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THERMAL BEHAVIOUR OF TEFLON/PHENOLIC LINERS IN SELF-LUBRICATING BEARINGS

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Abstract

The gun system of the M1 series tank rides on a pair of self-aligning spherical bearings that allows the elevation and depression of the cannon. Because these bearings are encapsulated within the rotor housing, periodic lubrication or maintenance is impossible. To overcome this problem self-lubricating bearings were incorporated into the system. There are two basic liner designs, molded and fabric. Molded liners are produced by applying a formulation of teflon and typically asbestos into a phenolic resin, which is applied to the bearing surface, then cured. Fabric liners utilize a woven fabric bonded to the bearing surface, then teflon which is mixed into phenolic resin is applied to the bearing surface and cured.

Initial studies of the existing bearing liner were completed to determine the liner composition and establish a baseline or standard to compare thermal and mechanical properties with potential vendors. DSC revealed an average teflon content of 39.53%, which varied significantly throughout the liner. TG analysis showed an asbestos concentration of 12.22%. The remainder of the liner was phenolic resin. Physical testing of the bearing from –20 to 120°C under normal loading conditions demonstrated excellent thermal stability with little wear.

Bearings from each vendor were tested and compared to the standard properties of the baseline bearing. Some properties were difficult to compare or insignificant due to the design differences between molded and fabric liners. The testing program resulted in the qualification of two bearings, which met or exceeded the established standards. Both of these bearings were designed with fabric liners.

Keywords: spherical bearings, teflon, thermal analysis

Introduction

When the motion in a system takes place along more then one axis, some type of self-aligning or multiaxial bearing is required. When lubrication and periodic service or maintenance are not practical, then the system requires some type of self-lubricating bearing. This is the type of bearing system that is required for use in the M1 series tank cannon gun system. This bearing must be able to sustained a constant radial loading, due to the mass of the tank cannon and maintain dimensional stability in both the static and dynamic states. It also has to be capable of sustaining very high radial forces due to the firing recoil of the gun system. Compounding the serviceability of the bearing is its complete encapsulation in the rotor housing assembly. This precludes the use of any bearing requiring periodic maintenance and/or lubrication.

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An ideal bearing to meet this application is the Self-Lubricating Spherical Bearing. The bearing is manufactured with an outer race and inner ball made from either steel or stainless steel. The inner surface of the race contains a liner with teflon embedded in an organic resin matrix, usually a phenolic, which is supported by a filler to improve dimensional stability and compressive strength. There are two basic liner designs, molded and fabric liners. Molded liners are produced by mixing teflon fibers and a filler material in a phenolic resin which is formulated as an adhesive. The resin system is applied over a plasma spray coating of aluminum bronze, rolled to almost finished dimension and after the inner pilot bearing is inserted, cured to attain the final dimension. After curing, the pilot is removed and the final inner ball is inserted. The second design, specified as a fabric liner, incorporates a woven fiber backing, typically produced from either a polyester or aramid fiber, bonded by an adhesive to the inner wall of the race. The teflon is again imbedded in a polymeric resin matrix, generally phenolic, in the form of chopped or long fibers. The mixture is then bonded to the fabric. The resin and teflon are then cured, under pressure in the case of phenolic, in order to maintain dimensional stability and remove solvent and water. This prevents the generation of porosity in the liner during cure. If a pilot ball is used to apply the pressure, it must be removed after curing and a finished inner ball inserted. Illustrated in Diagram 1 is a representation of each manufacturers liner design.

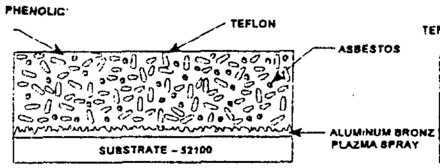

Fig. 1 TORRINGTON/SOLTAM

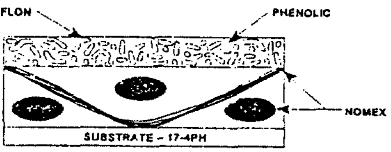

Fig. 2 NEW HAMPSHIRE

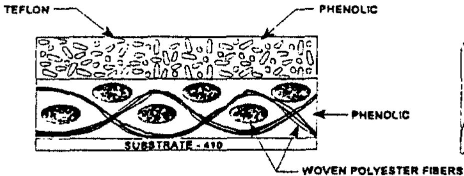

Fig. 3 KAHR

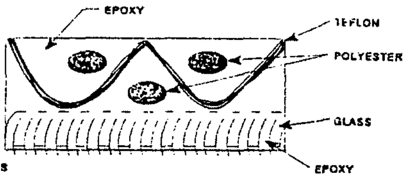

Fig. 4 PSI

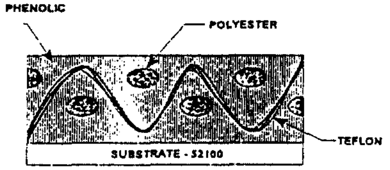

Fig. 5 SOUTHWEST

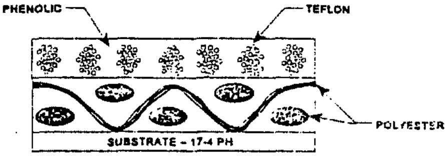

Fig. 6 ACCURATE

BEARING LINER CROSS-SECTIONS

Diagram 1 Liner design

Polytetrafluoroethylene (PTFE), is the lubricant used in self-lubricating bearings. PTFE can be utilized in the formation of chopped fibers, long fibers, with or without orientation, or it can be cross woven into a fabric. As a lubricant it has a very low coefficient of friction and good antistick properties. As a bearing material, once the bearing is 'broken-in', a monolayer of teflon is deposited on the surface of the inner ball, giving a net effect of teflon on teflon. Since the static and kinetic coefficient of friction are approximately equal, there is little or no stick-slip characteristic in the bearing.

PTFE is a highly crystalline thermoplastic, oriented in helical conformations, with a regular structure, lacking any appreciable crosslinking. The degree of crystallinity of PTFE can approach 90 to 95%. The degree of crystallinity is effected by molecular weight and the cooling rate during manufacturing. Rapid cooling from the melt, reduces spherulite formation, thus reducing crystallinity. Slower cooling permits larger crystals to grow, increasing crystallinity and making a stiffer material with improved tensile strength and flexural modulus.

PTFE for low speed bearing applications, where maintenance is difficult, has good load carrying capability. It has a typical tensile strength of $1.72–4.48\times10^4$ kPa, tensile modulus of 4.14×10^5 kPa, and a compressive strength of $4.8–12.4\times10^3$ kPa, depending on the reference source. Temperature has no effect on the mechanical properties up to 250°C. In tension, PTFE begins to cold draw at $1.03–1.38\times10^4$ kPa, elongating 300–450% before breaking at $1.72–4.48\times10^4$ kPa. It is subject to cold flow under stress, but exhibits some delayed elastic recovery. It's mechanical properties such as resistance to wear and deformation under load, stiffness and compressive strength can be improved by the addition of fillers. Under small loads PTFE will deform, but when the loading is removed the deformation recovers rapidly (elastic deformation). Increasing the loading beyond the yield point, PTFE initially experiences a large displacement, thereafter, the rate of displacement decreases, and all the deformation is non-recoverable (plastic flow). Teflon remains strong and tough down to −196°C showing a resistance to embrittlement. At low temperatures where the stiffness increases, the compressive strength also increases. Like all plastics, PTFE expands and contracts more then metals having a reported coefficient of linear thermal expansion of $1.35–1.51\times10^{-4}$/°C. The coefficient of friction of teflon decreases with both applied load and an increase in temperature.

Experimental

Bearing liners from seven manufacturers were analyzed using DSC, TG, TMA and Wear Testing. Samples were taken randomly from each vendors bearing liner for DSC analysis to determine the teflon concentration, TG analysis of the molded liners to determine the asbestos concentration and TMA analysis for expansion measurements.

Samples of the liners were sectioned for DSC, weighed and encapsulated in aluminum pans. The samples were placed in a Perkin-Elmer DSC7 to determine the teflon concentration. The samples were heated in a nitrogen atmosphere at 20°C min^{-1} from 50 to 350°C, held at temperature for 10 min, then cooled at 20°C min^{-1} back to 50°C. The samples were again scanned at 10°C min^{-1} from 50 to 350°C to measure the enthalpy of the melting peak. A teflon standard was analyzed using the same procedure to determine the melting temperature and enthalpy of the melting peak. The enthalpy obtained was used to measure the percentage of teflon in the liners.

Samples from the two molded liners were analyzed by TG to determine the asbestos concentration. Samples of 2–5 mg in size were placed in a Perkin-Elmer TGA7 and heated from 50 to 690°C at 20°C min^{-1} in an oxygen atmosphere. The percentage of asbestos was determined as the residue remaining after sample oxidation.

Samples of the teflon standard and steel of the bearing were sectioned and analyzed in a Perkin-Elmer TMA7 using an expansion probe with a 10 mN force. The samples were placed in the fixture and the instrument reservoir was filled and maintained with liquid nitrogen. The samples were given 15 min to come to equilibrium. The samples were then scanned at 5°C min^{-1} from –50 to 125°C in a nitrogen environment.

The oscillation or wear test was setup to simulate the extent of bearing wear in service by mounting one bearing in each of two pillow blocks, which were connected by a 4340 steel shaft. The bearing shaft was oscillated ±25 degrees, simulating elevation and depression of the tank canon, at a rate of 6 cycles/min using loads of 36 774, 49 486, 73 094, 96 702 and 120 310 kg. At each load the bearings were cycled 2500 times.

Results and discussion

The Trunnion Bearing self-lubricating liner is manufactured using two designs, molded or fabric as discussed previously in the introduction. Specimens from both types of liners were sampled and compared to a sample of teflon using DSC analysis. The standard teflon sample had an average melting onset temperature of 317°C and a heat of enthalpy of 20.83 ± 1.96 J g^{-1}. This measured value was used to calculate the % teflon for each of the manufactures liners. The thermograms for the Torrington and New Hampshire bearing liners in each case displayed only one peak, which corresponded to the melting peak of teflon. The same results were observed for both the Mistral and Southwest bearing liners. The PSI bearing liner displayed a melting peak at 238°C, which corresponded to the melting peak of polyester fibers added to the structure, to increase the compressive strength of the fabric liner. The second melting peak seen at 321°C is again the melting peak for teflon. The liner materials of Kahr and Accurate also reveal a polyester melting peak. The concentration of polyester was never calculated due to the inability to obtain an acceptable standard and our interest was only to verify the manufacturers product information. Listed in Table 1 is the thermal data and percentages of teflon in each manufacturers liner. Looking at the table it can be seen that the teflon concentration varies from a

Table 1 Thermal analysis results of liners

	Torr	Mist	Hew H.	Kahr	ACC.	S.W.	Psi
T_m onset peak 1	none	none	none	240°C	339°C	none	241°C
T_m peak peak 1	none	none	none	254°C	251°C	none	250°C
ΔH/ J G^{-1}	none	none	none	17.87± 3.64 J G^{-1}	8.13± 0.58 J G^{-1}	none	2.22± 0.64 J G^{-1}
T_m onset peak 2	325°C	324°C	326°C	324°C	321°C	322°C	321°C
T_m peak peak 2	330°C	329°C	330°C	328°C	327°C	328°C	327°C
ΔH/ J K^{-1}	8.92± 1.88 J G^{-1}	8.75± 1.25 J G^{-1}	6.81± 1.31 J G^{-1}	5.15± 1.78 J G^{-1}	10.02± 1.84 J G^{-1}	2.14± 1.24 J G^{-1}	1.78± 0.30 J G^{-1}
% Teflon	42.82± 9.53	42.01± 8.38	32.71± 6.3	24.74± 8.56	48.09± 8.85	10.27± 5.94	8.53± 1.42
% ABS-ESTOS	12.21± 1.04	11.81± 0.42	none	none	none	none	none

high of 48.09% for Accurate to a low of 8.53% for PSI, however as seen in the standard deviation the % of teflon varies significantly due to the heterogeneous nature of the liner chemistry.

The molded liners of Torrington and Mistral contained asbestos particles to increase their compressive strength, which possess a serious concern due to the potential health hazard. Figure 1 is a TG scan of a sample of the Torrington liner, which shows the decomposition of the liner in an oxygen rich environment and the 1st derivative of that decomposition. As seen in the figure, the liner undergoes a two-step decomposition with 13.25% residue remaining above 650°C, which corresponds to the asbestos added to the formulation. In Table 1, only the molded liners of Torrington with 12.21% and Mistral with 11.81% contain asbestos.

Thermomechanical analysis of the teflon standard, steel bearing components and the liner with substrate were run. Figure 2, is a DSC curve of the teflon standard used for calculation of the % teflon. As seen in the Fig. 2, at 26°C a transition

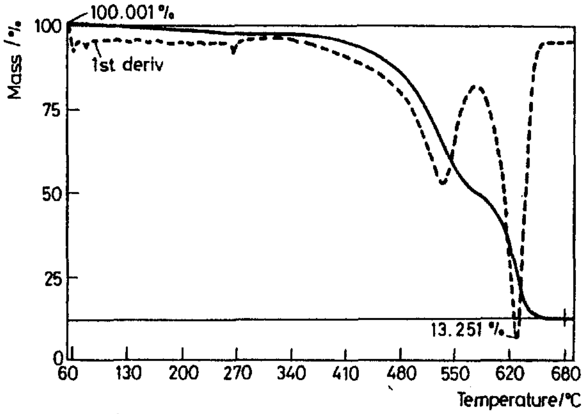

Fig. 1 Thermal decomposition Torrington liner

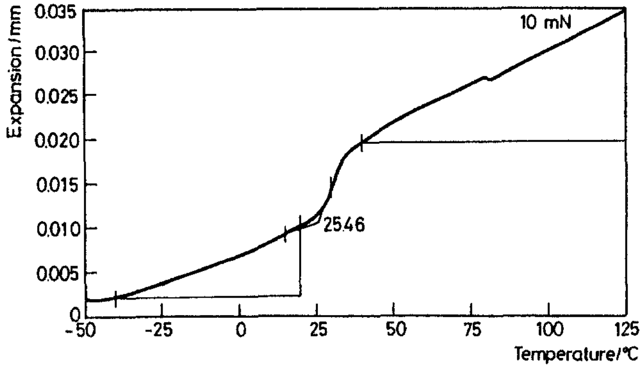

Fig. 2 Teflon

was noted that was not observed in the DSC scans. This is due to the low energy associated with the transition. This observed transition corresponded to some uncoiling in the teflon chain. Below the transition a linear coefficient of thermal expansion of 1.061×10^{-4}/°C was measured and above the transition the coefficient increased to 1.405×10^{-4}/°C. In Fig. 3 the linear coefficient of thermal expansion was measured for the bearing steel substrate yielding a value of 1.263×10^{-5}/°C. Samples were also analyzed for each of the vendors bearing liners, however inconsistent data was obtained due to the spherical and concave shape of the bearing. The bearing configuration made it impossible to obtain a flat specimen. The curved surface prevented the tip of the expansion probe from sitting securely on the sample surface.

Table 2 shows the results of the wear testing. Each manufacturer had three pairs of bearings placed in a press and loaded to 36774, 49486, 73094, 96702 and 120310 kg. The bearings were cycled 2500 times at each load. The results in the table show the average cumulative liner wear for each bearing. The PSI and Southwest bearings both failed within the first 2500 cycles. The Accurate bearing had one bearing fail between 5000 and 10000 cycles and one between 10000 and 12500 cycles. The Torrington bearing had one failure between 10000 and 12500 cycles. The

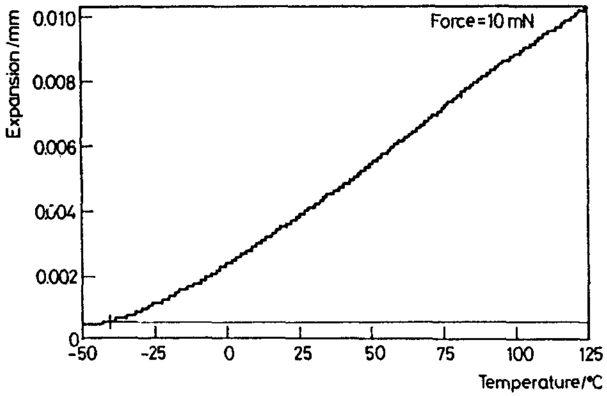

Fig. 3 52100 Steel

Table 2 Results of wear testing (liner wear cumulative)

Cycles	2500	5000	7500	10000	12500	Failed
Torr	.056 mm	.074 mm	.114 mm	.201 mm	.277 mm	1 of 3 1 > 10000
Mist	.02 mm	.048 mm	.079 mm	.145 mm	.262 mm	None
New H.	.02 mm	.041 mm	.056 mm	.084 mm	.124 mm	None
Kahr	.02 mm	.033 mm	.048 mm	.094 mm	.203 mm	None
ACC.	.086 mm	.13 mm	.168 mm	.213 mm	.304 mm	2 of 3 1 > 5000 1 > 10000
S. W.	Failed	Failed	Failed	Failed	Failed	All
Psi	Failed	Failed	Failed	Failed	Failed	All

Mistral, New Hampshire and Kahr bearings all successfully completed the wear testing.

Thermocouples were inserted in the test fixture to measure the frictional heating of the liner during testing. The average liner temperature during testing, for all seven liners at a load of 36774 kg was 49±5°C and when the load was increased to 49486 kg the temperature remained relatively constant, varying slightly from manufacturer to manufacturer. When the load was increased to 73094 kg the temperature increased to 59±6°C; at 96702 kg the temperature was 69±4°C and at 120310 kg the temperature reached 85±8°C. The fabric liners displayed a higher degree of frictional heating as the liners wore than did the molded liners, this was most likely due to an increase in the coefficient of friction associated with the liner fabric. When the liner failed, metal to metal contact, the temperature reached or exceeded 150°C due to the increased frictional heating associated with metal to metal contact.

Conclusion

Teflon as a lubricant for self-lubricating trunnion bearings provides an exception sliding surface, which requires no maintenance. The wear test data shows that when teflon is designed as a composite structure, the material properties, in particular the compressive strength can be increased to exceed the loading experienced during both cannon auto stabilization and firing.

The thermal data demonstrates that given the frictional heating observed during wear testing, that all the liner materials were well within their thermal stability. Even during liner failure when the temperature of the liner reached 150°C the liners were still within their thermal limits. The test results show that both fabric and molded liners performed satisfactorily, thus there is no performance advantage to either design.

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