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Bearing and Gear Steels for Aerospace Applications

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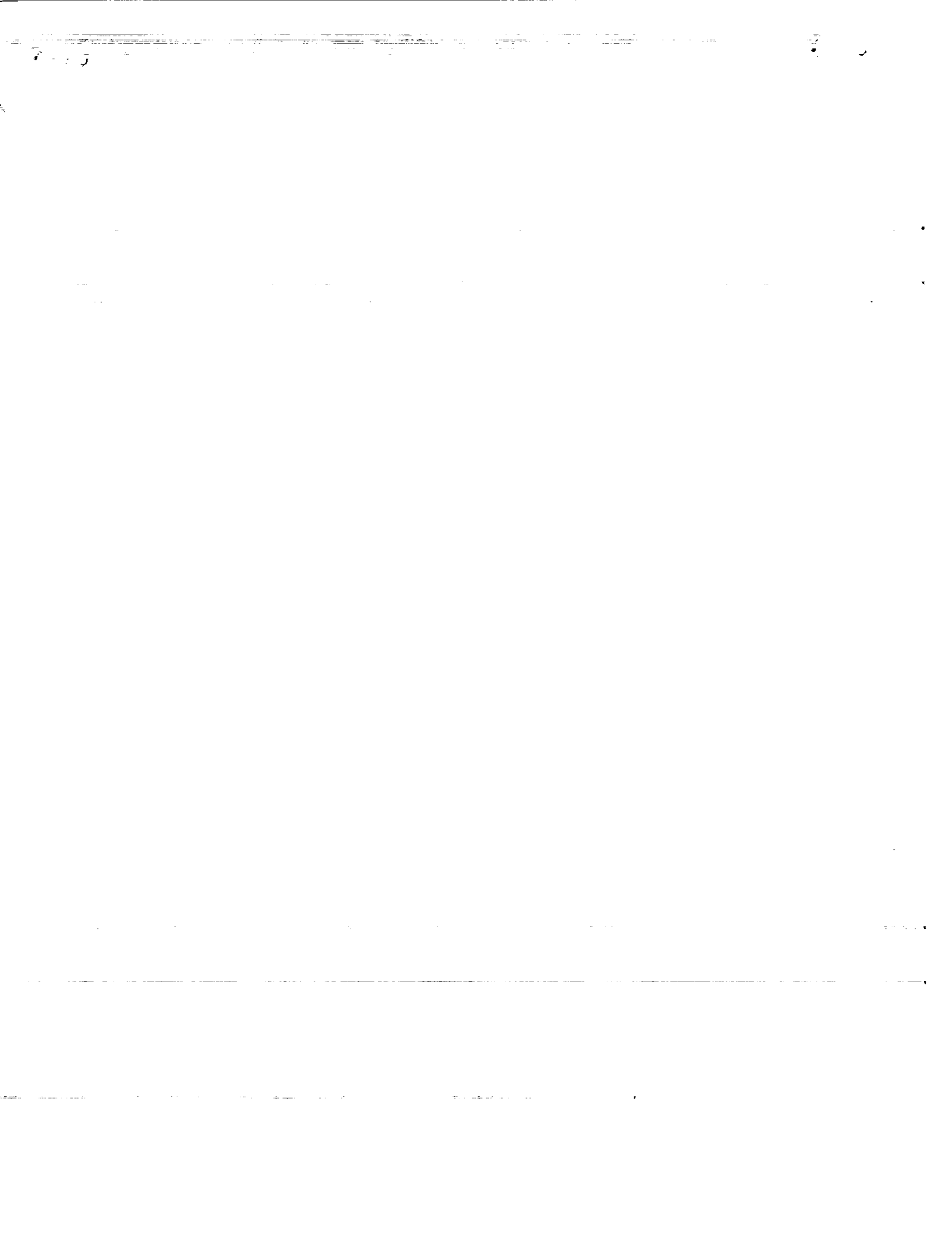
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BEARING AND GEAR STEELS FOR AEROSPACE APPLICATIONS

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ABSTRACT

Research in metallurgy and processing for bearing and gear steels has resulted in improvements in rolling-element bearing and gear life for aerospace applications by a factor of approximately 200 over that obtained in the early 1940's. The selection and specification of a bearing or gear steel is dependent on the integration of multiple metallurgical and physical variables. For most aerospace bearings, through-hardened VIM-VAR AISI M-50 steel is the material of preference. For gears, the preferential material is case-carburized VAR AISI 9310. However, the VAR processing for this material is being replaced by VIM-VAR processing. Since case-carburized VIM-VAR M-50NiL incorporates the desirable qualities of both the AISI M-50 and AISI 9310 materials, optimal life and reliability can be achieved in both bearings and gears with a single steel. Hence, this material offers the promise of a common steel for both bearings and gears for future aerospace applications.

INTRODUCTION

Research in steel metallurgy and processing has resulted in significant improvements both in bearing and gear life over that obtained in the early 1940's. For critical applications such as aircraft, these improvements have resulted in longer lived, more reliable commercial and military aircraft engines. As an example, in the early 1950's, a jet engine's life was limited by those of the rolling-element bearings which was usually 300 hr. Today

these bearings have lives in excess of 30 000 hr. In the 1960's, the improvements in bearing steel technology began to be applied to gear steels used in accessory gearbox drives in aircraft engines and in helicopter transmissions. The need for improved helicopter transmission systems became to gear steel technology what the jet engine had become to bearing steel technology. Fortunately, it was a matter of applying to gear steels the improvements already present in bearing steels.

A chart showing the major advances contributing to these life improvements is shown in Fig. 1. (Refs. 1 and 2).

Starting in the early 1940's, new developments in the making of bearing steels began. The improved steel-making developments were primarily initiated by the acceptance of a comprehensive material specification for AMS 6640 and AISI 52100 steel (A, Fig. 1). New heat-treatment equipment became available in 1941 which incorporated improved temperature controls and recorders. The use of neutral atmospheres during heat treatment eliminated, for all practical purposes, surface decarburization (B, Fig. 1).

As the requirement for bearing steel increased, large electric arc furnaces were installed which produced larger size billets. These larger billets necessitated working the material to reduce the billets to size for tubing or individual forgings. The working of the bearing steel refines the steel grain and carbide size and reduces the size of the material's inclusions and segregates (C, Fig. 1). This trend toward larger furnace size has continued to this time (Ref. 1).

Major advances in melting practice evolved over a period covering 1952 to the early 1970's. Immersion thermocouples were introduced in 1952 (D, Fig. 1). These thermocouples permitted better control of steel melting (Ref. 1).

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Some significant manufacturing process changes were made in the 1950's. Shoegrinding (E, Fig. 1) was introduced about 1953. This method improved race surface quality and tolerance. With this grinding method, it is practically impossible to grind eccentricity and face runout into the bearing race. Also, the transverse radii of the races, controlled by the grinding wheel dresser, are more consistent (Ref. 1).

The vacuum degassing and the vacuum melting processes were introduced to the bearing industry in the late 1950's. Consumable-electrode vacuum melting (CEVM) was one such process (F, Fig. 1). Vacuum melting releases entrapped gasses and reduces the quantity. It also alters the type of inclusions and trace elements present in the steel. At the same time, Pratt and Whitney Aircraft Division of United Technologies, Inc. began using AISI M-50 steel in their aircraft engine bearings.

In order to assure clean steel with the vacuum-melting processes, nondestructive testing, using eddy current and ultrasonic methods, was applied to billets, bars, and tubing (G, Fig. 1). This assured the quality of the steel for the bearing manufacturing process.

In rolling-element bearings, the elastically deformed rolling-element surfaces are separated by a thin lubricant film referred to as an elastohydrodynamic film (Ref. 3). The concept of elastohydrodynamic (EHD) lubrication, while recognized in 1949 (Ref. 4), was further recognized as a significant factor in affecting bearing fatigue life and wear (H, Fig. 1). It controlled the EHD film thickness through lubricant selection and control of operating conditions, and it improved surface finish, thus rolling-element bearings were able to operate at higher temperatures and for longer times (Ref. 5).

In the 1960's, argon atmosphere protection of the molten steel during teeming was introduced (I, Fig. 1). Drastic improvement in micro- and macroscopic homogeneity and cleanliness with a resultant improvement in fatigue was realized (Ref. 1).

Prior to the 1950's, as-ground races were hand polished to improve finish and appearance. Overly-aggressive hand polishing could create a thin layer of plastically-displaced or smeared material which was softer and more prone to fatigue failure. This manual process was replaced by mechanized honing in which all parts are smoothed in a more uniform manner (J, Fig. 1).

In 1958, NASA published their results of controlled fiber or grain on the effect of bearing life (Refs. 6 and 7). Controlled fiber can be obtained by forging to shape the raceway of angular-contract ball bearings. Forged raceways with controlled fiber orientation were introduced in 1963 (I, Fig. 1). This innovation improved the life of angular-contact ball bearings.

Work performed by NASA beginning in the late 1950's on material hardness effects culminated with the discovery of the differential hardness principle or controlled hardness (J, Fig. 1) (Ref. 8). Prior to this time, significant variations between rolling-element and race hardnesses could result in significant reduction in bearing life.

A combination of improved surface finishes obtained by honing, improved lubricants whose selection was based upon elastohydrodynamic principles, controlled fiber and hardness, consumable-electrode vacuum melted (CEVM) AISI M-50 steel as well as improved nondestructive inspection of the steel billet resulted in relative bearing life of approximately 13 times the 1940 standard being achieved in 1975 (Ref. 4). NASA research culminated in the use, for the first time, of vacuum-induction melted, vacuum-arc remelted (VIM-VAR) AISI M-50 (K, Fig. 1) bearings demonstrating lives in excess of 100 times the 1940

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standard at speeds to three million DN (where D is bore diameter in millimeters and N is rotational speed in rpm) (Ref. 9). The improvement in lives with the VIM-VAR process was accompanied by improved product consistency achieved by reducing human element variability through better process controls and audits (L, Fig. 1) (Ref. 1).

In 1983, General Electric Co. developed a significantly improved AISI M-50 steel called M-50NiL. This material was capable of being case hardened and exhibited lives in excess of twice that of through hardened VIM-VAR AISI M-50 (M, Fig. 1) (Ref. 10).

BEARING MATERIALS

Until 1955, AISI 52100 and some carburized grades of steel such as AISI 4320 and AISI 9310 were adequate for most applications. Materials such as AISI 440 were available in those cases where improved corrosion resistance was required. Bamberger (Ref. 11) reports that, in one of the classic textbooks on bearing analysis, by Shaw and Mack (Ref. 12), published in 1949, the only rolling-element bearing material discussed was AISI 52100.

In a 1957 book, Wilcock and Booser (Ref. 13) only incidentally noted that AISI 52100 is not useful over 177 °C (350 °F). Further they stated that "for temperatures above 350 °F, bearing manufacturers have made small lots of bearings from (AISI) M-1 and M-10 tool steels. These steels retain their hardness to temperatures approaching 538 °C (1000 °F). Evidence available to date indicates that they operate satisfactorily, provided lubrication is maintained." It was at this time that AISI M-50 steel was applied to the first aircraft engine bearings.

The need for higher temperature capability led to the evaluation of a number of available molybdenum and tungsten alloy tool steels as bearing materials. These alloys have excellent high-temperature hardness retention.

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Such alloys melted and cast in an air environment, however, were generally deficient in fatigue resistance because of the presence of nonmetallic inclusions. Vacuum processing techniques can reduce or eliminate these inclusions. Techniques used include vacuum-induction melting (VIM) and vacuum-arc remelting (VAR). These have been extensively explored, not only with the tool steels now used as bearing materials, but with AISI 52100 and some of the carburizing steels as well. AISI M-50, usually VIM-VAR or consumable electrode vacuum melted (CEVM) processed, has become a very widely used, quality bearing material for nearly all aircraft bearing applications. It is usable at temperatures to 315 °C (600 °F). T-1 tool steel (18-4-1) has also come into fairly wide use in bearings (Ref. 14), mostly in Europe. VIM-VAR M-50NiL is beginning to replace both VIM-VAR and CEVM AISI M-50 as the material of choice, particularly for aircraft engine bearing inner races for high-speed, long-life applications. A representative list of ferrous alloys from which most present day bearings and gears are manufactured is contained in Table 1.

Surface-hardened or carburized steels such as M-50NiL are used in many bearings where, because of shock loads or cyclic bending stresses, the fracture toughness of the through-hardened steels is inadequate. Carburized steels are of increasing importance in ultra-high-speed aerospace applications. Bearings with through-hardened steel races are currently limited to approximately 2.3 million DN because, at higher DN values, fatigue cracks propagate through the rotating race as a result of the excessive hoop stress present (Ref. 9).

Materials such as AMS 5749, AISI 440C and EX-7 are considered "corrosion resistant." This is theoretically correct when comparing them to AISI 52100 and AISI M-50. However, these materials will eventually corrode in the presence of an aqueous environment. As a result, these materials are not

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necessarily satisfactory for long term operation or storage in a corrosive atmosphere (Ref. 11). Chromium rich layers deposited either by conventional methods (Refs. 15 to 17) or chrome-ion implantation (Ref. 18) are approaches to inhibiting corrosion with these materials.

Through hardened materials with large percentages of alloying elements such as AISI 440C, can also be affected by stress corrosion. This is illustrated in Fig. 2. At a given hoop stress for an AISI 440C bearing ring, the time at which the ring can be maintained under static hoop stress before fracture can be limited. To date, however, AISI 440C is the material of choice for rolling-element bearings in cryogenic rocket engine turbopumps such as those used in the space shuttle engines. The use of AISI 440 is dictated primarily because of concerns involving corrosion. However, with the more recent recognition of the stress-corrosion problem, case-hardened materials such as AISI 9310 using surface chrome treatment may offer an acceptable substitute for the AISI 440C.

Rolling-element bearing separators, sometimes called cages or retainers, are components that are capable of exerting a vital influence on the efficiency of the bearing, although they never carry load. The primary function of a separator is to maintain the proper distance between the rolling elements and to ensure proper load distribution and balance within the bearing. An additional function of the separator is to maintain control of the rolling elements in such a manner as to produce the least possible friction through sliding contact. Furthermore, a separator is necessary for several types of bearings to prevent the rolling elements from falling out of the bearing during handling (Ref. 14).

For aerospace bearing applications, a one-piece machined separator is normally used. The simplification and inherent strength of one-piece

separators permit their fabrication from many desirable materials. For most aircraft engine applications, machined silver-plated (AMS 2410), low-carbon steel (AMS 6415) is used. These materials can be operated to at least 230 °C (425 °F). However, bronze separators which offer strength and low-friction characteristics are used. The bronze materials can also be operated at temperatures to 230 °C (425 °F). However, caution should be exercised because certain lubricant chemical types and additives may not be compatible with the bronze materials.

GEAR MATERIALS

The relative pitting fatigue lives of several steel alloys used for aerospace gearing are listed in Table 2. In addition to the resultant life, the choice of which material to use is based on a combination of operating conditions such as load, speed, lubrication system, and temperature plus the cost of producing the gears. For most, if not all aerospace applications, it becomes necessary to harden the gear teeth for improved strength and to case harden the gear tooth surface by case carburizing or case nitriding for longer pitting fatigue life, better scoring resistance, and better wear resistance. AISI 9310, AISI 8620, Nitralloy N, Super Nitralloy and M-50NiL are good materials for most aerospace applications. These materials can operate with bending stresses of 483 MPa (70 000 psi) and maximum contact (Hertz) stresses of 1.38 GPa (200 000 psi). The high-alloy steels should be case carburized (AISI 8620, AISI 9310 and M-50NiL) or case nitrided (Nitralloy) for a hard, wear-resistant surface (Ref. 19).

Gears that are case carburized will usually require grinding after the hardening operation, because of distortion during heat treatment. The nitrided materials offer the advantage of much less distortion during nitriding and therefore can be used in the as-nitrided condition without additional finishing. This is very helpful for large gears with small cross

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sections, where distortion can be a problem. Since case depth for nitriding is limited to approximately 0.051 cm (0.020 in.), case crushing can occur if the load is too high.

Gear surface fatigue strength and bending strength can be improved by shot peening (Refs. 20, and 21). The 10-percent surface fatigue life of the shot-peened gears was 1.6 times that of the standard ground gears (Ref. 20).

The low- and medium-alloy steels have a limiting operating temperature above which they begin to lose their hardness and strength. Above this temperature, usually around 149 °C (300 °F), the materials are tempered and early bending failures, surface pitting failures, or scoring will occur. To avoid these conditions, a material is needed that has a higher tempering temperature and that maintains its hardness at high temperatures. The generally accepted minimum hardness required at operating temperature is Rockwell C-58. In recent years, several materials have been developed that maintain a Rockwell C-58 hardness at temperatures from 232 to 315 °C (450 to 600 °F) (Ref. 22). Several materials have shown promise of improved life at normal operating temperature. The hot-hardness data indicate that they will also provide good fatigue life at higher operating temperatures.

AISI M-50 has been used for lightly loaded accessory gears for aircraft applications at high temperatures. However, the standard AISI M-50 material is generally considered too brittle for more heavily loaded gears. AISI M-50 is considerably better as a gear material when forged with integral teeth. The grain flow from the forging process improves the bending strength and impact resistance of the AISI M-50 considerably (Ref. 23). The AISI M-50 material can also be thermomechanically fabricated or ausforged, with integral gear teeth to give good bending strength and better pitting life (Refs. 24 and 25). However, around 760 °C (1400 °F) the ausforging temperature is so low

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that forging gear teeth is difficult and expensive. As a result, ausforging for gears has had considerably limited application. Test results show that the forged and ausforged gears can give lives approximately three times those of the standard AISI 9310 gears (Ref. 24).

Nitralloy N is a low-alloy nitriding steel that has been used for several years as a gear material. It can be used for applications requiring temperatures of 204 to 232 °C (400 to 450 °F). A modified Nitralloy N called Super Nitralloy or 5Ni-2Al Nitralloy was used in the U.S. supersonic aircraft program for gears. It can be used for gear applications requiring temperatures to 260 °C (500 °F). Table 2 gives relative surface fatigue data for Super Nitralloy.

Two materials that were developed for case-carburized, tapered roller bearings but also show promise as high-temperature gear materials are CBS 1000M and CBS 600 (Refs. 26 and 27). These materials are low- to medium-alloy steels that can be carburized and hardened to give a hard case of Rockwell C-60 with a core of Rockwell C-38. Surface fatigue test results for CBS 600 and AISI 9310 are also shown in Table 2. The CBS 600 has a medium fracture toughness that can cause fracture failures after a surface fatigue spall has occurred.

Two other materials that have been developed as advanced gear materials are EX-53 and EX-14. The fracture toughness of EX-53 is excellent at room temperature and improves considerably as temperature increases (Ref. 28). The surface fatigue results with VAR EX-53 show a 10-percent life that is twice that of the VAR AISI 9310 (Ref. 19).

Vasco X-2 is a high-temperature gear material that is currently being used in advanced CH-47 helicopter transmissions. This material has an

operating temperature limit of 315 °C (600 °F) and has been shown to have good

gear load-carrying capacity when properly heat treated. The material has a

high chromium content (4.9 percent) that oxidizes on the surface and can cause

soft spots when the material is carburized and hardened. A special process

has been developed that eliminates these soft spots when the process is

closely followed (Ref. 29). Several groups of Vasco X-2 with different heat

treatments were surface fatigue tested in the NASA gear test facility. All

groups except the group with the special processing gave poor results

(Ref. 30). Vasco X-2 has a lower fracture toughness than AISI 9310 and is

subject to tooth fracture after a fatigue spall. Further, there is a

suggestion that this material as well as some of the other higher alloy

carburized steels may be susceptible to stress corrosion under certain

environmental conditions. As a result, where the material is subject to a

corrosive environment, stress corrosion testing should be performed before

committing these types of materials to application.

As with rolling-element bearings, the M-50NiL is receiving attention as a

possible material for gearing. Extensive testing of this material was

performed at the NASA Lewis Research Center and the General Electric Company

(Ref. 31). Table 3 is a summation of these test results. These results are

also compared to other gear steels in Table 2. This material exhibits all the

benefits of AISI 9310 and, in addition, the VIM-VAR M-50NiL has over 11 times

the pitting fatigue life of VAR AISI 9310 and over 4 times that of VIM-VAR

AISI 9310. The VIM-VAR M-50NiL was also shown to have good resistance to

fracture through a fatigue spall in a gear tooth (Ref. 31).

METALLURGICAL PROCESSING VARIABLES

Research reported in the literature on gear metallurgical processing variables is not as extensive as that for rolling-element bearings. However, an element of material in a Hertz stress field does not recognize whether it is in a bearing or a gear. It only recognizes the resultant shearing stress acting on it. Consequently the behavior of the material in a gear will be much like that in a rolling-element bearing. The metallurgical processing variables to be considered are:

(1) Melting practice, such as air, vacuum induction, consumable-electrode vacuum remelt (CEVM), vacuum degassing, electroslag (electoflux) remelt, and vacuum induction melting-vacuum arc remelting (VIM-VAR);

(2) Heat treatment to give hardness, differential hardness, and residual stress;

(3) Metalworking, consisting of thermomechanical working and fiber orientation.

These variables can significantly affect gear and bearing performance. Other factors that can also significantly affect surface pitting (rolling-element) fatigue life and that have some meaningful documentation are not included. These are trace elements, retained austenite, gas content, and inclusion type and content. Although any of these factors can exercise some effect on rolling-element or surface pitting fatigue life, they are too difficult, from a practical standpoint, to measure or control by normal quality control procedures (Ref. 19).

Heat treatment procedures and cycles, per se, can also affect performance. However, at present no controls as such are being exercised over heat treatment. The exact thermal cycle is left to the individual producer with the supposition that a certain grain size and hardness range be met.

Melting practice

Sufficient data and practical experience exist to suggest that the use of vacuum-melted materials, and specifically consumbale-electrode vacuum melting (CEVM), can increase surface pitting fatigue life beyond that obtainable with air-melted materials (Refs. 32 to 35). Life improvements over air-melted steels to 13 times by CEVM processing (Refs. 15, 36 to 38) and to 100 times by VIM-VAR processing (Ref. 9) are indicated in the literature. Data available on other melting techniques such as vacuum induction, vacuum degassing, and electroslag remelting indicate that the life improvement approaches or equals that achieved with the CEVM process. However, it is also important to differentiate between CVM (consumable-electrode vacuum melting) and CVD (carbon vacuum degassing). The CVM process yields cleaner and more homogeneous steels than CVD.

Heat treatment

Rolling-element bearing materials for aerospace applications are usually through-hardened. However, material such as AISI 9310 and M-50NiL are carburized. Gears are usually carburized but some are through-hardened or nitrided, for the proper combination of toughness and tooth hardness.

Nitriding is a satisfactory method of hardening small and medium-size gears. Distortion is minimal because furnace temperatures are comparatively low. The hardening pattern is uniform, but the depth of hardness is limited. Best results are achieved when special materials suited to nitriding are specified.

Most bearing and gear manufacturing specifications do not designate heat treatment, but rather call for material characteristics (i.e., hardness and grain size) that are controlled by the heat treatment cycle. Hardness is the most influential heat-treatment-induced variable (Refs. 39 to 41). It is

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recommended that Rockwell C-58 be considered the minimum hardness for critical gear and bearing applications.

A relationship has been proposed in Ref. 37 that approximates the effect of hardness on surface fatigue life:

$$\frac{L_2}{L_1} = e^{0.1(R_{C,2} - R_{C,1})} \tag{1}$$

where L_1 and L_2 are 10-percent fatigue lives at gear hardnesses $R_{C,1}$ and $R_{C,2}$, respectively. Although this relationship was obtained for AISI 52100, it can be extended to other steels.

Short-term hot hardness measurements were made for groups of through hardened specimens of AISI 52100, AISI M-1, AISI M-50, Halmo, WB-49, AISI 440C, WD-65, and Matrix II. Measurements were also made of case-hardened specimens of Super Nitralloy (5Ni-2Al), AISI 8620, CBS 600, CBS 1000, and Vasco X-2. The results for the through hardened materials and for the case hardened materials were normalized and are shown in Fig. 3 (Refs. 22, 42, and 43). These normalized data show that regardless of the initial hardness, the hot hardness of the individual materials shows the same functional dependence. That is, the changes in hardness with increasing temperature are independent of material composition or room temperature hardness.

The data of Fig. 3, when plotted on log-log coordinates (Ref. 39), can be represented by a straight line having the form

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta \tag{2}$$

where

$(Rc)_T$ Rockwell C hardness at operating temperature,

$(Rc)_{RT}$ Rockwell C hardness at room temperature,

ΔT change in temperature, $T_T - T_{RT}$, K, (°F),

T_T operating temperature, K (°F),

T_{RT} room or ambient temperature, K (°F)

α temperature proportionality factor, $K^{-\beta}$ (°F$^{-\beta}$)

β exponent.

Values for α and β for various materials are given in Table 4 (Ref. 2).

Another concept to be considered is the effect of differences in hardness between the pinion and the gear (Refs. 8, 44 and 45). Evidence exists that hardness differences between the mating components can affect system life positively by inducing compressive residual stresses during operation (Ref. 45). Differential hardness (ΔH) is defined as the hardness of the larger of two mating gears minus the hardness of the smaller of the two. It appears that a ΔH of 2 points Rockwell C may be an optimum for maximum life. For critical applications, as a practical matter, it would be advisable to match the hardness of the mating gears or the rolling-elements and rings of a bearing to ensure a ΔH of zero and at the same time ensure that the hardness at room temperature is the maximum that is reasonably attainable. This will allow for maximum elevated operating temperature and maximum life. The ΔH effect has been verified experimentally for rolling-element bearings, but there is no similar published work for gears.

It is generally accepted in the bearing industry that prior austenite grain size should be ASTM Number 8 or finer, and individual grain size should not exceed ASTM number 5. For gears, it is generally accepted that grain size should not exceed ASTM Number 5 or finer, and individual grain size should not exceed ASTM Number 3.

In general, for through-hardened steels, the amount of retained austenite generally increases with increasing material hardness. For case carburized

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steels, however, large amounts of retained austenite will be present in the case. It is well known that retained austenite will transform to martensite under Hertzian cycle stress conditions and even at no load ambient conditions, resulting in dimensional instability of the bearing component. For this reason, a low level of retained austenite is desirable for aerospace bearing and gearing applications. For rolling-element bearings, typical maximum levels are in the range of 2 to 5 percent (Ref. 2). For gears, retained austenite should not exceed 10 percent.

Residual stresses can be induced by the heat-treatment process, differential hardness, or shot peening. There is no analytical method to predict the amount of residual stress in the subsurface region of gear tooth contact. However, these residual stresses can be measured in test samples by x-ray diffraction methods. The effect of these residual stresses on pitting fatigue life can be determined by the following equation (Ref. 20):

$$\text{Life} \propto \left(\frac{1}{\tau_{max} - \dfrac{S_{r,y}}{2}} \right)^9$$

where

τ_{max} maximum shear stress (45° plane)

$S_{r,y}$ measured compressive residual stress below surface at location of τ_{max}

Metalworking

Proper grain flow or fiber orientation can significantly extend pitting fatigue life (Refs. 46 and 47) and may improve the bending strength of gear teeth. Proper fiber orientation can be defined as grain flow parallel to the gear tooth shape or bearing raceway. Standard forging of bearing raceways or gears with integral gear teeth as opposed to machining teeth in a forged disk is one way of obtaining proper fiber orientation (Ref. 24). A controlled-energy-flow forming technique (CEFF) can be used for this purpose.

This is a high-velocity metalworking procedure that has been a production process for several years.

Test gears forged from AISI M-50 steel yielded approximately five times the fatigue life of machined vacuum-arc-remelted (VAR) AISI 9310 gears (Ref. 24). Despite its excellent fatigue life, AISI M-50 is not recommended for gears. Its low fracture toughness makes gears prone to sudden catastrophic tooth fracture after a surface fatigue spall has begun rather than to gradual failure and noisy operation typical of surface pitting. It is expected that forged AISI 9310 (VAR) gears would achieve similar life improvement while retaining the greater reliability of the tougher material.

Ausforging, a thermomechanical fabrication method, has potential for improving the strength and life of bearings and gears. Rolling-element tests with AISI M-50 steel show that 75- to 80-percent work (reduction of area) produces the maximum benefit (Refs. 23 and 25). The suitability of candidate steels to the ausforging process must be individually evaluated. AISI 9310 is not suitable because of its austenite-to-martensite transformation characteristic. Tests reported in Ref. 24 found no statistically significant difference in lives of ausforged and standard forged AISI M-50 gears. The lack of improvement in the ausforged gears is attributed to the final machining required, which removes some material with preferential grain flow. There is also a slightly greater tendency to tooth fracture in ausforged gears (Ref. 24). This tendency is attributed to poorer grain flow than in standard forged gears. The energy required limits the ausforging process to gears no larger than 90 mm (3.5 in.) in diameter.

Experience with ausforging of bearing raceways has shown that the process is not practical for large bearing bore sizes. This is because forging laps

have a tendency to occur in the raceway surfaces causing early facture. While
this problem has not occurred in small bore size bearings, the expense of
ausforging is not commensurate with any resultant improvement in bearing life
(Ref. 2).

CONCLUDING REMARKS

During the last five decades, significant advancements in material
technology have allowed for the design and manufacture of rolling-element
bearings and gears having lives approximately 200 times that which could be
achieved in the 1940's. The results of these achievements can be categorized
into improved material cleanliness, controlled material hardness, smaller and
evenly dispersed carbide structure, induced compressive residual stresses and
improved fracture toughness. It is apparent that steel chemical composition
does not necessarily have the effect on material hot hardness that it once was
thought to have. What appears to be of paramount importance in achieving a
uniform and consistent end product is the steel melting process, such as
VIM-VAR and optimized heat treating process, together with its related process
controls. The vast differences which were once thought to distinguish
through-hardened steels from case-carburized steels really never existed but
resolves to differences in fracture toughness necessary for either
highly-loaded or very high-speed applications or both. Through-hardened AISI
M-50 is the material of choice for aircraft engine and gearbox bearings.
Case-carburized AISI 9310 is the material of preference for aerospace
gearing. However, case-carburized M-50NiL appears to incorporate the
desirable qualities of both materials whereby optimal life and reliability can
be achieved. This material offers promise of a common aerospace bearing and
gearing steel not only for current and planned aerospace applications but for
those of the next century.

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TABLE 1. - REPRESENTATIVE BEARING AND GEAR STEELS

| 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	Cb	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 Al
HA1MO	Bearing steel	UNS T 11301; AISI M-1	.56	.003	.008	.36	1.12	4.84	.53	---	5.18	---	---	---	---
M-1	High speed tool steel		.80	.030	.030	.30	.30	4.00	1.00	1.50	8.00	---	---	---	---
M-2	High speed tool steel	UNS T 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	UNS T-11342; AISI M-42	1.10	.012	.007	.15	.17	3.77	1.15	1.66	9.51	7.99	---	---	---
M-50	Bearing steel	UNS T 11350; AISI M-50	.80	.030	.030	.30	.25	4.00	1.00	---	4.25	---	---	---	---
M-50 NiL[a]	Carburizing steel	AMS 6490, 6491	.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	.70	.030	.030	.30	.25	4.00	1.00	18.00	---	---	---	---	---
T-15	High speed tool steel	AMS 5626 UNS T 12015; AISI T-15	1.52	.030	.030	.26	.25	4.70	4.90	12.50	1.00 max	5.10	---	---	---
440C	Hardenable Cr stainless steel	UNS S 44004; AISI 440C	1.03	.018	.014	1.00 max	.41	17.30	.14	---	.75 max	---	---	---	---
AMS 5749	Martensitic stainless steel	AMS 5618, 5630, 5880, 7445	1.15	.015	.010	.50	.30	14.50	1.20	---	4.00	7.81	---	---	.35 max Cu
Vasco matrix II	Gear steel	UNS S 42700; AMS 5749	.53	.014	.013	.12	.21	4.13	1.08	1.40	4.80	---	---	.10	---
CRB-7	Bearing steel	UNS S 42800; AMS 5900	1.10	.016	.003	.43	.31	14.00	1.03	---	2.02	---	.32	---	---
AMS 5900	Martensitic stainless steel		1.10	.015	.010	.40	.30	14.00	1.00	---	2.00	---	---	.35 max	.25 Nb
9310[a]	Ni-Cr-Mo-alloy steel	UNS G 93106; AISI 9310	.10	.025	.025	.54	.28	1.18	---	---	.11	---	---	3.15	---
CBS 600[a]	Alloy steel	AMS 6260, 6265, 6267	.19	.010	.010	.61	1.05	1.50	---	---	.94	---	---	.18	.07 Al
CBS 1000[a]	Alloy steel	UNS K 21940; AMS 6255	.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	.21	.035	.040	.80	.25	.50	---	---	.20	---	---	.55	---
EX-53[a]	Gear steel	AMS 6274, 6276, 6277	.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	.20	.035	.040	.55	.25	---	---	---	.25	---	---	1.82	---
4720[a]	Ni-Cr-Mo-alloy steel	AMS 6294 UNS G 47200; AISI 4720	.20	.035	.040	.55	.25	.45	---	---	.20	---	---	1.05	---

[a]Carburizing grades.

TABLE 2. - RELATIVE SURFACE PITTING FATIGUE FOR
VAR AISI 9310 STEEL AND AIRCRAFT-QUALITY GEAR
STEELS (ROCKWELL 59-62) [REFS. 19,31]

Steel[a]	10-Percent relative life
VAR AISI 9310	1.0
VAR AISI 9310 (shot peened)	1.6
VIM-VAR AISI 9310	2.5
VAR Carpenter EX-53	2.1
CVM CBS 600	1.4
VAR CBS 1000	2.1
CVM VASCO X-2	2.0
CVM Super Nitralloy (5Ni-2Al)	1.3
VIM-VAR AISI M-50 (forged)	3.2
VIM-VAR AISI M-50 (ausforged)	2.4
VIM-VAR M-50 NiL	11.5

[a]VAR = Vacuum Arc Remelting.
CVM = Consumable-Electrode Vacuum Remelt.
VIM-VAR = Vacuum Induction Melting-Vacuum Arc Remelting.

TABLE 3. - FATIGUE LIFE RESULTS FOR TEST GEARS AND ROLLING-CONTACT BARS [31]

Material	System life, millions of stress cycles		Weibull slope	Failure index	Confidence number at 10-percent life level, percent[a]
	10 Percent	50 Percent			
Gears:					
VAR AISI 9310	18.8	46	2.1	18 out of 19	----
VIM-VAR AISI 9310	48	200	1.3	24 out of 33	92.5
VIM-VAR M50NiL	217	496	2.3	2 out of 20	99
Rolling-contact bars:					
VAR AISI 9310	4.2	9.4	2.3	10 out of 10	----
VIM-VAR AISI 9310	6.84	15.74	2.26	10 out of 10	76
VIM-VAR M50NiL	90.6	219	2.1	5 out of 20	99

[a]Percentage of time that the 10-percent life obtained with VAR AISI 9310 will have the same relation to the 10-percent life obtained with VIM-VAR AISI 9310 or VIM-VAR M50NiL.

TABLE 4. - TEMPERATURE PROPORTIONALITY FACTORS α AND EXPONENTS β
FOR REPRESENTATIVE STEELS [REF. 2]

$$[(Rc)_T = (Rc)_{RT} - \alpha \, \Delta T^\beta.]$$

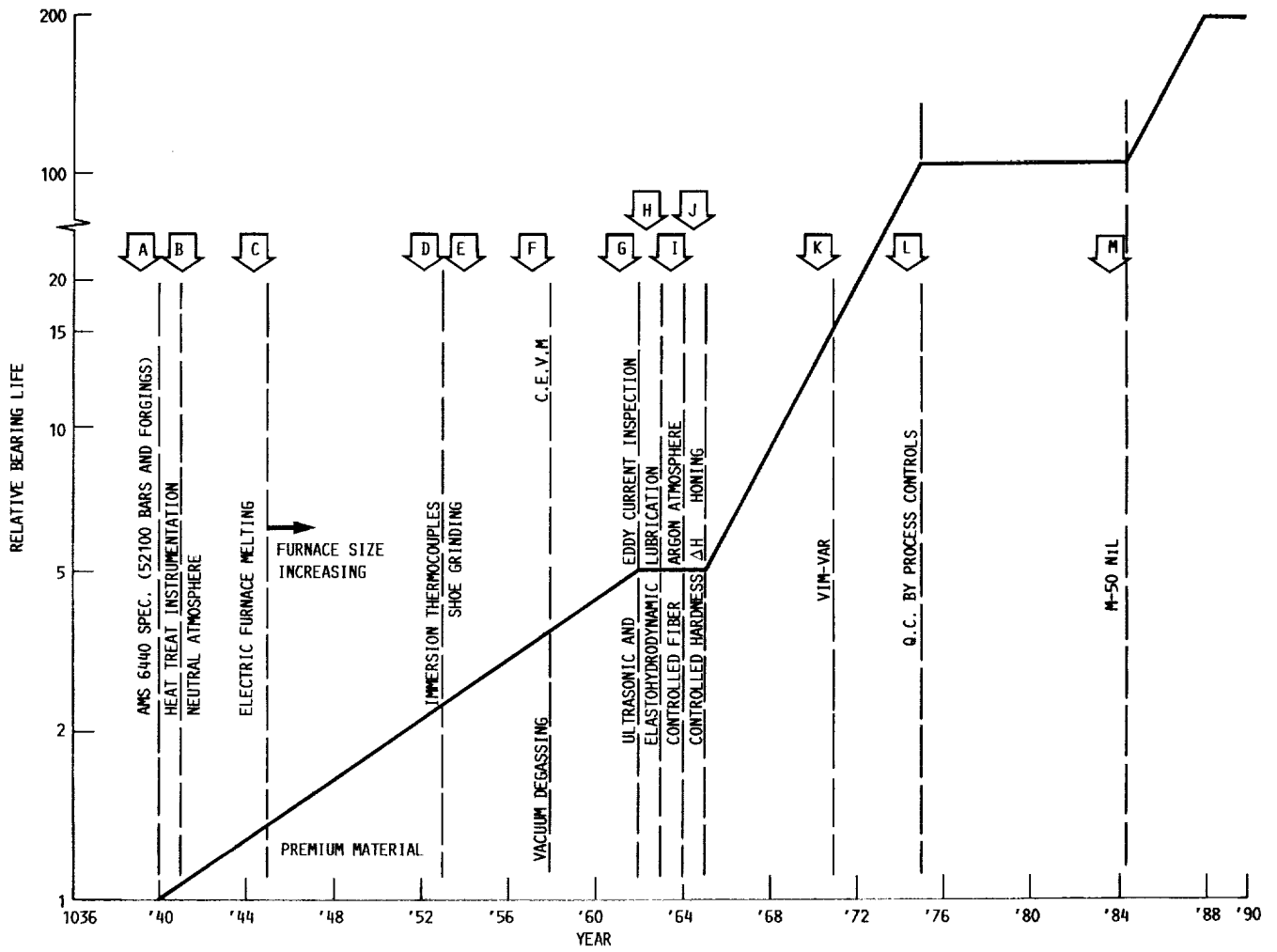| Material	Temperature range		α		β	
	K	°F	K, $\times 10^{-5}$	°F, $\times 10^{-5}$	K	°F
AISI 8260	294 to 589	70 to 600	73	26	1.7	1.7
CBS 600	294 to 589	70 to 600	.75	.18	2.4	2.4
Vasco X-2	294 to 811	70 to 1000	1.4	.38	2.2	2.2
CBS 1000	294 to 811	70 to 1000	93	38	1.5	1.5
CBS 1000M	294 to 811	70 to 1000	340	160	1.3	1.3
Super Nitralloy	294 to 769	70 to 620	1.3	.33	2.3	2.3
AISI 52100	294 to 533	70 to 500	92	34	1.6	1.6
AISI M-50	294 to 811	70 to 1000	133	54	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						
Matrix II						
AISI 440C						
AMS 5749						
M-50NiL						

FIGURE 1. - MAJOR ADVANCES CONTRIBUTING TO ROLLING-ELEMENT BEARING LIFE IMPROVEMENT OVER FIVE DECADES.
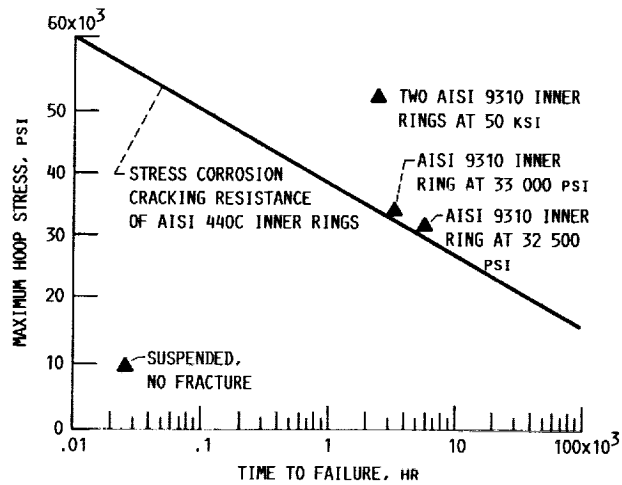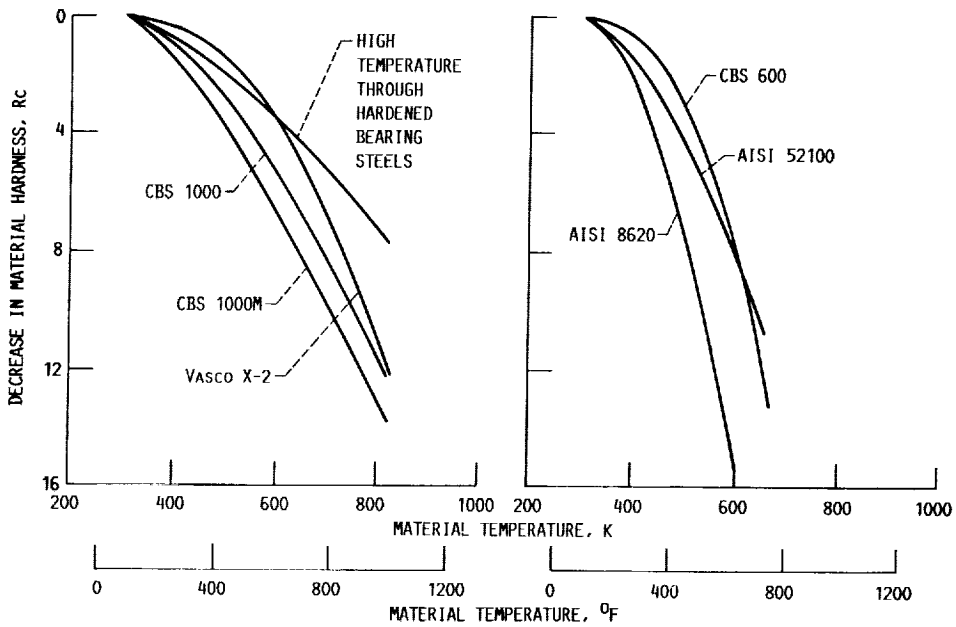
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FIGURE 2. - STRESS- CORROSION EFFECTS ON AISI 440C STEEL
BEARING INNER RINGS UNDER HOOP STRESS EXPOSED TO AM-
BIENT ENVIRONMENT CONDITIONS. (COURTESY PRATT AND
WHITNEY AIRCRAFT).

(a) COMPARISON OF CBS 1000, CBS 1000M, AND
VASCO X-2 WITH THROUGH-HARDENED BEARING
STEEL.

(b) COMPARISON OF AISI 8620 AND CBS 600
WITH AISI 52100.

FIGURE 3. - SUMMARY OF CASE HARDENED STEEL SHORT-TERM HOT-HARDNESS DATA AND COMPARISON WITH
THROUGH-HARDENED HIGH-SPEED TOOL STEELS AND AISI 52100.

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16. Abstract

Research in metallurgy and processing for bearing and gear steels has resulted in improvements in rolling-element bearing and gear life for aerospace applications by a factor of approximately 200 over that obtained in the early 1940's. The selection and specification of a bearing or gear steel is dependent on the integration of multiple metallurgical and physical variables. For most aerospace bearings, through-hardened VIM-VAR AISI M-50 steel is the material of preference. For gears, the preferential material is case-carburized VAR AISI 9310. However, the VAR processing for this material is being replaced by VIM-VAR processing. Since case-carburized VIM-VAR M-50NiL incorporates the desirable qualities of both the AISI M-50 and AISI 9310 materials, optimal life and reliability can be achieved in both bearings and gears with a single steel. Hence, this material offers the promise of a common steel for both bearings and gears for future aerospace applications.

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