRC) between race and rolling element. However, the beneficial effect of the differential hardness was not found in M-50.

In general, most aircraft engine manufacturers specify metallurgical characteristics resulting from the heat treating process rather than requiring specific heat treat cycles. This is because the required characteristics can be obtained only by an optimized heat treating process and can vary somewhat because of heat-to-heat variation or even a specific vendor's capabilities and facilities. Table 1 provides a typical heat treating cycle applied to VIM-VAR M-50. For example, the current General Electric Specification on bearing material M-50 specifies the following items:

- Rollers, balls, and races shall have an average hardness of HRC 62 to 64.
- All hardness values must be in the range of HRC 61 to 65.
- Retained austenite shall not exceed 3 percent as measured by X-ray diffraction analysis.
- Prior austenite grain size shall be ASTM #8 or finer. Individual grains shall not exceed ASTM #5.

High *DN* Bearing

Main shaft bearings in a typical high-technology engine operate at *DN* values to about 2.2 million; this is expected to approach 3 million in the coming decade. Figure 10 shows the evolutionary trend of increasing toward high *DN*, starting from the late fifties. The higher *DN* values are associated with improved performance and better fuel economy as well as lighter engine weight.

In anticipation and support of this trend, NASA launched an extensive R&D program in the area of high speed bearings with General Electric Company and Industrial Tectonics, Inc. The program

TABLE 1.—HEAT TREATMENT OF AISI M-50

Preheat:	816° C (1500° F) 15 min in salt
Austenitize:	1107° C (2025° F) 5 min in salt
Quench into:	566° C (1050° F) 10 min in salt
Temper:	524° C (975° F) 2 hr
Deep freeze:	—73° C (—100° F) 2 hr

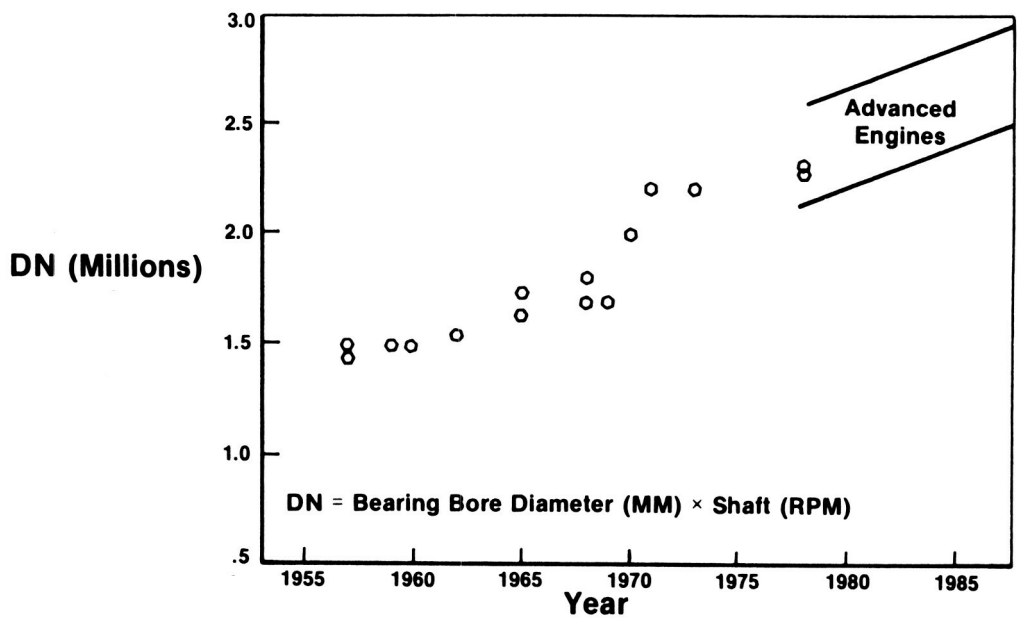

Figure 10. - Trend in aircraft engine main bearing DN.

title was "High DN Bearing Fatigue Investigation." Several modifications were made to maximize the program payoffs during the program period starting from May 1971 to February 1981. The objective was to obtain design information relating the effects of high rotational speeds (up to 25 000 rpm and 3×10^6 *DN*) on the fatigue life, thermal behavior, lubrication characteristics, and operational conditions of rolling element bearings. The bearings investigated were typical main shaft thrust bearings: thrust loaded, 120-mm-bore angular contact ball bearings.

Parametric information, which is a requisite for bearing design, was generated under varying thrust loads and speeds, bearing and lubricant temperatures, and lubricant flow rates (ref. 10). Endurance life tests were also performed at 3×10^6 *DN*. Main shaft bearings were successfully run at 3x106 DN. A B-10 life of more than 1000 hours was obtained, exceeding both the AFMBA catalog life of 16 hours and the ASME design guide prediction of 175 hours (ref. 1). This is shown in figure 11. During these endurance tests, it was found that two inner race failures exhibited cracking associated with fatigue spalling. When these cracks were opened up for inspection, it was observed that radial, inward propagation of the crack had occurred. This indicated a new mode of failure, race fracture at high rotational speeds. This was expected because of the significant tensile hoop stress, which develops in rotating races at high speed. Figure 12 shows the estimated tangential hoop stress as a function of bearing *DN* in a 120-mm bearing inner race (ref. 20). Figure 13 also schematically shows that bearing life will be decreased because of this new failure mode at high speed.

Consequently, it was decided in the NASA-GE-ITI program that the raceway fracture mode be verified in testing using 120-mm M-50 bearings at 3×10^6 *DN*. A bearing with an artificially induced defect in its raceway was installed in the high speed, high temperature fatigue tester. The bearing was run at 25 000 rpm (3×10^6 *DN*) with a thrust load of 5000 lb. The expected inner race spalling at the induced defect occurred after 6 hours and 17 minutes. Testing was continued until an obvious severe

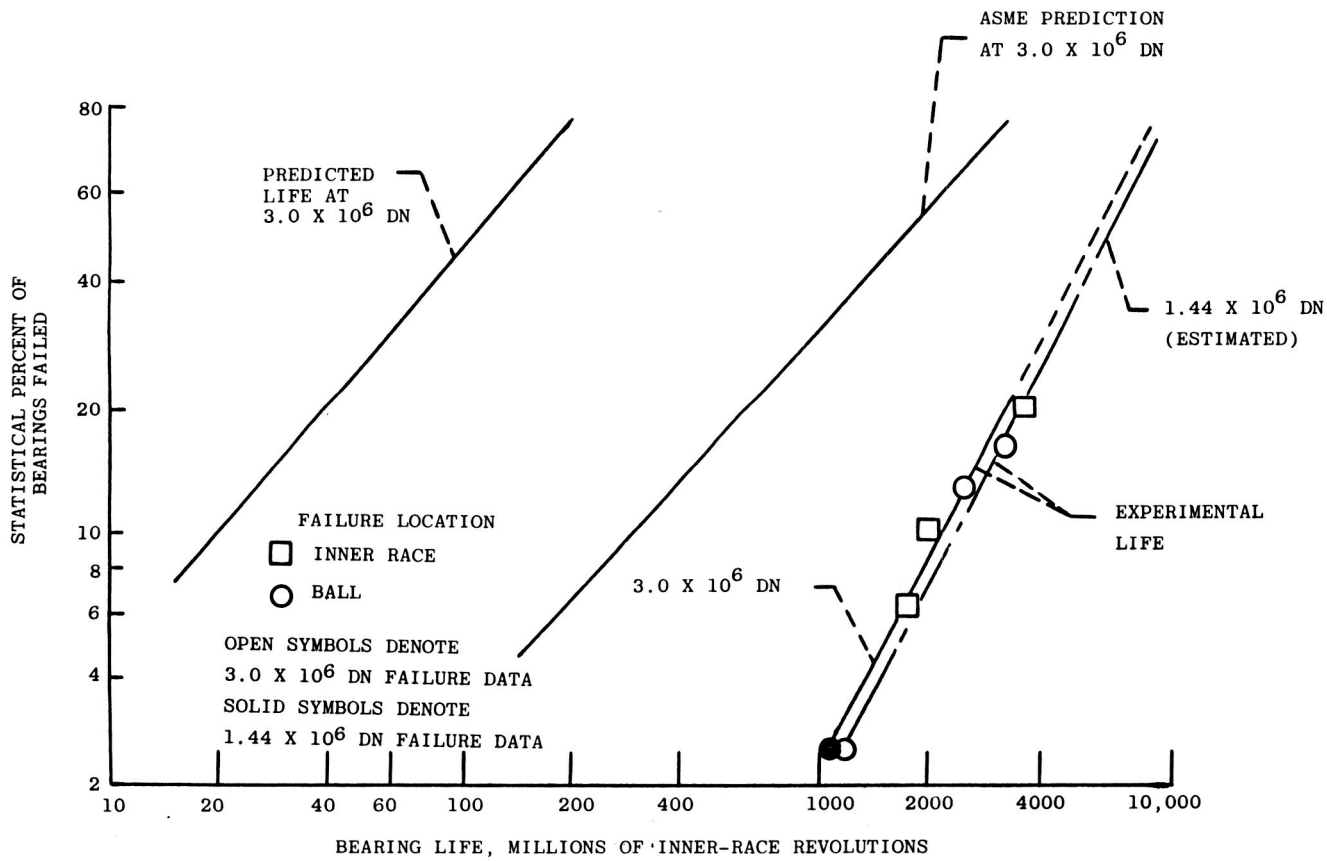

Figure 11. - Endurance characteristics of 120-mm-bore, angular-contact, ball bearings. Thrust load, 22 241 N (5000 lb); temperature, 492 K (425 F); material, AISI M-50 steel; lubricant, tetraester.

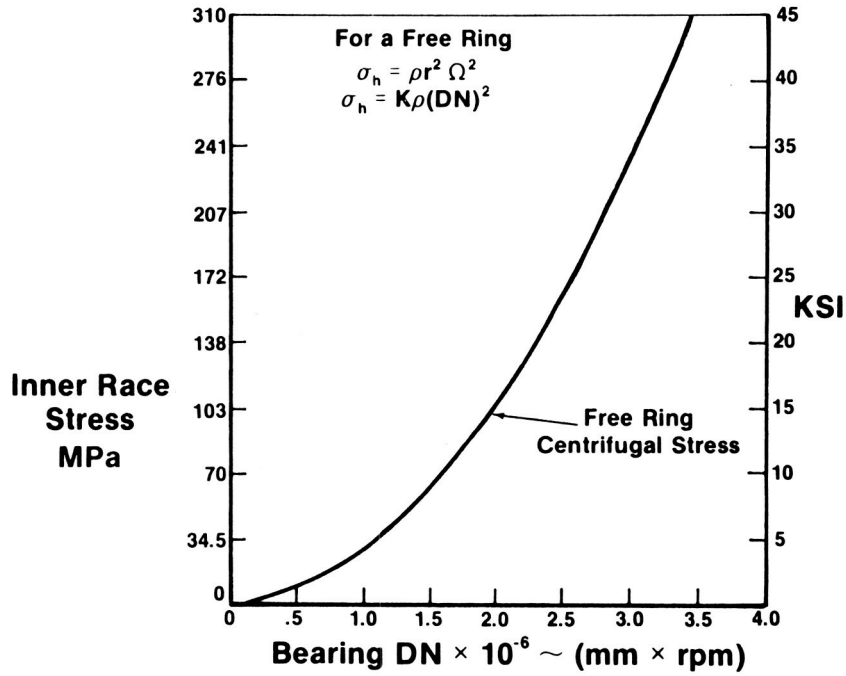

Figure 12. - Estimated inner race tangential stress versus bearing DN.

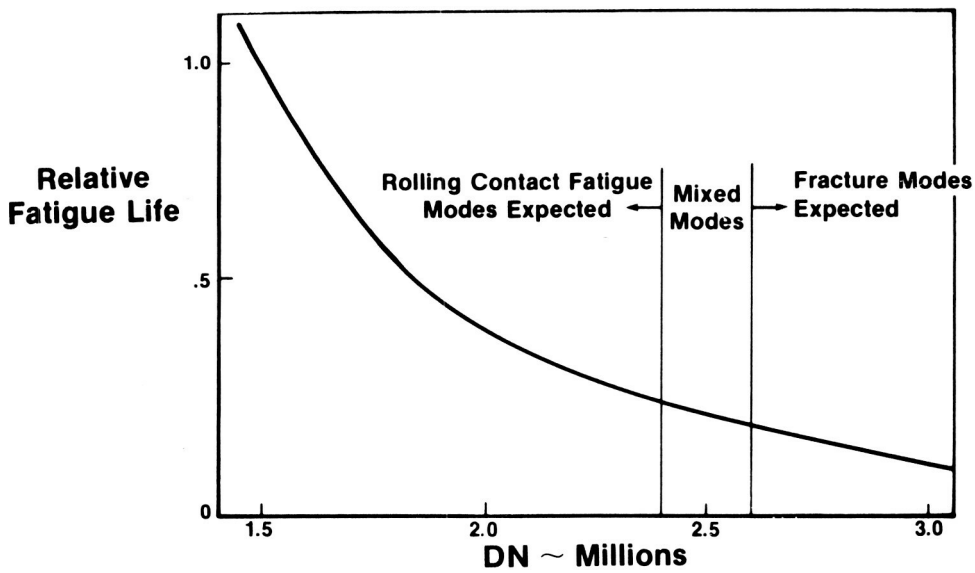

Figure 13. - Mainshaft bearing lives and expected failure mode as function of speed for a constant bore.

fragmentation fracture occurred to the inner race, terminating the test, 7.5 minutes after detection of the spalling. Post test examination showed that the inner race had fractured into eight discrete segments (fig. 14). The results of this are described in detail in reference 1. Because of this potential failure mode, GE (ref. 20) is currently limiting engine design up to the bearing speed of 2.4×10^6 *DN*. This remains in effect until a new material/process/design bearing becomes available. One way of mitigating this technical barrier is to utilize a bi-hardness (carburized) raceway in which the case structure will provide rolling contact fatigue life while the core will provide toughness. Work is continuing in this area.

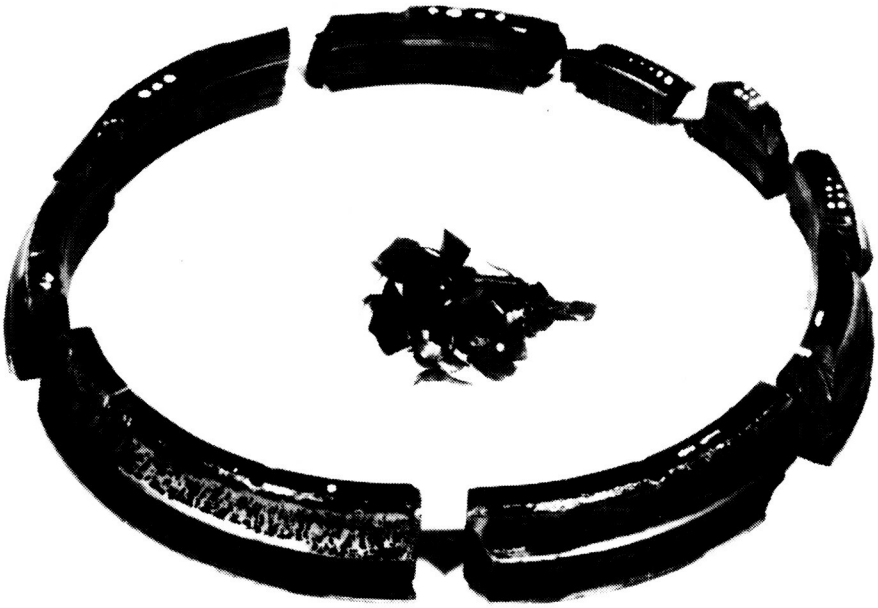

Figure 14. - Fractured bearing inner race initiated by a rolling-element fatigue spall.

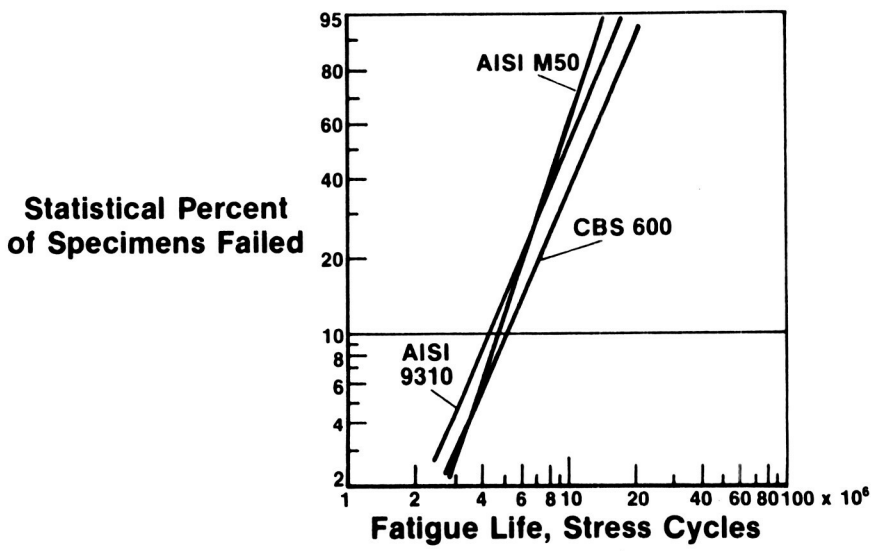

Figure 15. - Summary of rolling-element fatigue life data of CBS 600, AISI M-50, and CVM AISI 9310.

Alternate Materials

To overcome the technical challenges mentioned previously, fracture toughness and longer life in aircraft engine bearings, new processes, and materials other than M-50 may have to be utilized. Advanced engines may require more sophistication of the bearing, its support, and its mounting system.

General Electric has been working on a NASA sponsored program to evaluate the rolling contact fatigue life performance of various materials and processes (ref. 21). It was found that alloys, such as CBS600, AISI 9310, CBS1000, etc., had the equivalent rolling contact fatigue capability of M-50 (fig. 15). Based on this information, aircraft engine bearings using other materials can be considered;

for example, mounting or supporting brackets could be made integral with bearings made from case carburized material. This would be extremely difficult to achieve with through-hardened M-50 because of the difficulty involved in the final machining operation of the geometrically complex shape of a bearing system.

Typical chemical compositions of candidate bearing and gear steels are given in table 2. It is interesting that T-1 (18-4-1) is equivalent to M-50 in the rolling contact fatigue life comparison (ref. 22), as shown in figure 16. The T-1 material is widely used for bearings by British and European aircraft engine manufacturers.

TABLE 2.—TYPICAL CHEMICAL COMPOSITIONS OF SELECTED BEARING STEELS

Alloying Elements (% By Weight)

Designation	C	P (max)	S (max)	Mn	Si	Cr	V	W	Mo	Co	Cb	Ni
SAE 52100	1.00	0.025	0.025	0.35	0.30	1.45	—	—	—	—	—	—
MHT*	1.03	0.025	0.025	0.35	0.35	1.50	—	—	—	—	—	—
AISI M-1	0.80	0.030	0.030	0.30	0.30	4.00	1.00	1.50	8.00	—	—	—
AISI M-2	0.83	0.030	0.030	0.30	0.30	3.85	1.90	6.15	5.00	—	—	—
AISI M-10	0.85	0.030	0.030	0.25	0.30	4.00	2.00	—	8.00	—	—	—
AISI M-50	0.80	0.030	0.030	0.30	0.25	4.00	1.00	—	4.25	—	—	—
T-1 (18-4-1)	0.70	0.030	0.030	0.30	0.25	4.00	1.00	18.0	—	—	—	—
T15	1.52	0.010	0.004	0.26	0.25	4.70	4.90	12.5	0.20	5.10	—	—
440C	1.03	0.018	0.014	0.48	0.41	17.30	0.14	—	0.50	—	—	—
AMS 5749	1.15	0.012	0.004	0.50	0.30	14.50	1.20	—	4.00	—	—	—
Vasco Matrix II	0.53	0.014	0.013	0.12	0.21	4.13	1.08	1.40	4.80	7.81	—	0.10
CRB-7	1.10	0.016	0.003	0.43	0.31	14.00	1.03	—	2.02	—	0.32	—
AISI 9310(C)	0.10	0.006	0.001	0.54	0.28	1.18	—	—	0.11	—	—	3.15
CBS 600(C)	0.19	0.007	0.014	0.61	1.05	1.50	--	--	0.94	—	—	0.18
CBS 1000M(C)	0.14	0.018	0.019	0.48	0.43	1.12	—	—	4.77	—	—	2.94
Vasco X-2(C)	0.14	0.011	0.011	0.24	0.94	4.76	0.45	1.40	1.40	0.03	—	0.10

* Also Contains 1.36% Al
C - Carburizing Grades

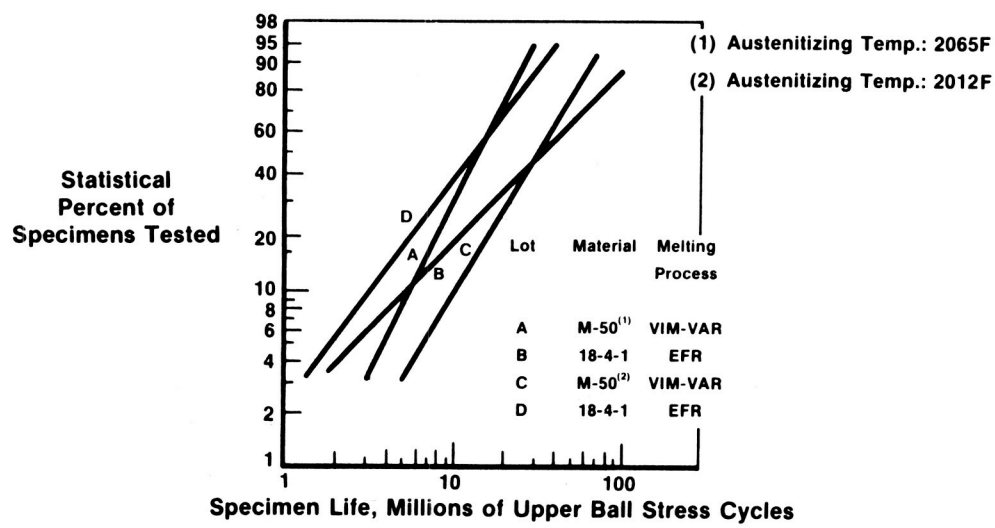

Figure 16. - Rolling-element fatigue life of VIM-VAR AISI M-50 and EFR 18-4-1 steel balls in five-ball fatigue tester. Maximum Hertz stress, 5520×10^6 Pa (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°; temperature, 65° C (150° F).

The ASME Design Guide (ref. 23) has become an underlying universal practice in aircraft engine bearing design. References cited in this document show that NASA has had a significant role in the contribution in this area of technology.

Summary

An attempt is made to briefly review the aircraft engine bearing materials and to discuss some of the impact made from a cooperative and collaborative effort among parties involved, such as government agencies, academic communities, steel companies, research institutes, and users (aircraft engine manufacturers). NASA's impact on the GE bearing design and specifications has been mentioned as an example. Without this concentrated and coordinated effort, the success we are enjoying in current gas-turbine-engine technology would be impossible. This team approach is important and must be continued to advance technology, to achieve improved performance, and to achieve better efficiency and reliability.

References

1. Bamberger, E. N.; Zaretsky, E. V.; and Signer, H.: Endurance and Failure Characteristic of Main-Shaft Jet Engine Bearing at 3×10^6 DN. J. Lubr. Technol., vol. 98, Series F, No. 4, Oct. 1976.
2. Bamberger, E. N.: Materials for Rolling Element Bearings. Bearing Design—Historical Aspects, Present Technology and Future Problems. ASME Century 2 Publication #H00160.
3. Anderson, W. J.; Zaretsky, E. V.: Rolling Element Bearing—A Review of the State-of-the-Art. NASA TM X-71441, 1973.
4. Jackson, E. R.: Rolling Contact Fatigue Evaluations of Bearing Materials and Lubricants. ASLE Trans., vol. 2, no. 1, 1959, pp. 121-128.
5. Carter, T. L.: A Study of Some Factors Affecting Rolling Contact Fatigue Life. NASA TR R-60, 1960.
6. Carter, T. L.; Butler, R. H.; Bear, H. R.; and Anderson, W. S.: Investigation of Factors Governing Fatigue Life with the Rolling Contact Fatigue Spin Rig. ASLE Trans., vol. 1, no. 1, Apr. 1958, pp. 23-32.
7. Johnson, R. F.; and Sewell, J. F.: The Bearing Properties of 1 Percent C-Cr Steel as Influenced by Steelmaking Practice. J. Iron and Steel Inst., vol. 196, pt. 4, Dec. 1960, pp. 414-444.
8. Morrison, T. W.; Tallian, T.; Walp, H. O.; and Baile, G. H.: The Effect of Material Variables on the Fatigue Life of AISI 52100 Steel Ball Bearings. ASLE Trans., vol. 5, no. 2, Nov. 1962, pp. 347-364.
9. Schlatter, R.: Vacuum Melting of Specialty Steels. J. Metals, April 1970.
10. Signer, H.; Bamberger, E. N.; and Zaretsky, E. V.: Parametric Study of the Lubrication of Thrust Loaded 120 mm Bore Bearings to 3 Million DN. J. Lubr. Technol. July 1974, pp. 515-526.
11. Butler, R. H.; Bear, H. R.; and Carter, T. L.: Effect of Fiber Orientation on Ball Failures Under Rolling Contact Conditions. NASA TN 3933, 1957.
12. Carter, T. L.: Effect of Fiber Orientation in Races and Balls Under Rolling Contact Fatigue Conditions. NASA TN 4216, 1958.
13. Zaretsky, E. V.: The Changing Technology of Rolling Element Bearings. Machine Des., vol. 38, no. 24, Oct. 13, 1966, pp. 206-223.
14. Baughman, R. A.: Effect of Hardness, Surface Finish and Grain Size on Rolling Contact Fatigue Life of M-50 Bearing Steel. J. Basic Eng., vol. 82, no. 2, June 1960, pp. 287-294.
15. Carter, T. L.; Zaretsky, E. V.; and Anderson, W. J.: Effect of Hardness and Other Mechanical Properties on Rolling Contact Fatigue Life of Four High-Temperature Bearing Steels. NASA TN D-270, 1960.
16. Scott, D.; and Blackwell, J.: Study of the Effect of Material and Hardness Combinations in Rolling Contact. Proc. Inst. Mech. Eng., vol. 180, 1965-66, pp. 32-36.
17. Zaretsky, E. V.; Parker, R. J.; Anderson, W. J.; and Reichard, D. W.: Bearing Life and Failure Distribution as Affected by Actual Component Differential Hardness. NASA TN D-3101, 1965.
18. Zaretsky, E. V.; Parker, R. J.; and Anderson, W. J.: Component Hardness Differences and Their Effect on Bearing Fatigue. J. Lubr. Technol., vol. 89, no. 1, Jan. 1967, pp. 47-62.
19. Irwin, A. S.: Effect of Bearing Temperatures on Capacities of Bearing of Various Materials. Paper Presented at ASME Third Spring Lubrication Symposium, New York, N.Y., March 14-15, 1960.
20. Clark, J. C.: Fracture Failure Modes in Lightweight Bearings. J. Aircr., vol. 12, no. 4, Apr. 1975.
21. Nahm, A. H.: Rolling Element Fatigue Testing of Gear Materials. NASA CR-135411 and CR-135450, 1978.
22. Parker, R. J.; and Zaretsky, E. V.: Rolling Element Fatigue Life of AISI M-50 and 18-4-1 Balls. NASA TP-1202, 1978.
23. Bamberger, E.N.; et al.: Life Adjustment Factors for Ball and Roller Bearings—An Engineering Design Guide, ASME, New York, 1971.