HYBRID POLYMERIC BEARINGS FOR SPACE APPLICATIONS

Simon D. Lewis & Robert A. Rowntree
ESTL (European Space Tribology Laboratory)
AEA Technology, Risley, Warrington WA3 6AT, UK
phone: +44 1925 252631, fax: +44 1925 252415, e-mail: simon.lewis@aeat.co.uk
phone:+44 1925 253564, fax +44 1925 252415, e-mail: robert.a.rowntree@aeat.co.uk

ABSTRACT

This paper presents a theoretical and experimental analysis of the performance of hybrid ball bearings in which polymeric balls, rather than more conventional monolithic ceramic or ceramic-coated balls and steel raceways, are used.

Three polymeric ball materials were selected for test, namely Delrin (polyacetal), PEEK (poly-ether-ether ketone) and Torlon (polyamide-imide). These were subjected to ball-on-disc tests, the most promising subsequently being subjected to bearing-level torque tests (in air and vacuum) and comparisons with predictions from the CABARET bearing analysis software of ESTL

The programme confirmed the potential of hybrid polymeric balled bearings for space applications. In comparison to all-steel bearings lubricated by either lead or MoS_2, hybrid polymeric bearings offer mass-savings of up to 70% and exhibit lower maximum/mean torque ratios. Though their DC torque levels can be high, and their stiffness is only around 15% of corresponding steel-balled bearings, it is considered that there may be a number of applications where hybrid polymeric balled bearings can be exploited.

1. INTRODUCTION

Hybrid ball bearings, where differing materials are used for rolling elements and raceways, are increasingly used in space mechanism applications. To date, the "hybrid" has usually involved TiC-coated 440C, or monolithic Si_3N_4 balls employed with 440C raceways. This combination provides improved friction and wear resistance over all-440C bearings often with the added advantages that adhesion of solid lubricants may be stronger or chemical degradation of liquid lubricants may be inhibited due to the use of these hybrid bearing materials.

In this paper we present a theoretical and experimental analysis of the performance of hybrid ball bearings where polymeric balls are used as the hybrid. Prior to carrying out this programme, the motivations for selecting these materials are primarily the potential for a reduced mass bearing which is likely to be less prone to launch vibration damage (due to the inherently high hysteresis of polymers) and the potential self-lubricating action of the materials. Concerns were that such bearings might provide extremely high torque and low stiffness compared to all-steel or ceramic hybrids. Both the experimental programme and theoretical analysis were therefore designed to quantify these performance issues.

2. POLYMER SELECTION

Clearly polymeric materials are suitable only for relatively lightly-loaded, low-speed applications, where there is insufficient frictional heat to damage the polymer. The main qualities important in selecting polymers for use in ball bearings for space are:

a) Low friction and wear in air and vacuum
b) High stiffness and strength - for component location
c) Creep resistance
d) Radiation resistance
e) Low thermal expansivity
f) Good machinability and dimensional stability

Generic properties of a number of polymers were reviewed taking into account both the above considerations and the availability of balls of suitable precision. The following materials were selected:

Delrin (polyacetal) - *Hoover Precision Products Inc.*

PEEK (polyetheretherketone) grade D450G - *Ensinger (U.K.) Ltd*

Torlon (polyamide-imide) -grade 4203L - *Hoover Precision Products Inc*

Selected mechanical properties of these materials provided by their manufacturers are shown in Table 1 below.

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	DELRIN	TORLON	PEEK
Elastic Modulus (GPa)	3-3.5	4.1-5	3.7-4
Poisson Ratio	0.35	0.35	0.35
Compressive Strength (MPa)	124	280	150
Tensile Strength (MPa)	60-70	120-180	70-100
Thermal Expansivity (μK^{-1})	80-100	36	20
Thermal Conductivity ($Wm^{-1} K^{-1}$)	0.22-0.24	0.13	0.24
Heat Distortion Temperature (°C)	100	274	-
Density (kgm^{-3})	1420	1400	1480

Table 1 Properties of Materials Tested

These materials were subjected to reciprocating pin-on-disc tests in an existing ESTL facility [Ref. 1] in order to characterise their frictional and wear behaviour as a function of sliding speed in air and vacuum. In all cases, the normal load applied was 5N, equivalent to stresses as shown in Table 2. The stress levels were chosen to be representative of those arising in an SNFA Type ED20 ball bearing with axial load of 40N (a frequently-used standard test condition for ESTL), in the range 52-65MPa. for all 3 polymers tested.

	Max Contact Stress for ED20@ 40N (MPa)	Max Contact Stress for POD Test @5N (MPa)	POD Max Contact Stress as % of Material Compressive Strength
DELRIN	65	52	42
TORLON	78	65	28
PEEK	69	57	46

Table 2 Contact Stresses in Pin-on-disc (POD) Tests and Bearing Tests with Different Polymeric Ball Materials

In the reciprocating tests, a trapezoidal velocity profile was used, with traverse length of 6mm and acceleration rates of 0.2, 1.25 and $5ms^{-2}$ at sliding speeds of 0.01, 0.05 and $0.1ms^{-1}$ respectively. The test profiles were chosen as representative of contact velocities in ball-race contacts and for comparability with other test data. Counterface materials used were steel (SAE52100 of hardness 800-850Hv) of roughness 0.05-0.15μm Ra and aluminium alloy (type 6082TF) for which the roughness was measured as Ra< 0.1μm.

Test environments were, air (Laboratory RH45%±5%) and vacuum (<10^{-6} Torr). In both cases the ambient temperature was maintained at 20°C±2°C.

In air, against steel, the frictional behaviours of PEEK and Delrin were similar (and typical of non-transferring polymers in general) as shown in Figure 1. Typical initial friction coefficients were around 0.15-0.2 increased with sliding distance to 0.4-0.5. However for Torlon at $0.05ms^{-1}$ and below the friction remained close to the initial value throughout test. Only at $0.1ms^{-1}$ was its behaviour similar to that of Delrin and PEEK, Figure 2.

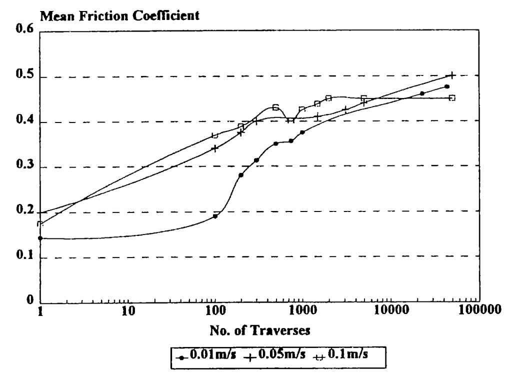

Figure 1 Reciprocating pin-on-disc test data for a PEEK pin vs SAE52100 Steel (load 5N) in air, speeds 0.01,0.05 and $0.1ms^{-1}$

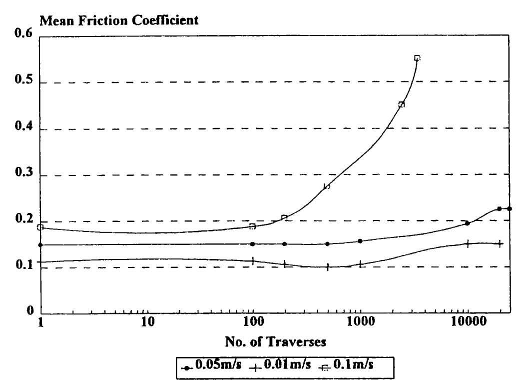

Figure 2 Reciprocating pin-on-disc test data for a Torlon pin vs SAE52100 Steel (load 5N) in air, speeds 0.01,0.05 and $0.1ms^{-1}$

Tests against the aluminium counterfaces in air were also carried out at $0.05ms^{-1}$. In this case, the friction coefficient of Torlon increased from 0.2 to 0.8 after only 4000 traverses. The behaviour of PEEK was similar, though its friction coefficient reached only 0.6-0.7.

In vacuo against the steel counterfaces, the initial friction coefficients of all 3 polymers were similar at 0.2-0.4, slightly higher than in air. However *both PEEK and Torlon demonstrated in-vacuo run-in behaviour* with friction peaking around 0.5-0.6 before falling to 0.15-0.3 in the case of PEEK and less than 0.1 for Torlon as shown in Figure 3. Delrin showed no such run-in characteristics. Comparison with data from an earlier study [Ref 2] demonstrated close similarity in frictional behaviour between Vespel SP3 and Torlon similar friction.

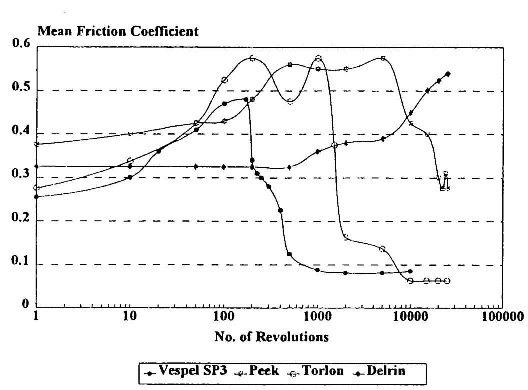

Figure 3 Comparison of in-vacuo friction of Vespel SP3, Torlon, PEEK and Delrin (5N load, speed $0.1ms^{-1}$)

Specific wear rates were calculated on a volume basis from the pin wear scars, but because the sliding distances were relatively low, only order of magnitude accuracy can be claimed. Specific wear rate data is summarised in Table 3 below

	AIR	VACUUM
DELRIN	19	2
TORLON	3	4
PEEK	9	24

Table 3 Mean Specific Wear Rates Measured in Pin-on-Disc Tests in Different Environments ($m^3/Nmx10^{-15}$)

Based on the results of the ball-on-disc tests summarised above, Delrin was rejected from the ball-bearing test programme as it exhibited no run-in behaviour in vacuo and had relatively high in-air wear. Both PEEK- and Torlon-balled hybrid bearings were tested in the next phase of the study.

3. THEORETICAL ANALYSIS

Before carrying out the bearing tests, a brief theoretical analysis of the expected behaviour was carried out using ESTL's CABARET (Version 1.00) bearing analysis software [Ref. 3].

Polymers have elastic (Young's) moduli a factor of approximately 0.02 times lower than for bearing steels. A sensitivity analysis using the CABARET software showed that this parameter has a dominant effect on predicted torque and axial deflection, Figure 4. Thus small differences in Young's modulus between polymers may be expected to have a large influence on torque and axial deflection (or stiffness) of the bearing.

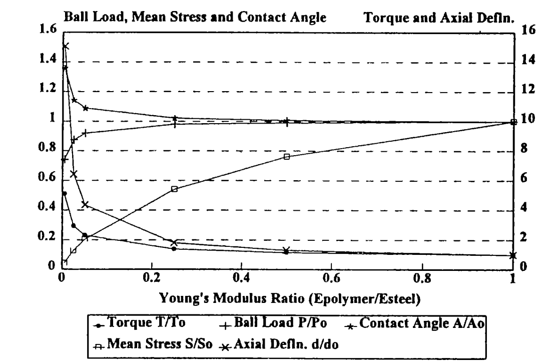

Figure 4 Sensitivity analysis for Predicted Mean Torque, Axial Deflection, Ball Load, Mean Hertzian Contact Stress and Contact Angle v Young's Modulus (based on CABARET V1.00 predictions for ED20 bearing under 40N preload, subscript o applies to all steel, no subscript to hybrid polymeric bearing)

For any assumed friction coefficient and preload, bearing torque is a function of Young's modulus, Poisson ratio and Hysteresis loss coefficient. For Poisson ratio there is an almost neutral effect on torque since this parameter does not vary over more than a few percent between steels and polymers. However for both Young's modulus and hysteresis loss coefficient, there are potentially large torque effects. The hysteresis loss coefficient for steels is typically 0.05, but for polymers this value could be much larger. A factor of 1 for hysteresis loss coefficient for example would be predicted to generate mean torque values a factor 13 times larger than for an all-steel bearing for given assumed sliding friction coefficient.

The approximate mass savings for adoption of hybrid polymeric bearings of different sizes are shown in Table 4 below.

Brg. Type	Bore (mm)	O.D (mm)	Ball No.	Mass-saving for Steel Rings	Mass-saving for Alumin-ium Rings
101H	12	28	10	19%	69%
ED20	20	42	10	22%	70%
SNR71915	75	105	24	17%	69%

Table 4 Approximate Mass-savings achievable by adoption of polymeric balls with steel and aluminium alloy raceways

As can be seen, whereas the mass-savings achievable using hybrid polymeric-balled/steel raceway bearings are around 20% compared to all-steel bearings, the adoption of polymeric-balled/aluminium alloy raceway bearings would generate savings of around 70% compared to an all-steel construction. For this reason, in addition to testing standard SNFA steel raceways, substitute raceways were manufactured from aluminium alloy in order to demonstrate their performance. Since these were not manufactured on a production facility, the tolerances on these rings were not directly comparable to the steel rings and though the conformity of the raceway was correct, the radial internal clearance of these bearings was much larger than for production all-steel bearings. This resulted in modified operating contact angles. On receipt, the PEEK balls were found to be oval and had to be re-lapped, resulting in smaller nominal diameter of 7.00mm. The Torlon balls were acceptable and of nominal diameter 7.14mm. For the above reasons, the geometries of the various bearings tested are not all identical making direct comparisons in experimental performance between all-steel, polymer-steel and polymer-aluminium hybrids difficult without "normalisations" using CABARET predictions to allow for the known test geometries.

4. BEARING TEST METHODOLOGY

Bearings were subjected to axial load-deflection tests in air followed by torque characterisation tests in air and vacuum. Prior to test, rings and polymeric balls were inspected under optical microscope and cleaned using ultrasonic agitation in Arklone-P. Bearings were then assembled using Delrin cages (this material was selected as being relatively benign - but its transfer characteristics versus other polymers are not known) in back-back configuration.

During load-deflection tests, axial loads were applied using deadweights and deflections measured using an LVDT. For torque characterisation, soft preloading was used for each test and set in the range 15-50N, bearings were tested with the bearing axis vertical, the cage mass being approximately 2 grammes. Air and vacuum conditions were as specified for the ball-on-disc tests above. A DC motor was used to drive the bearings in unidirectional motion at 100rpm (±15%) and a DG1.3 torque transducer used to measure bearing torque. The direction of motion was reversed at intervals in order to locate zero torque, during this procedure the motion speed was 2rpm. Mean and peak torque was continually monitored using a low-frequency response chart recorder for test durations which were in the range 30-130krevs.

5. LOAD-DEFLECTION TESTS

Figure 5 shows typical load-deflection results, demonstrating that the agreement between CABARET predicted and experimentally measured load-deflection characteristics of the bearings was very close. A further observation is that the deflection values obtained from curves during unloading of the weights was consistently 3-5 microns greater at a given load than for the loading-up curve (an indication of hysteresis losses)

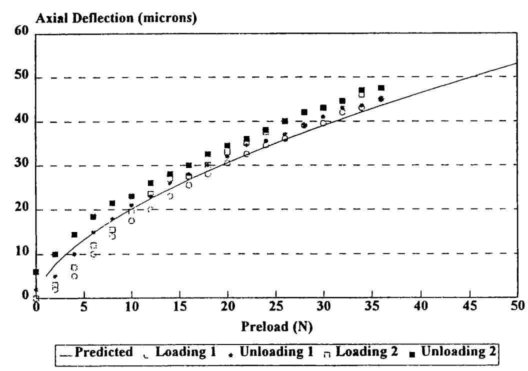

Figure 5 Experimental and Predicted Load v Deflection Curves for ED20 Bearings with Torlon Balls and Steel Rings (predictions use CABARET V1.00)

6. TORQUE CHARACTERISATION IN AIR

In all cases, mean and peak torque values increased from relatively low initial values to stable (occasionally quasi-stable) higher values after around 1000 revs, for example Figure 6. Stable frictional torque values were typically of order 20 times the values which would be expected for lead-lubricated bearings in air at equivalent preload, though the ratio of peak torque to mean torque was low, typically around 1.5.

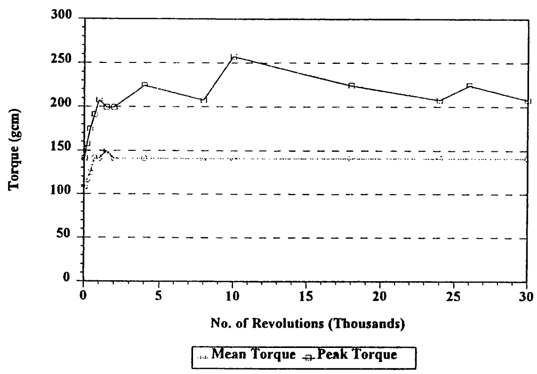

Figure 6 Torque v Revolutions for ED20 Bearings with PEEK Balls\Delrin Cages in Air (46N preload, 109rpm)

7. TORQUE CHARACTERISATION IN VACUUM

These tests followed a similar trend with torque stabilisation occurring rapidly. In-vacuo torque levels were generally higher than equivalent in-air tests by a factor 2-3. Though again the ratio of peak to mean torque was around 1.5, exceptionally for aluminium rings this ratio reached 2.5 for Torlon balls and 3 for PEEK as shown in Figure 7.

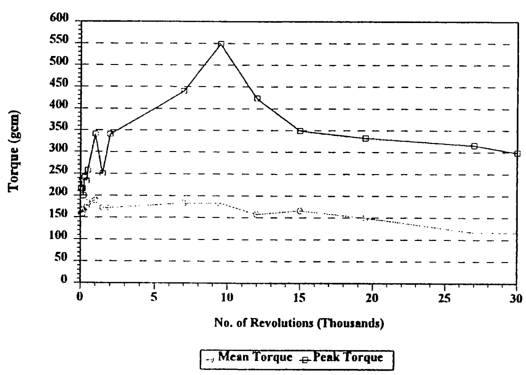

Figure 7 Torque v Revolutions for ED20 Bearings with Aluminium Rings, PEEK Balls\Delrin Cages in Vacuum (38N preload, 107rpm)

8. POST-TEST EXAMINATIONS

In all cases, there was some light dusting of loosely adherent ball debris on the raceways following test, however this was less evident on bearings tested with the aluminium raceways. All balls appeared polished after test in air or vacuum. For tests with aluminium raceways, occasional transfer of aluminium debris to the ball surfaces was observed.

9. DISCUSSION

The ball-on-disc tests demonstrated that both PEEK and Torlon undergo a run-in behaviour, suggesting lubrication by generation of a transfer film of ball material. However this mechanism is different from the usually accepted mechanisms of solid lubrication in spacecraft bearings for which it is more usual to rely either on a pre-deposited film or on transfer film formation from a cage material. Unlubricated polymer balls clearly undergo some wear during the formation of this film, therefore in order to qualify such bearings for flight, it would be necessary to demonstrate an acceptably low wear rate following run-in. This would require a series of long duration tests

When suitably high hysteresis loss coefficients (0.2 for Torlon and 0.8 for PEEK) were adopted combined with measured values of sliding friction coefficient in air and vacuum, both the stiffness behaviour and the initial torque of both PEEK- and Torlon-balled bearings could be predicted using CABARET. However, the steady state torque values could not be predicted - even when the assumption of a hysteresis loss coefficient of 0.8 was adopted for Torlon. A possible reason for this is that the high steady-state torques recorded may be a function of other effects such as slight thermal softening of the polymers, which could in turn lead to an increasing ball-raceway contact area due to lower effective Young's modulus or greater hysteresis loss coefficient than modelled. In-vacuo where heat dissipation is more difficult than in air, despite Torlon and PEEK having similar pre-run-in sliding coefficients of friction to the in-air values, and much lower post-run-in values, the mean bearing torques measured were always considerably higher than the corresponding air test values. This observation suggests that a heat dissipation effect may indeed be influencing the bearing test results.

When results of torque tests were normalised using CABARET predictions to take into account different geometries, it was found the normalised mean torque of peek-balled, steel ringed bearings in air is marginally less and in vacuo is considerably less than that of Torlon-balled bearings. With aluminium rings, PEEK and Torlon performed similarly in air and vacuum, generating torque levels comparable to that of PEEK balls versus steel raceways in vacuo as shown in Figure 8.

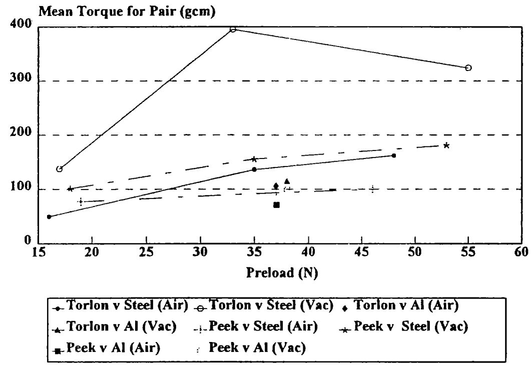

Figure 8 Measured Mean Torque of ED20 Bearings with Steel or Aluminium Rings, Torlon and PEEK balls. Normalised for geometric effects v preload.

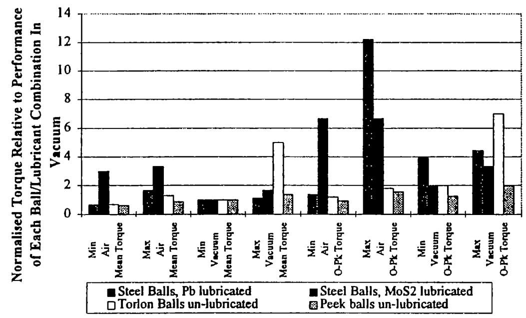

Figure 10 Experimental Mean and Zero-peak Torque Values (Maximum and Minimum) for ED20 Bearings with Various Ball/Lubricant Combinations using Steel Rings at 35-45N Preload in Air and Vacuum

Direct comparisons were also made with results of bearing tests from a separate test programme in which all-steel bearings lubricated by lead and MoS_2 were subjected to periods of running in air followed immediately by running in-vacuo. This allowed approximate comparisons of the hybrid bearing performance data with steel bearings using conventional lubricant systems. In these comparisons, minimum and maximum values of mean and peak torque obtained in both test programmes were normalised against in-vacuo test data in two ways: firstly against the torque behaviour of lead-lubricated steel balls; secondly by comparison with the behaviour of each ball and lubricant combination itself. As can be seen, relative to lead-lubricated bearings, in Figure 9, the hybrid polymeric bearings showed generally less-favourable performance, but as shown in Figure 10, their performance was more self-consistent with generally much lower variability in torque.

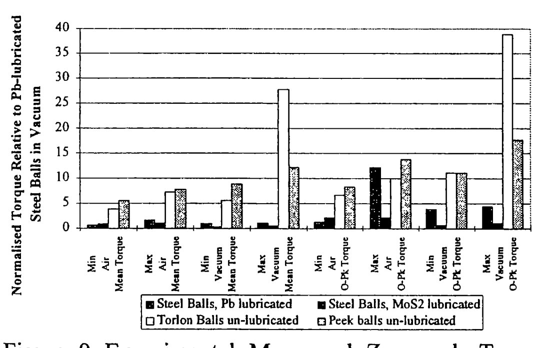

Figure 9 Experimental Mean and Zero-peak Torque Values (Maximum and Minimum) for ED20 Bearings with Various Ball/Lubricant Combinations using Steel Rings at 35-45N Preload in Air and Vacuum

10. CONCLUSIONS

Of the 3 polymers tested, Torlon and PEEK showed the greatest promise in terms of low sliding friction and wear for used in hybrid polymeric bearings.

The benefits of polymeric bearings identified and quantified in this work are their low mass and low torque noise to mean torque ratio. We can speculate that they will also have the capability to perform simulated ground tests without a need for any purge, and will have good vibration damping characteristics during launch which may result in a need for reduced preloads.

Disadvantages of hybrid-polymeric bearings quantified in this work are the high mean torque levels and low stiffness compared to steel-balled bearings. Though the high mean torque levels recorded in this programme are disappointing, we have shown that these may be attributable to thermal effects due to the relatively high test speed. Tests at low speed and investigations of the possible synergistic effects of polymers used in conjunction with other solid or liquid lubricants have not yet been carried out, but we can speculate that these will provide much more favourable torque performance. On this basis, we consider hybrid polymeric bearings to be worthy of further study and possible candidates for future flight applications.

11. REFERENCES

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