steel races can result in lives less than full complement steel bearings where the elastic modulus of the ceramic is greater than steel, as is the case of most ceramics.

3 Bearing power loss or heat generation is more a function of the individual bearing design and operation than whether steel or ceramic rolling elements are used within the bearing.

4 The lives of ceramic rolling elements are an inverse function of temperature. It is suggested based upon endurance tests with alumina to 1366 K (2000°F) that life is inversely proportional to temperature to the 1.8 power.

5 Unlubricated tests of a full-complement silicon nitride bearing at 644 K (700°F) resulted in catastrophic failure after 30 min, suggesting the need for lubrication at elevated temperatures.

6 Special design and mounting requirements are needed to accommodate a full-complement ceramic bearing into turbomachinery applications. Optimum designs have yet to be developed.

## Acknowledgments

The author wishes to acknowledge the technical contributions of Richard J. Parker and Salvatore J. Grisaffe, who with his other colleagues at the NASA Lewis Research Center collaborated with him in conducting the NASA nonmetallic bearing research over the years, which is reported herein. Also, the author wishes to thank Mr. Grisaffe for his technical recommendations and comments, which have been incorporated throughout this paper.

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## DISCUSSION

### Y. P. Chiu[1]

Mr. Zaretsky is to be congratulated for his extensive review on research in ceramic rolling element components, in which he has been involved for more than two decades at the NASA Lewis Research Center. While this discusser agrees with most of the statements in the paper about various aspects of ceramic rolling elements, he is somewhat surprised to find in the author's Table 1 that very low load capacity is given to full ceramic bearing, notably silicon nitride. This is contrary to early conclusions by Bhushan and Sibley (1982).

Recognizing the author's keen interest to generate simple factors for use by engineers, this discusser wishes to elaborate on several points regarding the possible limitations on the use of Table 1:

1 Presently, there is lack of endurance test data for all ceramic bearings. Such test data may be desired to assess the load capacity of rolling element bearings.

2 Most of the author's tests were performed prior to 1975,

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which is about the time Scott et al. (1971, 1973) published their experimental results on silicon nitride rolling elements. The author has correctly pointed out in the paper that the fatigue life of ceramic rolling elements depends on the size of voids and surface defects, but with improved manufacturing methods in recent years, much longer fatigue life should be expected. Based on the author's own argument, it is clear that Table 1 is applicable to silicon nitride rolling elements manufactured in the early 1970s, rather than in the late 1980s.

3 The results reported on the five-ball tests by the author (Fig. 1) contradict the RCF roll-disk test rig data for silicon nitride by Baumgartner (1973) shown in Fig. 2. The latter's test results yield a life about eight times that of the M50 steel rod at the same maximum stress level. Since the author's test and Baumgartner's test were conducted at about the same time and using very similar material, the reason the latter test yields significantly greater relative life than the author's test is a question of interest.

Although experiment shows that a silicon nitride ball (or rod) fails by spalling as with steel rolling elements, there is reason to believe that the spalling mechanism in ceramics is different from that of steel. In general, ceramic is a brittle material weak in tension but strong in compression. Although the process of fracture (or spalling) in ceramic rolling contacts is not well understood, the existence of tensile stress along the edge of the contact area and its effect on Hertzian fracture has been analyzed (Lawn, 1967; Johnson, 1983). Morrison et al. (1984) reported that fatigue spalls on ceramic balls in the hybrid bearings originate at the Hertzian cracks. The load-life exponent of the hybrid bearing is about the mean of the theoretical value of 3 for steel ball bearings and the author's value of approximately 5.4 from a five-ball test rig. Valori (1975) suggests that surface-initiated cracks causing fatigue spalling will not occur below a critical load or Hertz stress level.

In the five-ball test rig, the nominal area of contact is circular with the maximum tensile stress approximately 17 percent of the maximum contact stress. This drops to about 10 percent for an elliptical contact of axis ratio equal to 10. This smaller tensile stress will enable a greater load capacity in a ball (or roller) to race contact. Another possible cause for the conflicting data in five-ball and RCF rigs using ceramic specimens is the existence of spin in the five-ball tester, which can generate tensile stress inside the contact and initiate cracks or spalls.

Recent tests conducted in Japan by Komeya and Kotani (1986) using three 3/8 in. steel balls and silicon nitride disks show at least twice the fatigue life of the same test rig with steel disk under the same load (400 kgf).

Finally, the author has reported conflicting results in frictional loss in ceramic hybrid bearing tested by the authors and by Reddecliff and Valori (1980). The author attributed his finding of higher torque to the higher sliding traction in the steel-ceramic contact than in the steel-steel contact, which has been observed in early ball-disk rolling/sliding experiments (Delal et al., 1975). However, for high-speed ball bearings, the use of lightweight ceramic balls tends to decrease the inner ring contact angle (or less spin) and shorter contact ellipse (lower spin moment); both of these factors can contribute to lower friction loss than in the case where steel balls are used.

It is of interest to point out a recent observation by Aramaki et al. (1988) on testing silicon nitride hybrid ball bearings of two types, i.e., 95 mm bore, 40 deg contact angle, 1000 N axial load, lubricated by grease, and 65 mm bore, 17 deg, 75 N load lubricated with an oil and air mixture. These tests show greater (30-50 percent) reduction in power loss in hybrids than with steel balls when the bearing speed is greater than 3000 rpm.

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## T. E. Tallian[2]

1 The author rightfully stresses the significance of the high stress levels resulting for a given load from the high elastic modulus of the ceramics. It is not uncommon to see comparisons of the fatigue life of rolling contacts between steel and ceramics, based on identical *stress*, even though, for any practical purpose, the comparison must be based on *identical load*.

However, the disadvantage in stress arising from the high modulus of ceramics is severe only when both the rings and rolling elements are made of ceramic. *Hybrid* bearings (ceramic rolling elements only) suffer much less extra stress from the high modulus of the ceramic. Since hybrids are so much easier to use than full ceramic bearings, they are the design of choice for *high-speed* applications, leaving full ceramic designs for *high-temperature* or *dry lubricated* applications where no other solution serves.

2 While hybrid bearings running in conventional lubricants have undergone sufficient evaluation to be seriously considered where they present a life advantage, the same cannot yet be said about full ceramic bearings in dry lubricant. More than a decade of research has been devoted to this configuration, yet no consistently funded product development is reported by any group that had control over *fabrication and application* of the component, including the lubricant, and was faced with a *continuing major engineering need* that only a full ceramic bearing would solve. As a result, only pilot quantities of dry lubricated ceramic bearings have been made or installed. Neither the ceramic material nor its finishing are fully evolved. As the paper states, we do not even have proven solutions for mounting ceramic rings. All this is the case, since a way has so far always been found to design around the need for a truly high-temperature (over 800°F) rolling bearing (or, for that matter, a long-lived bearing, which must run in a cryogenic liquid).

It is instructive to contrast this situation with the development of aircraft gas turbine mainshaft bearings. The evolution of their material, finishing, and mounting techniques and lubrication methods to the present state has taken about twenty years, during which such bearings were made and used in large numbers. All improvements were incremental and driven by copiously funded major engineering centers at aircraft engine manufacturers and military users. The motivating force was, that turbine engine longevity was largely bearing limited and no design other than rolling bearings worked. If a similar situation were to arise for full ceramic bearings, then we would eventually see them realize their great potential and become a practical machine component.

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## Author's Closure

The author would like to thank Dr. Y. P. Chiu and Mr. T. E. Tallian for their respective discussions. Both men have made significant contributions to rolling-element bearing technology over the years and their discussions further add to the author's paper.

Dr. Chiu states that "the results of the author's Table 1 show a very low (relative) load (dynamic) capacity for full ceramic bearings, notably silicon nitride... contrary to early conclusions by Bhushan and Sibley (1982)." Bhushan and Sibley (1982) did not compare the dynamic load capacities of bearing steel and silicon nitride. What they did in their paper was to compare the experimental lives reported in the literature for silicon nitride rolling-element test specimens or hybrid bearings with silicon nitride rolling elements with the predicted lives of steel bearings or test elements using the Lundberg-Palmgren theory (Lundberg and Palmgren, 1947, 1949, 1952) without life adjustment factors (Bamberger et al., 1971). If Bhushan and Sibley had put life adjustment factors into their predictive lives for the steel bearing and test elements, they would have found that the predicted lives would have exceeded the experimental lives obtained with the silicon nitride in nearly all the tests reported. Had Bhushan and Sibley (1982) calculated the dynamic load capacities for the tests reported they would have found that in all the tests the dynamic load capacity of the silicon nitride would have been less than that of bearing steel. Bhushan and Sibley (1982) did not report on other ceramic materials in their paper.

Dr. Chiu is correct in pointing out that the data reported for the silicon nitride in the author's Table 1 were generated in the 1970s. However, the author could not find in the reported literature any other data except those of Morrison et al. (1984). While the author would expect improvement to have been achieved in the 1980s in the performance of silicon nitride and the other ceramic materials reported in the table, it would be reasonable to expect that these improvements, if they exist, would have been reported in the technical literature.

With regard to the comparison of the Baumgartner data (Baumgartner et al., 1973) with AISI M-50 (Fig. 2), the author reviewed data reported by Bamberger and Clark (1982), which were also generated in the rolling-contact (R-C) fatigue tester. The data generated by Baumgartner et al. (1973) were typical but on the low side of CVM AISI M-50 bearing steel fatigue data obtained with the R-C tester. Likewise, the data for CVM AISI M-50 reported in the author's Fig. 1 are consistent with similar data obtained in the NASA five-ball fatigue tester (Zaretsky et al., 1982). This would suggest differences in either manufacturing processes or material quality between the batches of hot-pressed silicon nitride tested by Baumgartner et al. (1973) and Parker et al. (1974). Both batches of material came from a single supplier.

Dr. Chiu states that "the load-life exponent of the hybrid bearing is about the mean of the theoretical value of 3 for steel ball bearings and the author's value of approximately 5.4 (for silicon nitride) from the five-ball test rig." In order to ensure that there is no misunderstanding of the author's data, the stress-life exponent *n* given in Table 1 would be for a full-complement ceramic bearing and not for a hybrid bearing. For the silicon nitride material, the value for *n* of 16.1 was independently determined from Parker et al. (1974, 1975) and Baumgartner et al. (1973) in the five-ball rig and the R-C rig, respectively. For the hybrid bearing calculations of Table 3, the author assumed ceramic rolling elements and steel races. The author further assumed that the ceramic rolling elements would not fail. Hence, it was assumed that the life of the bearing was solely dependent on the failure of the steel races. Since the stress-life exponent *n* of bearing steel is 9, the load-life exponent for a steel bearing would be 3. However, should there be a combination of steel race failures and ceramic rolling-element failures, the apparent load-life relation of the hybrid bearing would fall to between 3 and 5.4. If only the silicon nitride rolling elements failed, then the load-life exponent would be around 5.4. This is illustrated by the work of Morrison et al. (1984).

Morrison et al. (1984) tested four groups of hybrid 45-mm bore angular-contact ball bearings having double-vacuum melted (VIM-VAR) AISI M-50 steel races and silicon nitride balls. There were seven balls in each bearing. The bearings were tested at four thrust loads. These were 4.45, 5.00, 6.45, and 9.56 kN (1000, 1125, 1450, and 2150 lb). These loads produced inner-race maximum Hertz stresses of $1.95 \times 10^9$, $2 \times 10^9$, $2.17 \times 10^9$, and $2.44 \times 10^9$ N/m$^2$ (281, 290, 315, and 354 ksi), respectively. The failure index on the number of bearings failed out of those tested for each load were 5 out of 10, 4 out of 20, 11 out of 20, and 5 out of 10, respectively. All of the failures for each thrust load were spalling of a silicon nitride ball. There were no failures of the steel raceways. The experimental lives obtained by Morrison et al. (1984) are given in Table 4, together with the theoretical lives calculated by the author for full-complement AISI M-50 bearings having the same dimensions. The life and dynamic capacity of the hybrid bearing were less than the theoretical life and capacity of full-complement AISI M-50 steel ball bearings.

Morrison et al. (1984) reported that the load-life exponent for the hybrid bearings was 4.29 with 95 percent confidence limits of 3.16 and 5.42. Based upon a load-life exponent of 4.29, the stress-life exponent *n* for these bearings is approximately 13, which is solely a function of the failure of the silicon nitride balls. From the experimental data, the actual stress-life exponent was approximately 14. These values are not significantly less than those obtained in the five-ball and R-C rigs previously discussed.

The author has read the paper by Komeya and Kotani (1988). They concluded that "silicon nitride retains a rolling life equivalent to or better than that of a conventional bearing steel." Unfortunately, the information reported in the paper is not sufficient to determine with reasonable certainty whether the steel and ceramic specimens were run under the same load or the same stress.

The work of Aramaki et al. (1988) comparing hybrid bearings with full-complement steel bearings reinforces the author's conclusion that differences in power losses are a function of the individual bearing design. For the same design the operating contact angle on the inner race for the full-complement steel bearing can be higher than with a hybrid bearing. The higher contact angle can result in higher heat generation due to increased spinning relative to the same bearing using lighter weight silicon nitride balls. However, the geometry of a full-complement steel bearing can be optimized to reduce heat generation. Differences in Coulomb friction properties between steel and silicon nitride should not have any effect on rolling-element bearing power losses under reasonable elastohydrodynamic lubrication conditions.

The author agrees with Dr. Chiu's statement that "there is a lack of endurance test data for all (full-complement) ceramic bearings." However, manufacturers of these bearings have been claiming without the benefit of data that these bearings "will last 5 to 100 times longer than high-performance steel bearings in standard operating environments and infinitely longer in hostile operating environments." These same manufacturers further claim that "ceramic bearings run 100 percent faster and 30 percent cooler than steel bearings." Considering that steel bearings have been run to speeds of 3 million DN (DN equals bearing bore in mm multipled by bearing speed in rpm) at lives equivalent to those obtained at lower speeds (Bamberger et al., 1976), it is difficult to imagine the

Table 4 Comparison of experimental lives obtained with hybrid 7209-size angular-contact ball bearing having silicon nitride balls with theoretical lives of full-complement AISI M-50 angular-contact ball bearings (contact angle, 27 deg; speed, 9700 rpm, lubricant, MIL-L-23699, oil-in temperature, 311 K (100°F)) (Morrison et al., 1984)

| Thrust load, N (lb) | Inner-race stress, N/m² (ksi) | $L_{10}$ life, millions of inner race revolutions | | | Relative hybrid life to AISI M-50 | | Relative hybrid dynamic capacity to AISI M-50[d] | |
|---|---|---|---|---|---|---|---|---|
| | | Experimental hybrid[a] | Predicted AISI M-50 | | | | | |
| | | | CVM[b] | VIM-VAR[c] | CVM | VIM-VAR | CVM | VIM-VAR |
| 44 500 (1 000) | $1.95\times10^9$ (281) | 404 | 4698 | 9396 | 0.09 | 0.05 | 0.24 | 0.19 |
| 50 000 (1 125) | $2.00\times10^9$ (290) | 244 | 3358 | 6716 | 0.07 | 0.04 | 0.24 | 0.19 |
| 64 500 (1 450) | $2.17\times10^9$ (315) | 82.0 | 1641 | 3282 | 0.05 | 0.03 | 0.24 | 0.19 |
| 95 600 (2 150) | $2.44\times10^9$ (354) | 15.1 | 548 | 1096 | 0.03 | 0.02 | 0.23 | 0.18 |

[a] Silicon nitride ball failures only, no steel race failures.

[b] Life adjustment factors: material and processing 6; lubricant, 2.9 (Bamberger et al., 1971).

[c] Life adjustment factors: material and processing, 12 (Bamberger et al., 1976); Lubricant, 2.9 (Bamberger et al., 1971).

[d] Load-life exponent: hybrid bearing, 4.29; steel bearing, 3.

basis for the performance claims attributed to the full-complement ceramic bearings.

Ceramic and hybrid bearings have found application in severe chemical and industrial environments where conventional steel bearings are adversely affected by the environment. Hybrid bearings have also found limited application in high-speed machine tool spindles and unmanned missile applications. However, full-complement ceramic rolling-element bearings cannot be retrofitted into an existing design meant for a full-complement steel bearing without redesign of the application. Further, full-complement ceramic rolling-element bearings, and hybrid bearings with today's technology for a given envelope size and load, will not produce longer fatigue lives than an equivalent steel bearing nor necessarily run faster. The problems faced by ceramic bearings are the same as those for other ceramic structures. These are:

1 Fracture toughness
2 Batch-to-batch quality assurance
3 Nondestructive inspection methods
4 Manufacturing technology
5 Design methods and optimization
6 Environmental interaction

As these problems are solved, then as Mr. Tallian states "we would eventually see them (full-complement ceramic bearings) realize their great potential and become a practical machine element."

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