SINTERED ALPHA SILICON CARBIDE PUMP BEARINGS—TRIBOLOGICAL MATERIALS OPTIMIZATION TO IMPROVE RELIABILITY

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ABSTRACT

The material properties of sintered silicon carbide, such as universal corrosion resistance, hardness, strength, and thermal conductivity, offer a great potential as sealless pump bearings and mechanical seal faces.

In order to exploit the positive properties of pure silicon carbide, one also has to deal with its most negative property, brittleness. The brittleness requires knowledgeable ceramic design combined with appropriate material properties as the necessary requirements for reliable performance of a ceramic component.

Both materials properties and design features are discussed with regard to the successful application of sintered silicon carbide as sealless pump bearings.

INTRODUCTION

In the past, two problems have prevented the widespread use of sintered silicon carbide components for tribotechnical, wear reducing applications: a) a complicated production process marked by relatively high costs and inadequate availability, and b) the brittleness of ceramic materials [1]. Recently, progress has been made in both of these areas. The technology used for producing sintered SiC has become cost competitive, and much has been learned about ceramic-oriented brittle materials design.

There have been only a few reports on investigations aimed at clarifying the behavior of ceramic materials in general, and of sintered SiC in particular, for tribological applications. Previously published technical literature describes the typical material properties of SiC and the advantages to be drawn from its use. The potential applications include hydrogenation of coal [2, 3], desulfurization of flue gases [4], and adaption of pumps for very corrosive and/or abrasive liquids, primarily in the chemical industry [5, 6, 7, 8]. Various reports have been written on theoretical and experimental investigations concerning the fundamental consideration that the strong covalent bond of SiC should make it less susceptible to adhesive seizure and, thus, have a relatively low coefficient of friction [9]. Model investigations involving SiC have shown the coefficients of friction against various materials, even itself, to be a function of contact stress [10] and have documented the anisotropic wear behavior of monocrystalline SiC crystals [11].

In the past, excellent results have been achieved in developing sliding bearings for hermetically sealed pumps [12] optimized for severe duty usage in the chemical industry. Pumps of this kind, such as canned motor or magnetic drive, are designed to be leak proof, whether in operation or shutdown, and they are, therefore, of great advantage for environmental protection. However, their design is such that the sliding bearings of the pump shaft must be flushed and lubricated by the pumped medium. This caused problems, because existing materials used for sliding bearings could not cope with these harsh conditions and were quickly destroyed by corrosion and abrasion. Consequently, pump operation was always difficult and considerable costs were incurred because of short service life of the bearings.

Sintered SiC has now improved the situation. Hermetically sealed pumps, equipped with media-lubricated sintered silicon carbide sliding bearings [Figure 1] have demonstrated consistent long life and reliability, and are now standard in many chemical pumps. This technical development not only benefits the environment, but is also of great economic value. However, there is and always has been, one problem concerning the use of sintered silicon carbide in sliding bearings—its relatively limited dry running capability as compared to its excellent tribological performance under boundary lubrication and lubricated conditions.

Concepts of product development to improve reliability of silicon carbide sliding bearings is discussed along with materials optimization for better tribological performance under all operating conditions.

CONCEPTS OF PRODUCT DEVELOPMENT

Product development of sintered silicon carbide for slide bearings and for mechanical seal rings must concentrate on improving its weak points without degrading its strong points.

If the tribological reliability in adverse conditions of lubricant film breakdown or loss is to be improved, one must first carefully consider the key properties of sintered SiC that are the basis for its successful use in bearings and seals, and maintain them. These key properties (Tables 1 and 2) are:

- *Universal corrosion resistance.* Any liquid media (alkalis, acids, organic solvents) can be used as a lubricant for mechanical seal rings and hermetically sealed pump bearings as compared to silicon bonded silicon carbide (SiSiC) which would be attacked in alkalis and some acids.
- *Outstanding mechanical wear resistance.* Liquids containing abrasive particles do not restrict the use of sintered SiC.
- *Thermal stability.* Corrosion resistance and wear resistance are not influenced by changing temperatures. Thermal shock in boundary lubrication and short (seconds to minutes) dry run situations will not cause cracks in silicon carbide components.

The coefficients of friction of hard, wear resistant ceramic materials and of surface coatings are always > 0.1 under dry run conditions. This value is too high to allow the development of reliably performing dry running bearings, especially under high loads. Although sintered SiC easily resists the heat that is produced, high temperatures may cause high thermal stresses in the overall structure and components that results in breakage and failure [12]. Since materials research indicates that it is improbable to develop hard ceramic materials with dry run coefficients of friction lower than in lubricated conditions (< 0.01), the concepts for improved product development must take these factors into consideration:

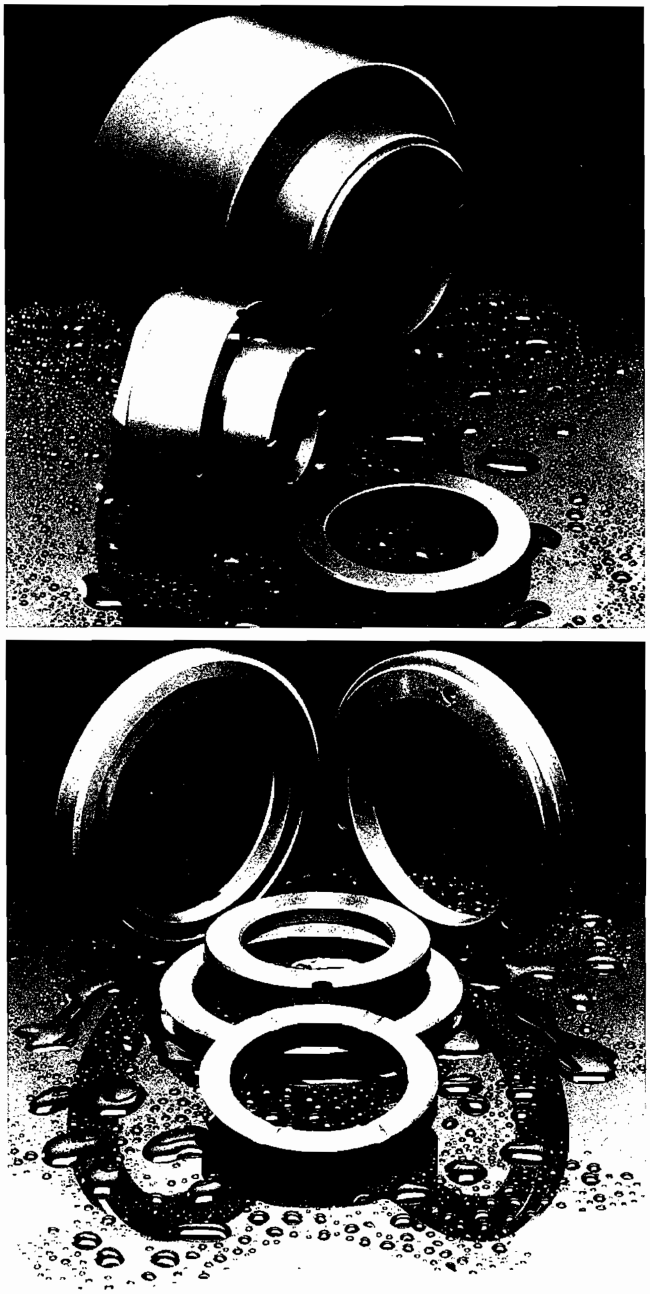

Figure 1. Bimodal Sintered Alpha SiC Axial and Radial Slide Bearing Components

- Stabilization of the hydrodynamic lubricant film.
- Prevention of dry run.
- Reduction of friction and wear if hydrodynamics break down.

The stabilization of the hydrodynamic lubricant film of a running bearing can be achieved in two ways: first, the evaluation of the optimum design, including the topography of the slide face. Second, the optimization of the SiC bearing material. Without negatively affecting the universal corrosion resistance, the microstructure of the SiC can be improved with regard to tribological performance by improving the grain morphology. This is achieved by incorporating pores which act as lubricant pockets, and/or by incorporating graphite particles which act as a solid lubricant.

Table. 1. Mechanical and Physical Property Values of Bimodal Sintered Alpha SiC.

Property	*Units*	*Temperature (°C)*	*Value*
Density	g·cm^{-3}	20	3.10
Porosity	Vol %		3.5
Hardness (Knoop 100)		20	2700.0
Compressive Strength	MNm^{-2}	20	2200.0
Bend Strength (4-pt)	MNm^{-2}	20	410.0
		1000	410.0
		1400	410.0
Weibull Modulus	GNm^{-2}	20	3.2
Fracture Toughness (sharp crack)	MNm$^{3/2}$	20	3.2
Young's Modulus	GNm^{-2}	20	410.0
Poisson's Ratio		20	0.17
Electric Resistivity	Ω·cm	2	10.0-100.0
Thermal Conductivity	Wm^{-1}K^{-1}	20	110.0
		1000	45.0
Thermal Expansion	10^{-6}K^{-1}	20 to 500	4.0
		500 to 1000	5.8
		1000 to 1500	6.0

MATERIAL DEVELOPMENT

The reliability of any mechanical seal or sliding bearing depends on the presence and stability of the load carrying hydrodynamic lubricant film. The development of sintered SiC with improved tribological properties, therefore, must concentrate on the improvement of the stability of the lubricant film on the sliding face. Close attention must be given to the effects of the surface texture on the slide face with respect to wear behavior. In the presence of a hydrodynamic lubricant film, a smooth, level slide face may be assumed to represent the technically most appropriate solution. The situation changes, however, when the hydrodynamic lubricant film breaks down, resulting in unlubricated operation. When this happens, a surface exhibiting a texture that is capable of providing some form of residual or forced lubrication will provide the better sliding properties. Such structures could consist of machined lubricating/cooling grooves or shallow holes coming from the lapping process of the slide face. Another possibility is controlled introduction of isolated pores or graphite particles into the material microstructure.

Consecutive short periods of dry run or extended periods of boundary lubrication conditions will result in wear of the sliding face because of solid state interaction. If the topography of the sliding face changes, its tribological properties may change as well. The better tribological material therefore is a material which does not significantly change its surface properties if wear occurs. Very good results have been achieved in this regard with EKasic® D alpha sintered SiC. EKasic® D is a trademarked sintered alpha silicon carbide with a bimodal grain size distribution containing ≈ 30 volume percent of larger hexagonal platelets (≈ 100 µm in length) and ≈ 70 volume percent of smaller grains (≈ 10 µm in length), as shown in Figure 2. Alpha (∝) SiC is the stable hexagonal crystal structure phase of silicon carbide. This material shows superior performance, especially if paired against softer carbon material.

Table. 2. Chemical Composition and Corrosion Behavior of Bimodal Sintered Alpha SiC.

Analysis	*wt %*	*Corrosion Behavior*	
SiC	98.5	aqueous	no attack
free Carbon	1.0	acids and mixtures	no attack
Al	0.3	alkali solutions and mixtures	no attack
free Silicon	0.0	organic solvents	no attack
O$_2$,N$_2$	traces		

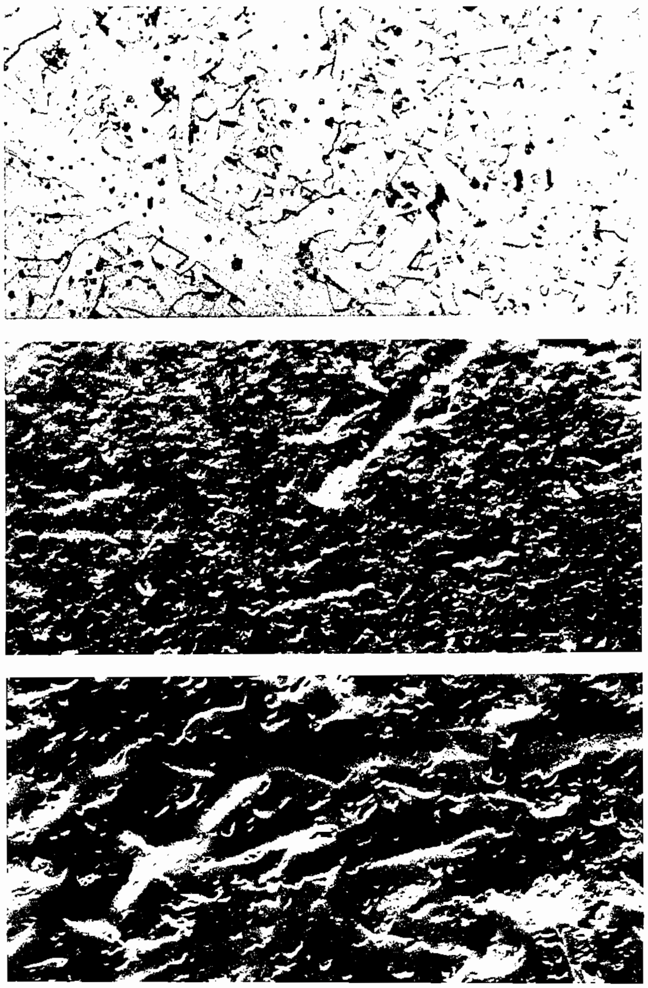

Figure 2. Etched Microstructure and SEM Micrographs of a SiC Sliding Face after Approximately 4000 Hours of Successful Service as a Mechanical Seal Face.

It is of particular interest to note that the surface topography shown in Figure 2 developed in a smooth, matte lapped surface during in-service conditions. The relief structure develops as a result of the SiC crystals anisotropic tribological properties [10] that are most conspicuous in the presence of relatively large crystallites. The depressions in such a textured surface can effectively serve as reservoirs for lubricant, thus improving the emergency running properties for situations in which the lubricating film separates and produces a dry running condition. A schematic representation of these conditions is presented in Figure 3.

The good tribological properties of the bimodal grain structure compared with other SiC materials are also demonstrated in dry run situations. The development of frictional heat [13] in a dry run test of seal faces is shown in Figure 4. The bimodal sintered alpha

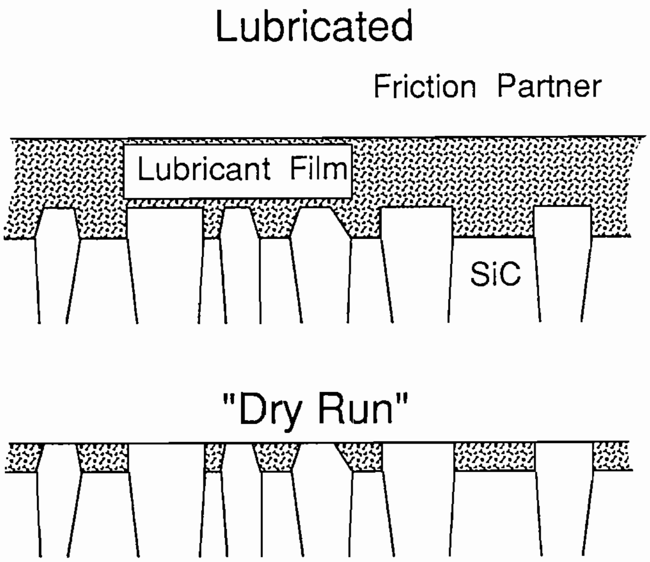

Figure 3. Schematic of the Operational Condition of a Relief Structured Sliding Surface in the Lubricated State and after Breakdown of the Lubricant Film.

SiC shows the least development of heat, thus indicating the lowest coefficients of friction. In an extended DOD/DARPA study on "Tribological Fundamentals of Solid Lubricated Ceramics" [14] the bimodal grain size/shape distribution was judged best in terms of wear resistance, when compared with other fine grain, dense sintered alpha SiC materials.

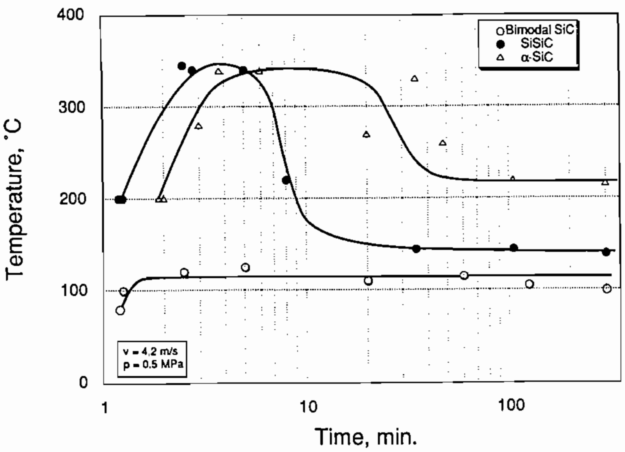

Figure 4. Temperature of Dry Running Seal Faces as a Function of Time [13].

Under boundary lubrication conditions and breakdown of the lubricant film on dense, sintered SiC sliding pairs there is another possible problem. The sliding action during solid state contact causes a polishing effect on the surface, as shown in Figure 5. Polished flat faces of sintered SiC show strong adhesion upon solid state contact. The adhesive forces can be strong enough to break out particles of the sliding face. If this happens, these SiC particles may quickly destroy the functional quality of the sliding face. Silicon carbide bearings should typically be finished to an R_a 0.25 ± 0.01 µm surface roughness to exhibit the best tribological performance.

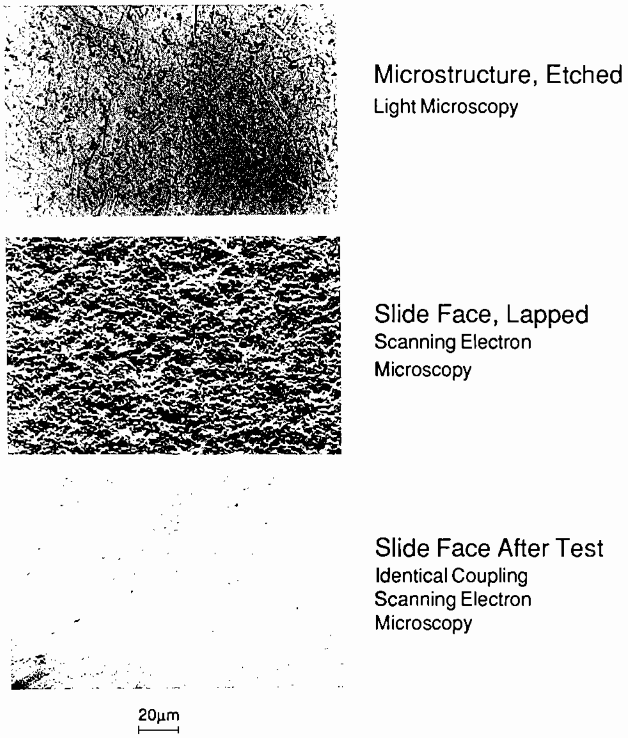

Figure 5. Microstructure and Surface of Slide Face of Bimodal Sintered ∝-SiC.

In addition to a bimodal grain structure, pores or graphite particles can be incorporated into the bulk SiC material to prevent adhesion of flat surfaces, Figure 6. If the material wears, pores or graphite inclusions are present at the surface, to counteract the adhesion and assist lubrication. The microstructure of these special bimodal sintered alpha SiC materials and in each case the sliding face before and after test are shown in Figures 7 and 8. These materials were designed to contain either only pores (Figure 7) or both graphite particles and 40 to 60 µm pores (Figure 8). The pores acting as lubricant pockets can be clearly seen in Figure 7. After wear, there are still pores present at the surface. Pores and graphite particles in the surface of the sliding face, before and after test, are shown in Figure 8. Some comparative mechanical, physical, and chemical properties of standard bimodal and SiC containing pores and graphite particles plus pores are shown in Figure 9.

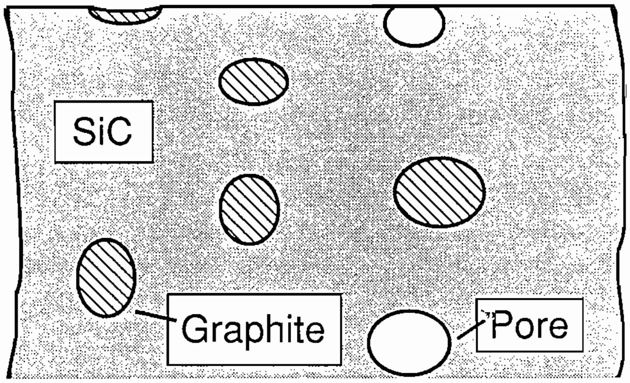

Figure 6. Schematic Cross-Section of SiC Containing Graphite Particles and Pores.

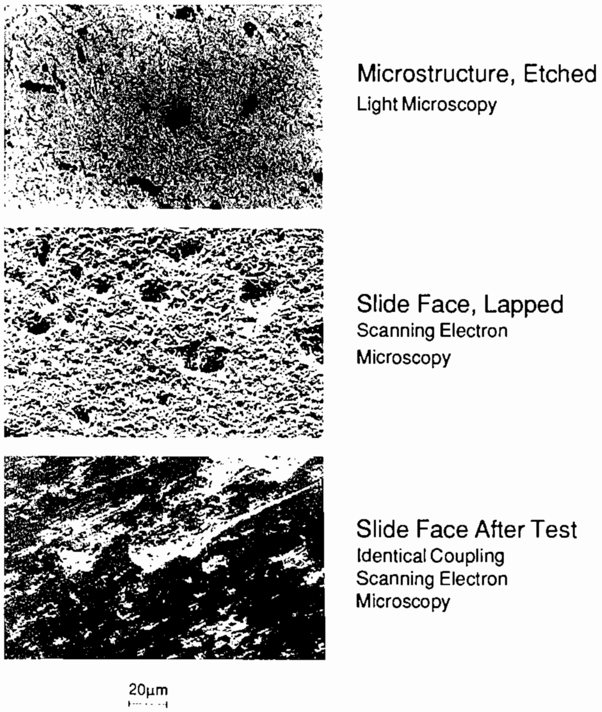

Figure 7. Microstructure and Surfaces of Slide Face of Bimodal Sintered SiC Containing Pores in the Size Range of 40 µm.

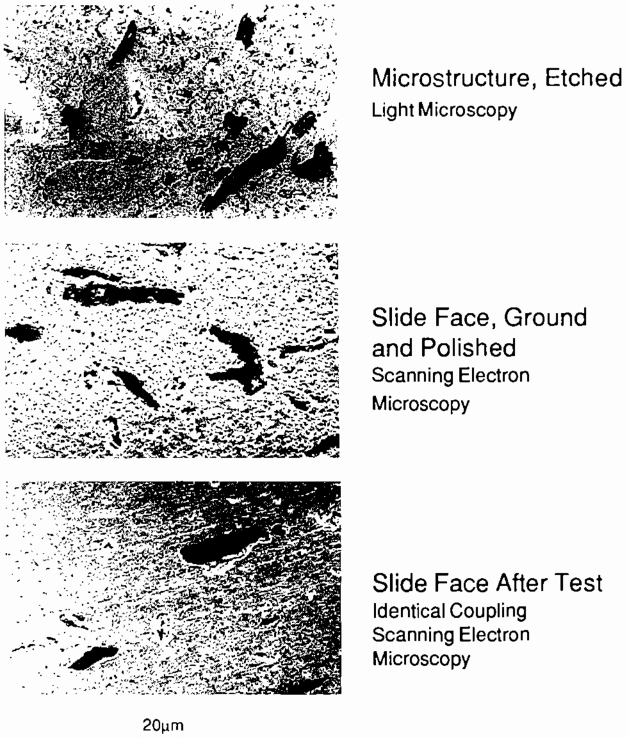

Figure 8. Microstructure and Surface of the Slide Face of Bimodal Sintered SiC Containing Pores and Graphite Particles in the Size Range of 60 µm.

Pores and graphite inclusions act as internal flaws and, thus, the strength is reduced when compared with the standard "flaw free" material. On the other hand, since pores and graphite inclusions are "flaws" of intended size, the variation in strength is reduced and the Weibull Modulus is significantly increased, an important design criterion. Young's modulus is slightly reduced by the porosity and/or softer graphite inclusions. Friction under boundary lubrication conditions is decreased, as desired, while the corrosion resistance remains excellent.

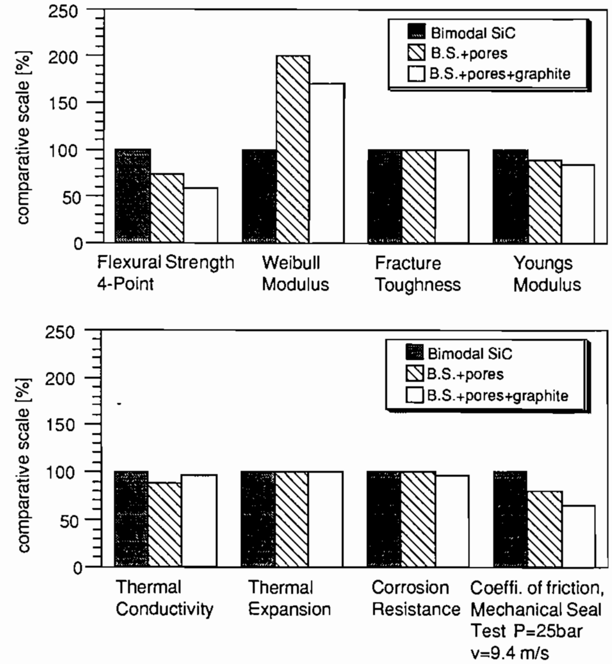

Figure 9. Comparison of Properties of Controlled Porosity, Pore plus Graphite Containing Material, and Standard Bimodal ∝-SiC.

APPLICATION RESULTS

The SiC materials containing controlled porosity and porosity plus graphite were tested in comparison to the bimodal base material. The Stribeck testing method was used to evaluate the coefficient of friction as a function of sliding velocity. In this axial bearing test method a stationary circular segment is lubricated on a rotating ring of the same material. The torque between segment and ring is then measured. The load bearing capacity of the hydrodynamic lubricant film is of special interest. The better tribological material will show stable hydrodynamics down to lower sliding velocities before the lubricant film breaks down and the bearing comes into solid state contact. An example is shown in Figure 10. In this case, the graphite containing material is exhibiting a higher hydrodynamic friction level and a deviation of hydrodynamics at a higher velocity compared to the controlled porosity containing material, and the standard bimodal material. Summarizing all Stribeck test data, the porosity containing material shows the best performance in stabilizing the hydrodynamic film down to the lowest velocities. This is important for sliding bearings and has been confirmed in many cases. The poorer performance of the graphite plus porosity containing material in this sliding bearing test is not clearly understood, but it may be caused by the poor wetting behavior of graphite in water under normal pressure.

Mechanical seal faces can be considered as a flat rotational thrust bearing and as such seal face test data are of considerable value in designing pump bearings. In these seal applications, under differential pressures of less than 15 bars, the same ranking of materials is observed in terms of friction and wear. However, under extreme situations such as very high differential pressure

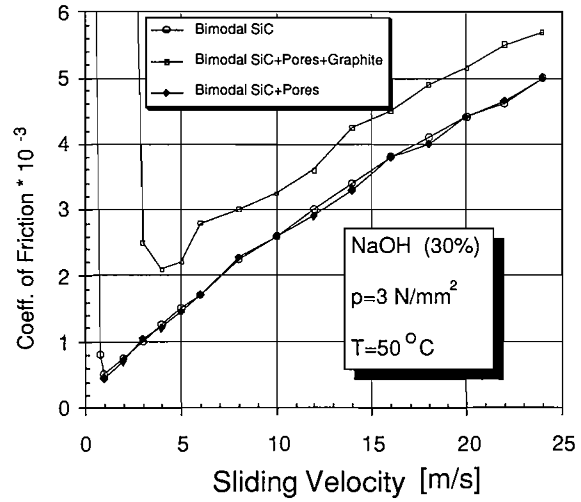

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Figure 10. Coefficient of Friction as a Function of Sliding Velocity for Identical Sliding Pairs of Sintered Alpha SiC Materials.

(continuous boundary lubrication) or pump cavitational conditions (breakdown of hydrodynamic film under frequent uncontrolled loads), the graphite and porosity containing material shows the best performance. The wear of the optimized materials is depicted in Figure 11, and compared with standard bimodal SiC, in a seal application using identical material ring pairs. The comparative application tests show that the optimized sintered SiC materials containing controlled porosity or porosity plus graphite exhibit improved tribological properties that result in greater reliability in sliding bearing and rotating seal applications.

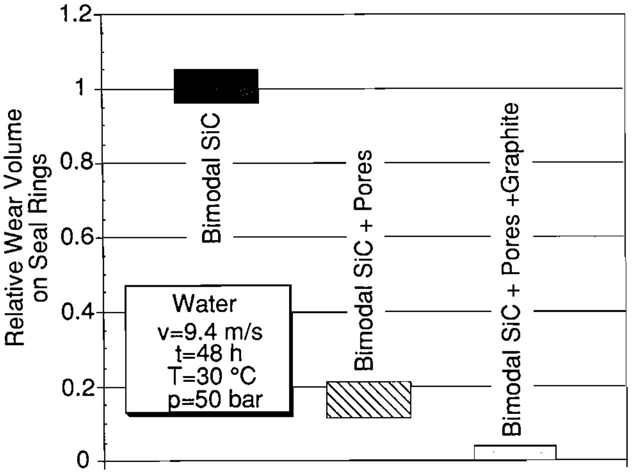

Figure 11. Relative Wear Volume on Seal Rings of Sintered SiC Materials

CONCLUSIONS

Bimodal sintered alpha SiC in mechanical seals or in slide bearings for sealless pumps runs successfully and reliably as long as lubrication can be guaranteed. If the hydrodynamic lubricant film breaks down, dry friction followed by frictional heat and mechanical wear may cause problems. Therefore, the concepts for product development have concentrated on the stabilization of the hydrodynamic lubricant film.

An improved sintered SiC material with optimized tribological properties has been developed based on standard, bimodal, alpha SiC. The universal corrosion resistance and reliability of this base material is maintained. The improved SiC contains additional defined pores (diameter ≈ 40 μm) that act as efficient lubricant filled pockets in the sliding face to help stabilize the hydrodynamic lubricant film and assist lubrication on short breakdowns of the film. This material shows advantages in slide bearing applications and mechanical seal applications in which steady hydrodynamic lubrication cannot be guaranteed and reliability improvement is desired.

Another material showing promising properties is a sintered SiC, also based on a bimodal grain structure, which contains ≈ 60 μm graphite particles in addition to the pores. This material demonstrates improved performance in hard/hard paired seal rings which run under high pressure differentials or pump cavitation conditions. It has potential for further development which is currently underway.

Permanently dry running SiC bearings are not possible since the coefficient of friction (≈ 0.4) is too high. Hard surface coatings, especially CVD diamond-like carbon, can reduce the coefficients of friction down to values of 0.1 to 0.2 for a period of time. However, upon development of frictional heat, the coating deteriorates, and the reliability of the bearing again depends on the inherent properties of the bulk sintered alpha SiC, with or without microstructure modifications.

Thus, silicon carbide component life can be extended under marginal, and/or dry, conditions, but not indefinitely. Operating conditions and system design will determine the length of extended running time made possible through the use of these modified silicon carbide materials.

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