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DISCUSSION

R. M. Barnsby[2]

The design of ball bearings for high speed operation is receiving much attention and lightweight rolling elements provide a realistic solution to an outer race life limited design problem by reducing the centrifugal load on the outer race. Ceramic materials are a prime candidate in this application and it is encouraging to learn from the authors' ball fatigue data that silicon nitride balls, processed from quality grade material, compare favorably with conventional solid steel balls. The importance of material cleanliness, bulk density and homogeneity has been well demonstrated. The authors may wish to comment on the 0.99 Weibull slope value obtained for HS-110 silicon nitride since, statistically, it represents non-fatigue failure.

It should be emphasized that testing has been conducted at stress levels much greater than those anticipated in practice, presumably so that sufficient data could be obtained within a reasonable time. Extrapolation of the authors' data (Fig. 4) to more normal stress levels, 300,000 psi for example, indicates that the fatigue life of NC-132 hot-pressed silicon nitride balls exceeds that of 52100 and M-50 balls by a factor of at least 10. This result is extremely encouraging and merits careful consideration when extending the ball fatigue data to bearing design.

This discussor has serious reservations regarding the analytical part of the paper. It is certainly premature to conclude that bearings with silicon nitride balls have lower fatigue lives than conventional bearings. This conclusion appears to be based on a simplified stress correction factor, related to high inner race stress with silicon nitride balls, and does not give due consideration to the fundamental concepts of the Lundberg-Palmgren fatigue theory. The authors may wish to consider the following two points which are intended to provide constructive criticism.

First, the simplified life-stress relationship assumed by the authors is very useful to illustrate trends in ball fatigue data but it is not applicable as a general analytical method. In particular, it is not valid for analytical comparisons of bearings with different ball material, even if the geometry is constant. Examination of the fundamental Lundberg-Palmgren relationships shows that life depends on the stressed volume, which is proportional to the contact area for a given geometry, as well as on the subsurface alternating shear stress. Reduction of this relationship to a life-load relationship involves a material fatigue constant which contains the effective elastic modulus and which has been evaluated only for conventional steel bearings. The appropriate form of the fatigue constant for materials other than steel shows a life (L_{10})-modulus dependence given by

$$L_{10} \sim \frac{1}{E_0 6.3}$$

where

$$E_0 = [\tfrac{1}{2}\{\frac{1-\nu_a{}^2}{E_a} + \frac{1-\nu_b{}^2}{E_b}\}]^{-1}$$

The 6.3 exponent in this expression assumes the Lundberg-Palmgren values for c and h (authors' reference [17]), which are material dependent, and further testing is needed to revise these values for silicon nitride. Owing to lack of such data the 6.3 exponent will be assumed here to determine the reduction in life due to the higher modulus material.

As a comparison, the 120 mm bore bearing analyzed by the authors has been evaluated at the mid-range conditions of 3000 lb. thrust load and 3 million DN with steel balls and with silicon nitride balls. For common race curvatures of 0.54, the lower density and higher modulus of silicon nitride lead to a 4 percent decrease in subsurface shear stress with a 21 percent decrease in contact major axis and stress depth at the outer race contact; and an 18 percent increase in subsurface shear stress with a 4 percent decrease in major axis and depth at the inner race contact. All maximum contact stress levels are below 300,000 psi. After including the ball density effect on race loads and contact angles the contact lives may be compared from the above equation. However, the relative contact lives will be increased due to the higher life of silicon nitride balls at these stress levels. For a ball life increase factor of k the contact life will increase by

$$[\frac{2}{1+\frac{1}{k^\beta}}]^{1/\beta} \qquad \text{where } \beta = 10/9 \text{ from the authors' reference [17].}$$

The authors' ball fatigue data indicates that $k > 10$, while it is feasible that $k \gg 10$. The corresponding increase in contact lives is between 1.74 ($k = 10$) and 1.87 ($k \to \infty$). The complete bearing life is obtained by combining the contact lives and the results show up to 10 percent improvement in bearing life when silicon nitride

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balls are used. This should replace the authors' result of a 57 percent decrease in life (Fig. 5 *(a)*).

The second criticism is that it is inappropriate to compare bearings of identical race curvature. Since contact heat generation partially governs the selection of this curvature the contact ellipse dimensions must be considered. It is found that an inner race curvature of 0.535 for silicon nitride balls leads to equivalent major axis dimensions. The corresponding bearing life increases by up to 30 percent. Further reduction of the inner race curvature leads to life increases of over 100 percent.

These comparisons apply to constant bearing cross-sections. No attempt has been made to optimize the design of the silicon nitride ball bearing. The major advantage of lightweight balls is to transfer the limiting fatigue criterion from the outer race to the inner. This enables larger silicon nitride ball diameters to be used for a realistic comparison and life improvements would be even greater. If the arguments presented here in this discussion are accepted then the need for additional silicon nitride fatigue properties data is immediately apparent. The authors are therefore encouraged to extend their test program, particularly to obtain a more accurate value of k at the lower stress levels. Even the available data shows that bearings with silicon nitride balls offer great potential. Other benefits, such as thermal stability and freedom from the internal stress problems associated with hollow balls, lead this discussor to reject the conclusion that bearings with silicon nitride balls do not offer distinct advantages over conventional bearings for high speed operation.

R. Valori[3]

At the present time there is a great deal of interest in the potential use of silicon nitride as a low mass ball material for high speed bearing application, especially for advanced gas turbine aircraft engines. The authors are to be commended for presenting a timely paper which rather than merely characterizing the fatigue properties of silicon nitride, addresses the question of silicon nitride's usefulness in high speed ball thrust bearings. The authors have calculated that no advantage in fatigue life of bearings containing silicon nitride balls at high speeds will be realized over bearings containing steel balls. This conclusion is valid to the extent of the constraints and assumptions considered. However, other factors which point to silicon nitride's usefulness as a low mass ball material should be considered, namely:

(a) Gas turbine engine bearing thrust loads resulting from thrust balancing to achieve nonskid bearing operation through most of the duty cycle can be expected to decrease with decreasing ball mass because less traction is required to maintain nonskid operation. Therefore comparisons of the fatigue lives between M50 steel and silicon nitride should be made with the silicon nitride bearing having a somewhat reduced thrust load.

(b) The authors' calculations are based on the reasonable assumption that the load-life behavior will remain the same as the Hertz stress is reduced below the range for which the authors have fatigue data. However, there is evidence (reference [10]) that fatigue spalling is initiated from cracking at the edge of the wear track and that this cracking will not occur below a critical load or Hertz stress level. If this is the case, then the fatigue life of silicon nitride at the Hertz stress levels experienced in bearings may never occur.

(c) Contrary to the fatigue life results obtained by the authors using silicon nitride balls, references [10] and [19][4] reported that the fatigue life of silicon nitride rollers are far in excess of that of M50 steel. Also, the life of silicon nitride was found to be dramatically effected by surface finish processing. The surface finish processing of silicon nitride balls is generally unknown for proprietary reasons. It is conceivable that the fatigue life of silicon nitride balls may be substantially improved through changes in surface finish processing.

The incentive to develop low mass balls for high speed bearing application is not only related to fatigue life, but includes such incentives as reduced ball-to-cage impact loads, lower operating contact angle with consequent reduction in inner ring land height, and lower heat generation as a result of reduced ball spinning.

Testing at Naval Air Propulsion Test Center (reference [19]) has shown some evidence that silicon nitride has a detrimental effect on the fatigue life of its mating M50 steel surface especially at elevated temperatures. This is of serious concern since silicon nitride's usefulness as a low mass ball material will be in its ability to reliably operate in a bearing having steel races. The discusser would like to ask if the authors noted any reduction in the fatigue lives of the steel support balls when run against silicon nitride? Also, in examining the fatigue spalls on the silicon nitride balls was there any indication of cracking at edges of the wear track?

Additional Reference

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[3] Naval Air Engineering Center, Aero Engine Lab., Fuels and Lubricants Division, Philadelphia, Pa.

[4] Number [19] in brackets designates Additional Reference at end of discussion.

Authors' Closure

The authors wish to thank the discussors for their interest and for taking the time to comment on this paper. Their comments tend to emphasize the controversy that has existed relative to the merits of using silicon nitride balls in bearings with steel races for high-speed applications. It should be added that discussions such as these were not unexpected in view of the attention that silicon nitride is receiving for this application.

It should be pointed out at the outset of this closure that the authors' data, supplemented by data of [9, 10, 19], indicate that hot-pressed silicon nitride has great promise for the appropriate rolling-element bearing applications. The performance of this material, under rolling conditions, far surpasses any other ceramic or cermet material that has been tested. The rolling-element bearing applications where hot-pressed silicon nitride is desirable may include high temperature or corrosive environments where the use of bearing steels is not desirable. Such bearings would require that the complete bearing, that is, races as well as balls or rollers, be made of the silicon nitride material. The fabrication of races of silicon nitride presents some problems, particularly with shaft and housing fitting techniques, because of thermal expansion properties which are very different from currently used shaft and housing materials. There has been some success in minimizing these problems [9, 10].

It is the authors' opinion, as reinforced by the analysis in this present paper, that the potential applications for silicon nitride do not include that of substituting silicon nitride balls for steel balls in high-speed bearings in order to counteract the anticipated fatigue life reduction due to centrifugal effects. It is on this point that the discussors appear to take issue. Mr. Barnsby is correct in assuming that a simplified stress correction factor has been applied to the life prediction of bearings with silicon nitride balls. A correction or adjustment to the predicted lives as calculated by the computer analysis program [16] is required, since the program does not account for materials of elastic modulus different from that of steel. The program can calculate the correct Hertz stresses in the contacts of silicon nitride balls and steel races. But, these stresses are not considered in the Lundberg-Palmgren type capacity and life calculation which is common to this and other computer programs commonly used for bearing life prediction, such as the program based on [20]. For a given contact load and geometry, the Hertz stress in the contact of a silicon nitride ball on a steel race will be significantly higher than that of a steel ball on a steel race because of the elastic modulus difference.

The stress correction factor applied in the reported life prediction is the ninth power of the ratio of the Hertz stress in the contact of a silicon nitride ball and a steel race to that of a steel ball on a steel race for identical contact load and geometry. This factor is multiplied by the contact life of the steel ball on a steel race for these conditions and is assumed to be the life of the contact of a silicon nitride ball in contact with the steel race. It is true that this simplified correction neglects the effect of stressed volume on fatigue life, but this effect is found to be very small relative to the stress effect. In fact, it is easily shown that the small stressed volume effect is nearly offset by the additional effect of the depth of the maximum shear stress. From the Lundberg-Palmgren analysis [17],

$$\frac{L_2}{L_1} = \left(\frac{Z_{0_2}}{Z_{0_1}}\right)^{2.1}\left(\frac{V_1}{V_2}\right)^{0.9}\left(\frac{\tau_{0_1}}{\tau_{0_2}}\right)^{9.3}$$

where

L = contact life
Z_0 = depth to maximum shear stress
V = stressed volume
τ_0 = maximum shear stress

and subscript 1 denotes the steel ball case, and subscript 2 denotes the silicon nitride ball case. Also, the values of the exponents are assumed to be as given by [17] which is a valid assumption, since we are concerned with the life of steel races. Bearing life calculations taking into account the stressed volume effects are shown in Table 5 and are very similar to those taken from Table 4*(b)* where the simplified correction was used. This comparison shows that the simplified correction is applicable and valid, contrary to Mr. Barnsby's conclusion.

The authors recognized that comparison of bearings with identical geometry for silicon nitride and for steel balls is not a fair comparison. Life predictions for a bearing with reduced curvature at the inner race (0.52 as opposed to 0.54) were made and are shown in the original paper in Fig. 5*(b)*. As Mr. Barnsby suggested, the lives are increased. However, with the exception of the very low loads and very high speeds, the life improvements over the steel ball cases are small. For the case of 3 million DN and 13 300 N (3,000 lb) thrust load, the life improvement is less than 14 percent.

The discussions by both Mr. Barnsby and Mr. Valori concern the magnitude of the life improvement factor of silicon nitride rolling elements over steel rolling elements. Lundberg-Palmgren [17] states that for deep-groove ball bearings, the dynamic capacity (and thus the fatigue life) is *not* increased where it is assumed that the balls will never fail. If this is true for deep-groove ball bearings, it may be expected to be true for angular-contact ball bearings as considered herein. However, Mr. Barnsby refers to an analysis by Johnson [13] which shows that the contact life is increased by a factor of 1.87 if the balls are assumed to have infinite life. But, as shown in the discussion, the predicted bearing life improvement

Table 5 Predicted life of 120-mm bore high-speed ball bearing with silicon nitride balls accounting for stressed volume effects. Thrust load, 13 300 N (3,000 lb).

Shaft speed, 10^6 DN	Bearing Fatigue Life, Hours: Including stressed volume effects	Simplified correction (from Table 4*(b)*)
2.0	285	248
2.5	235	208
3.0	195	175
3.5	155	144
4.0	120	112

for the 3 million DN and 13 300 N (3,000 lb) thrust load case is a modest 10 percent. Thus, the concern for the magnitude of the life improvement factor has little significance for such an application of silicon nitride balls in contact with steel races.

The authors share Mr. Valori's concern for the ability of silicon nitride balls to operate reliably in a bearing having steel races. Examinations at higher magnification of the running tracks of the silicon nitride ball specimens from the five-ball fatigue tests show some very small pits all over the running track surface. These pits appear identical to those on the running tracks of silicon nitride rolling-contact fatigue test bars shown in [10] and described as intergranular pullout of silicon nitride grains. The steel lower balls in the five-ball tests showed a definite change in surface texture which could be slight wear. This surface texture change occurred on the lower balls in tests where the silicon nitride upper ball had not spalled, but to a lessor degree than those tests which resulted in a spalled silicon nitride upper ball. It is believed that this slight abrasive wear is caused by the grains of silicon nitride removed from the minute surface pits in the silicon nitride balls. There is concern that this abrasive wear could be detrimental to the steel races in a bearing containing silicon nitride balls.

The frequency and average life of lower ball spalling fatigue failures were not significantly different in the tests with silicon nitride upper balls than has been experienced with steel upper balls. This observation indicates that the silicon nitride has not adversely affected the fatigue life of the contacting steel rolling-elements as observed in [19] by Mr. Valori.

In answer to Mr. Valori's final question, no cracks at at the edge of the running tracks were observed on any of the test balls of either the HS-110 or the NC-132 silicon nitride materials. Fatigue spalling of the silicon nitride surfaces occurred without edge cracking. It is possible that the edge cracking may be peculiar to the loading and dynamics of the test machines used in [10] and [19] which were similar rolling-contact (RC) fatigue rigs.

The authors agree with Mr. Valori that surface processing significantly affects the fatigue life of silicon nitride rolling elements. The appearance of the surfaces of the silicon nitride balls tested in the five-ball fatigue tester, both before and after test, were very similar to those shown for the improved surface processing reported in [10]. Processing must be improved to a greater degree if improved fatigue life and wear resistance of silicon nitride rolling elements are to be realized. This accomplishment would still not improve the position of silicon nitride rolling-elements in contact with steel races; since, as shown previously, the fatigue life of high-speed bearings containing silicon nitride balls will still be limited by the steel raceway lives.

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