THE DEVELOPMENT OF DRY-LUBRICATED CERAMIC CAGES

W B Price and E W Roberts

European Space Tribology Laboratory,
AEA Technology, Risley, Warrington, U.K. WA3 6AT

ABSTRACT

An initial attempt has been made to fabricate, and lubricate with MoS_2, ceramic cages for use as ball retainers in bearings. The materials tested were reaction-bonded silicon carbide, reaction-bonded silicon nitride and sintered silicon nitride. Of these, the silicon carbide cages performed best in bearing tests. Reaction-bonded silicon carbide, coated with sputter-deposited MoS_2 was also tested in sliding motion using a tribometer (pin-on-disc test machine). Contrary to initial expectations, alkali-etching the surface of the ceramic, to increase its porosity, led to a reduction in durability of the MoS_2 lubricant film. Vacuum impregnation of the porous ceramic with powdered MoS_2 prevented the subsequent layer of sputter-deposited MoS_2 from bonding to the ceramic substrate, and led to a catastrophic reduction in lubricant life.

Keywords: Bearing cages, ceramic, solid lubricant, vacuum, MoS_2.

1. INTRODUCTION

There is currently much general interest in the use of ceramics in tribological applications, an interest which is beginning to extend to space applications. The perceived advantages (over steel components) for space are lower weight, higher temperature capability and, as shown recently (Ref.1), a compatibility with thin solid film lubricants which can lead to low friction and long film life.

High-precision all-ceramic ball bearings are now commercially available and their utilisation, at least in terrestrial applications, is growing. However, for a ball bearing to be truly capable of operation in hostile (eg high temperature, vacuum) environments, it is necessary for the cage also to be made from a ceramic material. Yet, little work has hitherto been directed towards developing such cages.

In this paper we present the results of a study aimed at developing dry-lubricated ceramic cages. The first stage was to assess the parameters which characterise the behaviour of solid-lubricated ceramics, and how this is affected by changes in porosity. Changes in porosity were sought by manufacturing ceramic materials containing free silicon. Some of this free silicon was subsequently chemically etched away so as to generate a porous surface. This modified surface was then impregnated with the solid lubricant molybdenum disulphide and its tribological properties assessed. The second stage was to procure ceramic cages, for use in ball bearings. These cages were treated with MoS_2 solid-film lubricant, and then tested in assembled bearings.

2. PRELIMINARY PIN-ON-DISC TRIBOLOGICAL TESTS.

2.1 Test specimens and test method

The purpose these tests was to assess the effectiveness of MoS_2-lubricated surfaces of silicon carbide prepared with modified (ie porous) and un-modified surfaces.

The test specimens were discs, of diameter 38 mm., made from reaction-bonded silicon carbide, containing free silicon (either 10% or 30% by weight), and supplied by Morgan Matroc Ltd., Advanced Engineering Materials Division. Prior to coating, some discs were etched in aqueous sodium hydroxide solution to increase the disc porosity by dissolving some of the free silicon near the surface. Certain of these etched discs were powder-impregnated with MoS_2, the intention being to use the pores as a reservoir of MoS_2. The discs were then coated with 1-micron thick MoS_2 films produced by magnetron-sputtering.

Proc. 'Fifth European Space Mechanisms and Tribology Symposium', ESTEC, Noordwijk, The Netherlands, 28-30 October 1992 (ESA SP-334, April 1993)

Friction/wear tests were performed in a dry nitrogen atmosphere, using a single pin-on-disc test machine (CSEM tribometer). In the absence of a silicon carbide pin or ball, silicon nitride balls of diameter 6 mm were used to rub against the discs; these balls were not coated with MoS_2.

To obtain additional information, further tribological tests were performed on (silicon containing) SiC discs coated with different thicknesses of sputter-deposited MoS_2. The nominal MoS_2 film thicknesses used in these tests were 1, 5 and 10 micrometres. Flat steel (Type En31) discs were coated simultaneously with MoS_2, and used to measure the film thickness by X-Ray fluorescence (XRF).

Two discs were etched in aqueous potassium hydroxide solution (1 Molar) at 70-80°C for 5 minutes. These discs were then washed several times in deioned water, to remove residual potassium hydroxide solution. The discs were then dried overnight at 100°C in a vacuum oven, prior to coating with sputter-deposited MoS_2.

Friction and wear tests were performed on a pin-on-disc apparatus as described above. By altering the wear track radius, it was possible to conduct several friction/film-life tests on each coated disc. These tests were performed at applied loads of 5, 10 and 20 Newtons.

The surface finish of selected discs was measured using a Talysurf Profilometer. The R_a parameter was used to compare the roughnesses of different discs. All the discs examined gave comparable R_a values, in the range 0.07 - 0.09 micrometres, and this was not significantly changed when one of the discs was etched in aqueous alkali to dissolve free silicon from the surface.

2.2 Results of pin-on-disc tests.

The results of tests to determine the efficacy of porous ceramics are shown in Table 1. The main observations made are:

a) etching the SiC/Si discs with NaOH does not improve the durability of the sputter-deposited MoS_2 film during tribometer tests.

b) impregnation of etched SiC/Si with MoS_2 powder, prior to sputter-deposition of MoS_2, was highly deleterious, probably because the impregnated material prevented the sputter-deposited MoS_2 from achieving satisfactory bonding to the SiC/Si surface.

The results of the additional pin-disc tests aimed at examining the effects of film thickness and load are presented in Table 2. A typical plot of friction coefficient versus number of disc revolutions is shown in Figure 1. For the 1-micron thick MoS_2 films, the mean durability results are shown in Figure 2 as a function of applied load. These results confirm that alkali etching of silicon-containing SiC, to remove some of the silicon to make the surface more porous prior to sputter-deposition of MoS_2, did not improve the film durability - indeed, there was a slight reduction in the average MoS_2 film-life.

TABLE 1. TRIBOMETER TEST RESULTS, MoS_2 ON SiC/Si DISCS

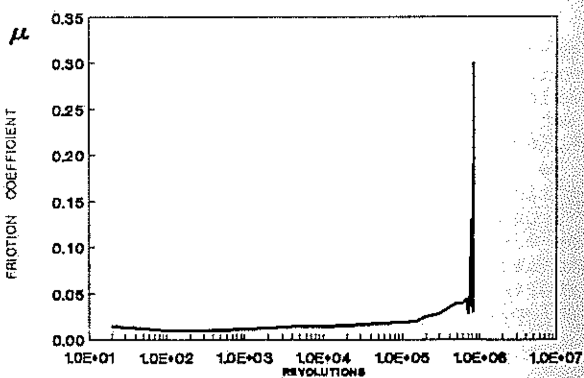
DISC ETCH TIME (MINUTES) IN NaOH	MoS_2 POWDER IMPREGNATION DETAILS	FILM DURABILITY (REVOLUTIONS)
0	–	200,000
300	–	100,000
300	VACUUM	20,000
300	VACUUM	2,000
300	SLURRY	200

TABLE 2. EFFECT OF LOAD AND FILM THICKNESS ON DURABILITY OF MoS_2 ON SiC/Si DISCS IN TRIBOMETER TESTS

MoS FILM · THICKNESS (μm.)	LOAD (N)	MEAN FILM DURABILITY (REVOLUTIONS)
1	20	78,000
	10	197,000
	5	2,103,400
3.5	20	290,600
	10	826,900
	5	1,717,700
6.2	20	200,000
	10	1,100,000
	5	> 15,000,000
1.2 *	20	705,000
	10	1,288,200
	5	2,029,700
1.1 *	20	252,000
**	10	824,000

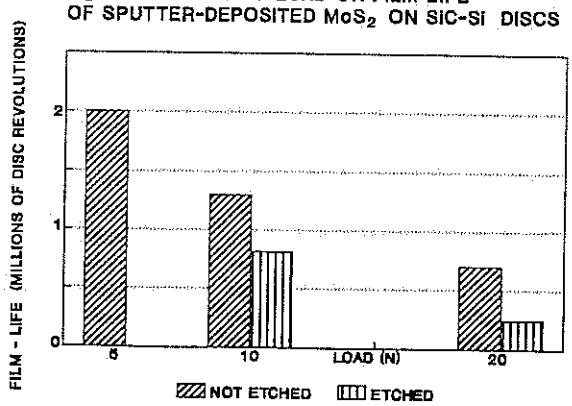
NOTES
* SI CONTENT OF DISCS - 30% (THE OTHER DISCS HAD 10% SI)
** THIS DISC ETCHED IN NaOH (SEE TEXT)

Fig.1 TRIBOMETER TEST RESULTS
MoS2 FILM ON SiC-SI DISC



TESTED IN NITROGEN ATMOSPHERE

Fig.2 EFFECT OF LOAD ON FILM-LIFE OF SPUTTER-DEPOSITED MoS_2 ON SiC-Si DISCS



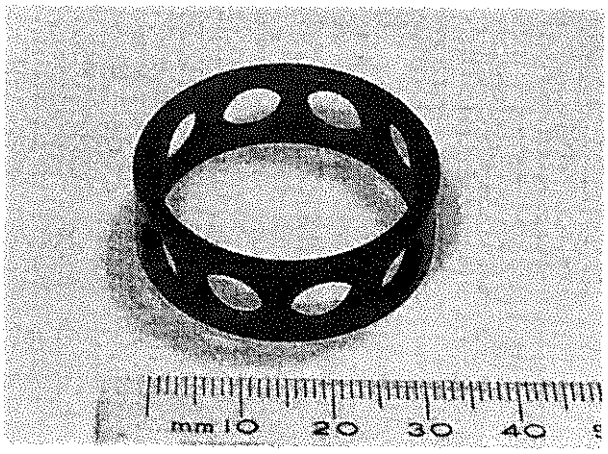


Fig. 3 SILICON CARBIDE CAGE, PRIOR TO COATING WITH MoS_2

Based on a limited amount of data, for unetched SiC/Si discs, the MoS_2 film durability was increased when the Si content was increased from 10% to 30%. However, previous experience has shown that film durability results can be highly variable, so additional data would be necessary to make definite conclusions about the effect of Si content on tribological performance.

The effect of MoS_2 film thickness on film durability (on SiC/Si) was, in general, that the durability increased as the film thickness increased to about 3 micrometres. Further increases in film thickness had only a small effect on durability.

The effect of load on film durability was typically that halving the applied load led to a 2- to 4- fold increase in the durability of sputter-deposited MoS_2.

3. TESTS ON CERAMIC CAGES.

3.1 Test Specimens

Ceramic cages were designed and manufactured to fit in ED20 (20mm ID, 42mm OD) angular-contact bearings. They were outer-race riding. The cages (Fig.3) were supplied by Tenmat Ltd. in the following materials:

(a) reaction-bonded silicon carbide

(b) reaction-bonded silicon nitride.

(c) sintered silicon nitride (REFRASIL S)

Since the earlier pin-on-disc tests had shown that introducing porosity at the surface of the ceramics was not advantageous, only one SiC/Si cage was etched prior to MoS_2 deposition, all other cages tested remaining unmodified .

The surface finish of selected cages was measured on the rim, using a Talysurf Profilometer, as described for discs in the previous section (visual inspection showed little difference in the surface finish in the cage pockets and on the rim; profilometer measurements within the cage pockets are difficult to make). The reaction-bonded silicon nitride cage had the roughest surface, giving R_a values in the range 2.3 - 2.5 micrometres. The sintered silicon nitride cage was much smoother, giving R_a values between 0.10 and 0.17 micrometres. The silicon carbide cage was less homogeneous in its surface finish, giving R_a values lying between 0.13 and 0.50 micrometres.

Ceramic cages were coated with sputter-deposited MoS_2, with a nominal film thickness of 5 micrometres. A Type EN31 steel disc was located within the cage perimeter during sputter-deposition, for quality control purposes, and was also coated with MoS_2. The discs were used in the measurement of MoS_2 film thickness by X-ray fluorescence. Two deposition runs were required for each cage, to ensure thorough penetration of all the pockets by sputter-deposited MoS_2. The MoS_2-coated cages were inserted into Type ED20 ball bearings (ABEC 7 specification); the steel races and balls were generally uncoated. However, one test was performed (with SiC cages) in which the races were coated with approximately 1 micrometre of MoS_2.

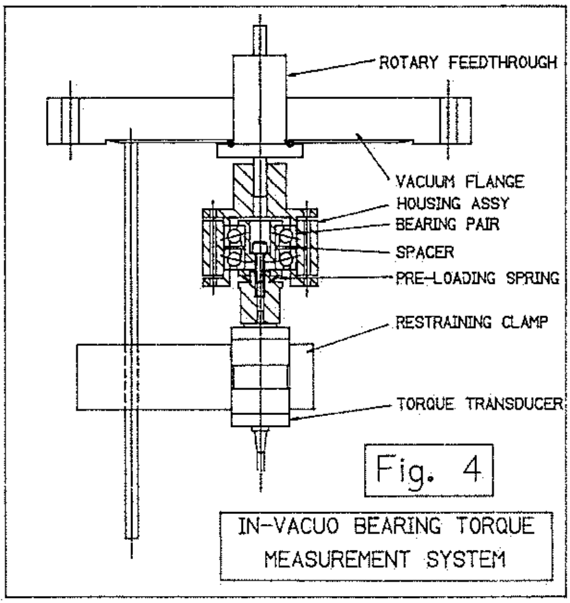


Fig. 4

IN-VACUO BEARING TORQUE MEASUREMENT SYSTEM

3.2 Bearing tests.

Pairs of bearings were assembled in a back-to-back configuration, with an applied soft preload of 40 Newtons. The assembled bearings were attached to a torque transducer (Teldix Type 1.3.), and to a rotary drive mechanism (Fig.4). The tests were performed in vacuum, with the pressure < 10^{-6} mbar. The torque was monitored by use of a calibrated chart recorder. For purposes of comparison, a bearing test was also performed using a pair of MoS_2-coated steel cages.

3.3 Bearing test results.

The torque results are shown in Figures 5-9. The solid lines represent the mean torque level as a function of the number of revolutions of the bearing pair. As the tests proceeded, the torque traces tended to become noisy, or exhibit spikes. For reasons of clarity, the noise and spikes are not shown in the figures.

The silicon carbide, and sintered silicon nitride, cages gave roughly comparable performances (Figs.5,6). Alkali-etching of the silicon carbide cages, prior to sputter-deposition of MoS_2 had little effect. The torque plot (Fig.7) was very similar to that obtained with unetched silicon carbide cages (Fig.5).

The least satisfactory results were obtained using the reaction-bonded silicon nitride cages (Fig.8), the mean torque level starting to increase after about 7,000 revolutions, with a rapid increase in torque after 18,000 revolutions, at which point the test was terminated.

As might be expected, MoS_2-coating of the steel races, as well as the SiC cages, led to a significant increase in low torque lifetime (Fig.9).

Fig.5 BEARING TEST TORQUE RESULTS IN VACUUM

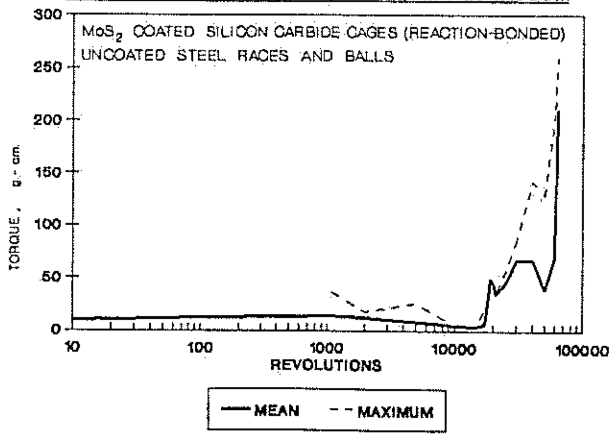


Fig.6 BEARING TEST TORQUE RESULTS IN VACUUM

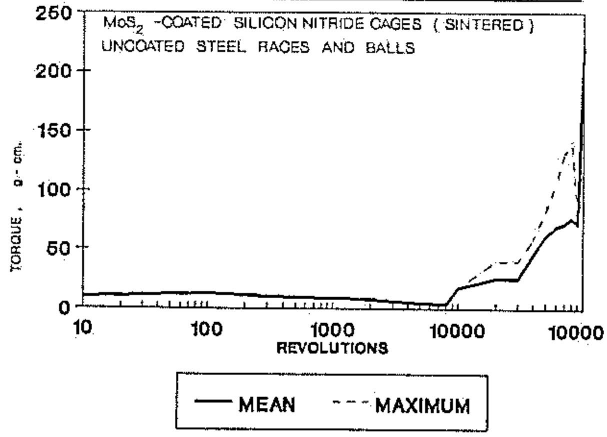


Fig. 7 BEARING TEST TORQUE RESULTS IN VACUUM

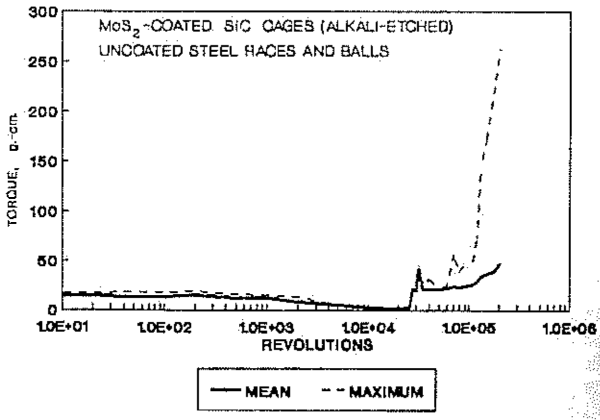


Fig.8 BEARING TEST TORQUE RESULTS IN VACUUM

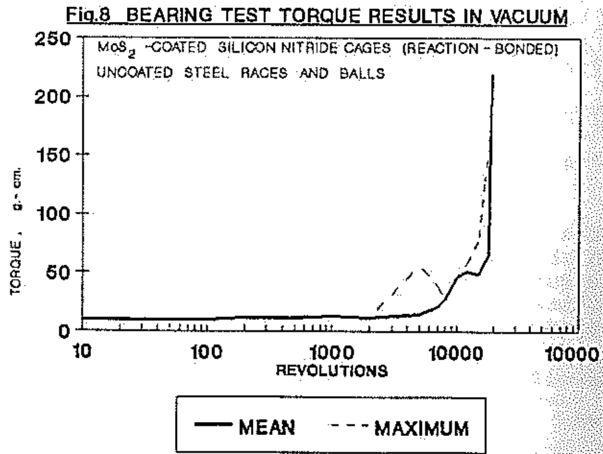
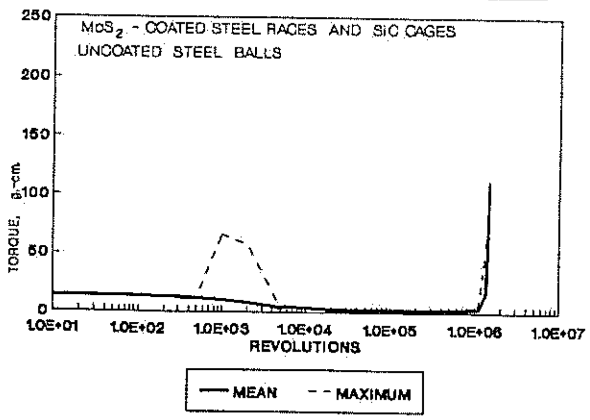


Fig.9 BEARING TEST TORQUE RESULTS IN VACUUM



4. DISCUSSION.

The results indicate that the torque-behaviour of MoS_2-coated ceramic cages is dependent on the ceramic material from which the cage is fabricated. This may, at least in part, be due to differences in surface finish of the cage materials. The worst film performance was obtained with the reaction-bonded silicon nitride cages, which had R_a values exceeding 2 micrometres. The sintered silicon nitride and the silicon carbide cages had R_a values in the range 0.1 to 0.5 micrometres. As noted previously, all the surface finish measurements were performed on the rims of the cages, which are more accessible to the profilometer than the cage pockets. In the case of ceramics, the surface finish is dependent on the size of particles used in the fabrication of components. Thus, it would be difficult to improve the surface finish without reducing the particle size of the starting materials.

It is evident that alkali-etching of the surface of reaction-bonded silicon carbide did not improve the tribological performance; indeed, on balance, this treatment was somewhat detrimental. Vacuum impregnation of MoS_2 powder into the surface pores of alkali-etched reaction-bonded silicon carbide, prior to sputter-deposition of MoS_2, proved to be deleterious, in that the low-friction life of the lubricant was much reduced. It is probable that the MoS_2 powder acts as a barrier, preventing the sputter-deposited MoS_2 from forming chemical bonds to the silicon carbide substrate. It is known that such bonding is necessary if sputter-deposited MoS_2 is to give long durability.

5. CONCLUSIONS.

Ball bearing cages have been successfully fabricated from silicon carbide and silicon nitride. Lubrication of these cages by sputtered molybdenum disulphide has proved effective but to different degrees. The best-performing MoS_2-lubricated cages were those manufactured from silicon carbide (sintered or reaction bonded) whilst the poorest results were obtained on reaction-bonded silicon nitride. Attempts to create lubricant reservoirs in ceramic surfaces by rendering the surface more porous did not bring about any enhancements in tribological performance.

6. REFERENCES.

1. Cunningham J M & al, The tribology of some MoS_2-lubricated engineering ceramics, Proc. 5th. ESMATS Symp., Noordwijk, The Netherlands, 1992, ESA SP- ,

ACKNOWLEDGEMENTS.

The preliminary tribological tests were performed by A.N.Austin.