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Ceramics for High Performance Rolling Element Bearings: A Review and Assessment

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SUMMARY

Modern, high performance structural ceramics offer the potential for a significant increase in many of the performance characteristics of both rolling element and sliding contact bearings. Thus, substitution of high performance ceramics for conventional metals is becoming an increasingly attractive option in applications where systems performance is currently constrained by state-of-the-art bearing technology. This paper will review the potential benefits of ceramics and provide selected examples where these benefits have been demonstrated in research and development programs. The emphasis will be on rolling element bearings. The desired properties for ceramic bearings and the properties of currently available high performance ceramics will be reviewed. The problem areas which are impeding the implementation of ceramic bearing technology, and directions for future research and development to resolve these impediments, will be discussed.

1. INTRODUCTION

The development of the first high performance structural ceramic, fully dense hot-pressed silicon nitride (HPSN), in the late 1960s coincided with a growing awareness that new materials for rolling elements would be required to meet the evermore stringent systems demands imposed on aircraft gas

DEMONSTRATED BEARING PERFORMANCE IMPROVEMENTS →	ENHANCED SYSTEMS PERFORMANCE
• INCREASED LIFE	• REDUCED SPECIFIC FUEL CONSUMPTION (SFC)
• INCREASED SPEED	• INCREASED TIME BETWEEN OVERHAUL
• REDUCED HEAT GENERATION	• INCREASED POWER DENSITY
• LUBRICATION STARVATION TOLERANCE	
• INCREASED OPERATING TEMPERATURE	
• INCREASED CORROSION RESISTANCE	
• BRINELLING RESISTANCE	

Fig. 1. Potential benefits of ceramics in bearings.

turbine bearings. Thus, the past dozen years have seen a number of modestly funded research and development programs aimed at the application of HPSN element bearings in high performance gas turbine engines.[1–7] What advantages do high performance ceramics offer the bearing designer to merit this effort?

Figure 1 lists the effects that ceramic elements could have on bearing performance. These benefits have their ultimate pay-off in several areas of enhanced systems performance, also listed in Fig. 1. The increased fatigue life of HPSN rolling elements has been demonstrated for roller elements by Baumgartner,[2] and for balls by Dalal,[4] both via rig tests. Baumgartner[5] has reported verification of the increased fatigue life of HPSN rolling elements in actual bearing tests. In this reference, Baumgartner also discusses the mechanism of fatigue failure in NC-132 HPSN,* pointing out that the fatigue spalls which cause failure result from non-elastic behavior of this material. The increased fatigue life of NC-132 HPSN rolling elements (balls) is very dependent on the quality of the surface finish, as shown by Dalal's data in Table 1[4] and Sibley's data.[7] Increased speed (DN) results from the lower mass density of silicon nitride as compared to steels. This lower density will also reduce skidding. Sibley[7] has pointed out that ceramic balls can reduce heat generation. Thus, they may allow the reduction of the size of oil cooling systems, thereby reducing cost and vulnerability.

Perhaps one of the most intriguing benefits of ceramic rolling element bearings is the possibility of lubrication starvation tolerance. Bersch[3] has reported that a bearing with HPSN rollers survived a rig test for 117 h with the lubricant shut off. The bearing condition at the end of the test was reported as 'good'! Figure 2 shows the result of a lubrication starvation test

* NC-132 is a commercial hot-pressed silicon nitride (containing magnesium oxide additive) manufactured by the High Performance Ceramics Division of Norton Company, Worcester, Massachusetts, USA.

TABLE 1
Rolling Four-ball Fatigue Life Test Data on 17·5 mm CVM M-50 Steel and Silicon Nitride Balls Finished by Various Methods

Spindle ball	*Spindle speed /rpm*	*Max. Hertz stress /GPa (ksi)*	*No. of CVM M-50 steel support ball set failures*	*Test life /10⁶ revs*	*Spindle ball condition after test*
M-50	5 200	4·7 (680)	0	20·2	Spalled
			0	3·2	Spalled
			1	26·0	Spalled
			0	11·0	Spalled
			0	7·1	Spalled
			0	11·7	Spalled
As-received silicon nitride (NC-132)	5 200	4·7 (680)	2	117·3	Spalled
	10 000	5·5 (800)	1	12·0	Spalled
	10 000	5·5 (800)	0	66·6	Spalled
	10 000	5·5 (800)	0	24·6	Spalled
	10 000	5·5 (800)	1	41·5	Spalled
	10 000	5·5 (800)	2	18·3	Spalled
Diamond lapped silicon nitride (NC-132)	10 000	5·5 (800)	1	190·8	Intact
			1	183·6	Intact
			3	183·0	Intact
			1	182·4	Intact
			3	102·0	Spalled
			3	183·6	Intact

of an all NC-132 HPSN (except for the cage) roller bearing in an engine. All components survived approximately one hour of full engine testing. This attribute of silicon nitride for rolling element bearings offers enormous potential for aircraft safety in general and battlefield survivability in particular. Sibley has reported[7] that in one instance an HPSN ball bearing, with M-50 steel races running at 93 000 rpm and 200 N load, survived the complete destruction of the cage. In this instance the HPSN balls and M-50 races both emerged in excellent condition. This is further substantiation of the ability of HPSN rolling elements to endure very abusive environments.

Given the above benefits of ceramics, their future application in high speed and ultrahigh speed turbomachinery would seem to be a natural progression. A potential application for ceramic roller bearings is the adiabatic turbocompound diesel engine (ATDE). In the ADTE there is no radiator (or forced cooling), the cylinder walls are insulated and waste heat previously rejected to the environment via the radiator is now entrained in the exhaust. The hot exhaust is then run through a small gas turbine, the output of which is geared back into the main power shaft. This is the

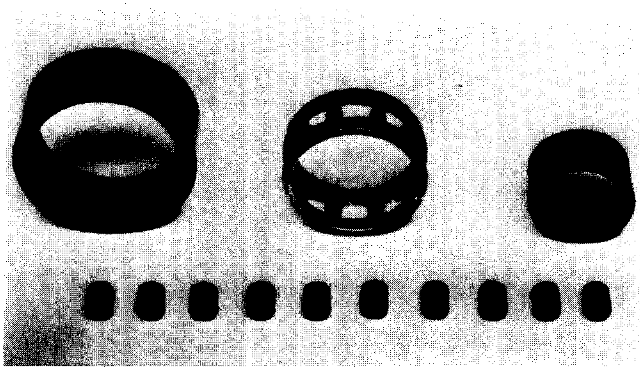

Fig. 2. NC-132 HPSN roller bearing tested in an engine 50 min at 39 000 rpm without lubricant.

turbocompounding feature. The ultimate refinement of such an engine is the minimum friction–minimum heat rejection ATDE as described by Bryzik and Kamo.[8] In this refinement, as illustrated in Fig. 3, sliding friction is converted into rolling friction with an attendant reduction of friction by a factor of 3–5 times. If the piston rings are replaced by a piston which operates as a gas bearing, as also shown in Fig. 3, friction and heat rejection will be further reduced. Full implementation of this concept requires bearings which do not require oil lubrication or oil cooling. Thus, dry lubricated ceramic bearings are the currently favored design option. Should this be demonstrated as feasible technology, the demand for ceramic roller bearings could be very large. In any event, it is apparent that there are several applications in which ceramic bearing elements would provide significant benefits. We now turn our attention to the question 'Which ceramics?'.

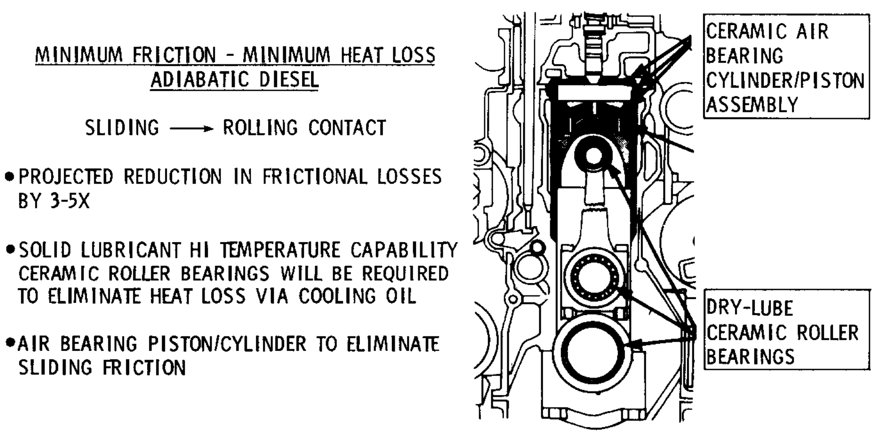

Fig. 3. Ceramic bearings for diesel engines.

2. POTENTIAL CERAMIC BEARING MATERIALS

Before discussing which ceramics have potential for application as bearing materials we must have a clear idea of what properties we would like in an enhanced bearing material. Table 2 provides such a listing. The desire for low density has been discussed above. However, it is important to point out that low density cannot be provided by porosity in the bearing material. From a microstructural standpoint the bearing must be essentially 100% theoretical density. The need for hardness, strength and corrosion resistance are self-explanatory. While a high fracture toughness is listed as a desired property, this must be put into the proper context. M-50 steel, the state-of-the-art high performance bearing steel, has a fracture toughness of only about 15 MN $m^{-3/2}$. Hot-pressed silicon nitride, which gives excellent rolling contact fatigue life, has a fracture toughness value of only 5 MN $m^{-3/2}$. Thus, a value somewhere between 5 and 15 MN $m^{-3/2}$ is a realistic goal. What is of note is that while fracture toughness is an important parameter for high performance bearings, the magnitude of the toughness which is required is much less than in many other highly loaded structural applications. This is an important point for the application of ceramics to such bearings. A low value of elastic modulus, E, is desired to minimize contact stresses. However, all of the current generation high performance ceramics (silicon nitride, silicon carbide and zirconia) have values of E equal to, or significantly greater than, steel. The upper use temperature listed is far above that which any oil-lubricated bearing could tolerate. However, under lubrication starvation or uncooled, dry lubricant conditions, such high temperature capability is to be desired. Finally, we must address the subject of failure mode. While we do our best to reduce the possibility of bearing element failure (and consequently bearing failure), we cannot entirely eliminate it. Thus, when a bearing element does fail it should be in a relatively benign mode such as spalling, rather than by catastrophic

TABLE 2
Desired Properties for Bearing Ceramics

Fracture toughness, K_{1c}	High	> 5 MN $m^{-3/2}$
Hardness	High	$> 1\,200$ kg mm^{-2}
Elastic modulus	Low	< 210 GPa
Density	Low	< 4 Mg m^{-3}
Bend strength	High	> 700 MPa
Corrosion resistance	High	—
Upper use temperature	High	> 800 °C
Failure mode	'Steel-like' spallation	Small spalls

TABLE 3
Properties of High Performance Structural Ceramics and M-50 Steel

Property	*Silicon nitride*	*Silicon carbide*	*Alumina*	*Zirconia*	*M-50 steel*
Description	Hot-pressed NC-132	Sintered	Fully dense sintered	Sintered transformation-toughened	Wrought ingot
Fracture toughness, K_{Ic} /MN m$^{-3/2}$	5–6	4	5	8–10	12–16
Hardness, H /kg mm^{-2}	~1 800–2 000	~2 800	~2 000	~1 300	~800
Elastic modulus, E /GPa	310	410	385	205	210
Density, ρ/Mg m^{-3}	3·2	3·1	4	5·6	8
Modulus of rupture /MPa	700	450	550	600–900	NA
Corrosion resistance	High	High	High	High	Moderate
Upper use temperature /°C	1 100	1 400	1 000+	800–900	325
Failure mode	Spalling	Fracture	Fracture	Spalling	Spalling

fracture. Clearly, the spalls should be as small as possible and certainly not significantly larger than those resulting when M-50 bearing elements fail.

Given the above list of desired properties, how do the modern high performance structural ceramics appear? Table 3 lists the properties of NC-132 HPSN, sintered silicon carbide, sintered alumina, sintered transformation-toughened zirconia (TTZ) and M-50 steel. While HPSN has been the choice for ceramic rolling elements in the demonstration programs described above, transformation-toughened zirconia has a rather intriguing set of properties. It is possible that, if this material could be fabricated with near zero porosity and a significantly reduced grain size, it would be an outstanding rolling element. In any event the silicon carbide, the alumina and the TTZ materials all have potential as sliding bearings materials.

Given the performance gains and successful bearing demonstrations described in the introduction and the desirable properties described above, why are the ceramic bearings not in wider use today? The following section deals with that question from the standpoints of design and manufacturing technology.

3. PROBLEM AREAS

In most instances where the potential for material substitution exists, there are institutional, technological and economic factors which are actual or perceived problems, and which act to retard the rate of implementation of the new technology. In the specific case of ceramics for rolling element bearings these factors include brittleness, different design practices, reliability and reproducibility of product, and cost.

Ceramics, even the modern high performance ceramics, are brittle materials. Yet, as we saw in Fig. 5, M-50 steel is also a brittle material (low fracture toughness). Since current metallic high performance bearings utilize brittle materials, bearing designers are already familiar with probabilistic design techniques. Also, at least in the case of HPSN, the rolling contact fatigue failure modes of the metallic and ceramic bearings are the same, namely spalling. Thus, brittleness *per se* is not a problem. When people cite it as a problem they are probably using the word as a form of shorthand for three real problems often associated with, but not necessarily related to, brittleness. First, for ceramics other than fully dense silicon nitride and tough zirconias, there is the worry about failure mode (i.e. rolling elements made of the other ceramics fracture rather than spall). Secondly, existant design codes, predictive models and related computer programs have been developed and optimized based on steels. As pointed out by Bersch[3] and Sibley,[7] this produces both non-optimal designs and erroneous life and heat generation rate predictions when applied to ceramics with their very different properties. Thus, a critical need is to generate design and life prediction programs appropriate for ceramics—in particular, fully dense silicon nitride. The authors are aware that some work on the development of such codes for both metal/ceramic hybrid and all-ceramic bearings is currently under way. Thirdly, greater scatter in the performance of ceramic (HPSN) rolling elements than that in M-50 elements was occasionally observed prior to 1980. Such scatter in properties may be exacerbated by brittleness but its root cause was the small scale and relative immaturity of ceramic bearing manufacturing technology. This scatter has been reduced or eliminated over the past several years by process improvements which stress cleanliness and control. In some recent cases it has been observed that NC-132 HPSN is more reliable (less scatter) than M-50 steel.

Until recently, silicon nitride rolling elements have been made by hot-pressing billets, cutting the billets into blanks, rough machining the blanks into spheres or cylinders and then finally grinding and polishing the elements. All machining, grinding and polishing requires diamond abrasives and is thus inherently expensive. Additionally, there is at present no cost-effective, real-time, high-reliability quality control methodology to identify substandard blanks prior to adding value in the finishing process, or even to ensure high life elements after machining has been accomplished. In order to ensure high-reliability ceramic rolling elements, a manufacturing-based reliability strategy must be developed, as illustrated in Fig. 4. The key points in Fig. 4 are the focus on in-process quality assurance (QA), analysis and

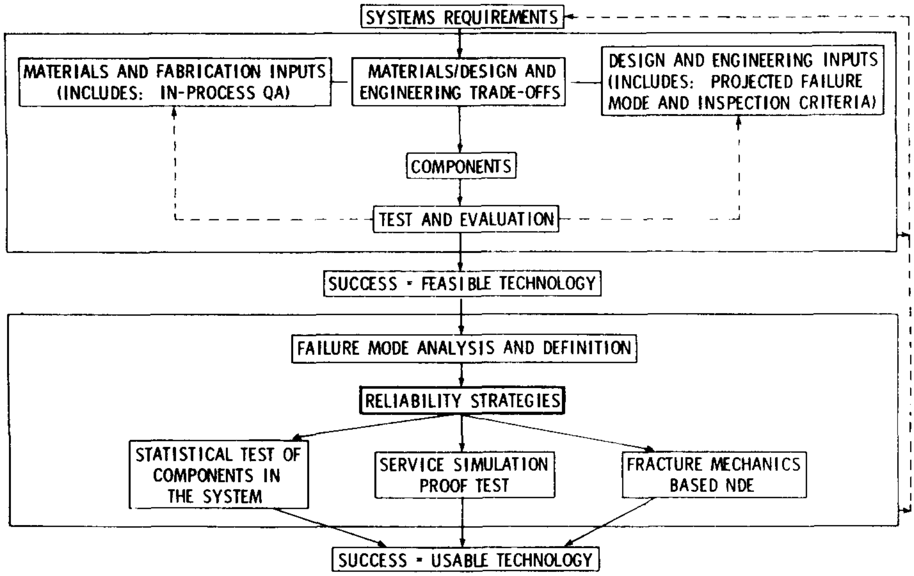

Fig. 4. Brittle materials design/reliability—systems trade-off logic.

definition of failure modes leading to realistic inspection criteria, and the development of a post-processing quality monitoring methodology which will both measure the product quality and provide input into how the process should be modified to correct any detected deficiencies.

Development of such a manufacturing based reliability strategy will clearly improve reliability and reproducibility of the ceramic rolling elements. But what about cost? Part of the current high cost of ceramic rolling elements is attributable to the fact that thus far they have only been produced in limited size prototype batches. However, part of the high cost is also the result of starting with billets which require excessive diamond cutting and polishing. The economic feasibility of ceramic bearing elements requires techniques to fabricate blanks to near net shape.

Currently, one of the authors is involved in developing a pilot scale process for producing near net shape silicon nitride bearing components. The recent technical advances in this area will allow for the cost-effective manufacturing of these components. Work is also proceeding in the area of quality assurance. Non-destructive examination (NDE) techniques as well as proof testing are being evaluated at several stages in the manufacturing process. The goal of this effort is to produce bearing elements that are competitive with high performance steels. Examples of some net shape components are shown in Fig. 5. Preliminary test results of near net shape parts show rolling contact fatigue life comparable to, or better than, that of hot-pressed billet material.

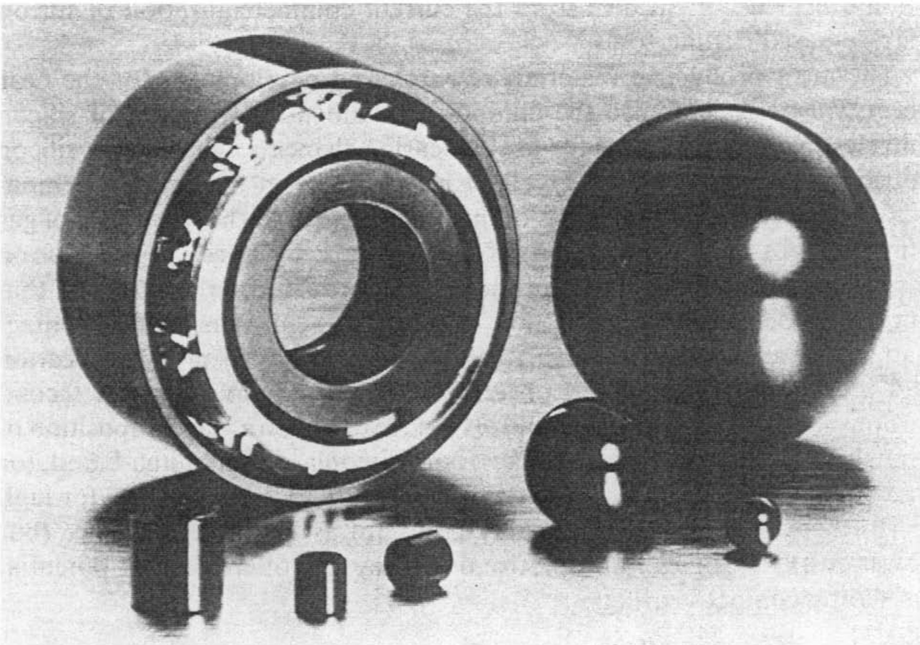

Fig. 5. Examples of net shape components.

4. DIRECTIONS FOR FUTURE RESEARCH

The main thrust of research and development on ceramics for rolling element bearings for the near term future must be on processing and manufacturing technology if the two impediments to application, reliability and cost are to be overcome. In particular, a method to produce near net shape preforms, from which fully dense silicon nitride elements can be fabricated, is an urgent requirement. As mentioned above, at least one US manufacturer is working in this area. One potential route to achieve this is to use a two-step nitrogen overpressure sintering process to effectively 'cladless' hot isostatically press (hip) the silicon nitride elements. In this process silicon nitride preforms are sintered to the closed porosity state (about 92–95% of theoretical density) under one or two atmospheres of nitrogen and then the nitrogen pressure is increased to 20–100 atm. The result, as described by Gazza *et al.*,[9] is a material with microstructure and properties similar to HPSN. The advantages of such a technique over conventional hipping technology are less potential for surface reactions or damage, less labor and lower capital cost for equipment. Both net shape processing and quality assurance of small high quality fully dense silicon nitride components should benefit a great deal from the current commercialization of silicon nitride-based cutting tools.[10,11]

The most productive materials research and development for the near term will be to optimize the composition and microstructure of silicon nitrides (including sialons) for use as bearing elements. The current silicon nitrides which have shown excellent performance in the bearing demonstration programs are materials optimized for use in the hot flow path of gas turbines, not as bearing materials! Recent work by Lucek at the Norton Company on optimized compositions of silicon nitride has shown that improved performance is possible. This improvement in rolling contact fatigue life and performance variability is obtained by proper densification aid addition, as well as key process parameter manipulation. A second promising area would be to optimize the microstructure and composition of transformation-toughened ceramics, both zirconia- and alumina-based, for bearing application. These materials, in addition to their potential for high performance rolling elements, may be useful as lower performance (but lower cost) bearings for automotive use. They also offer excellent potential as sliding contact bearings.

5. CONCLUSIONS

This paper has shown that ceramic materials (NC-132 HPSN in particular) have demonstrated high potential and feasibility for application as rolling elements in bearings.

The major point of this paper is that the significant potential of ceramic bearings will require a major effort in manufacturing science and technology in order to be realized. Because such an effort must be highly focused and will require a large expenditure for any given material to be developed, only materials such as fully dense silicon nitride with demonstrated bearing performance are likely to be beneficiaries of such programs.

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