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AXIOMATIC DESIGN OF THE HYBRID COMPOSITE JOURNAL BEARING

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ABSTRACT

Journal bearing materials are required to have special characteristics such as compatibility with journal interface materials, embeddability for particles and wear debris, conformability to accommodate misalignment, thermal and corrosion resistance. Although conventional journal bearing materials such as white metals or babbitt metals meet almost the required characteristics, they have possibility of seizure between the bearing material and the journal when the oil film is broken. From the manufacturing point of view, the functional requirements of journal bearing are "to reduce the manufacturing cost with easy processes," "to be easily repaired and maintained," and etc. These functional requirements are not easy to satisfy simultaneously with conventional manufacturing methods such as centrifugal casting of white metals and filament winding of composite materials.

In this study, a hybrid composite journal bearing composed of carbon fiber reinforced phenolic composite liner and metal backing was developed to solve the problem of the conventional journal bearings with the axiomatic design approach.

Keywords[1]: composite, hybrid, bearing, wear

1 INTRODUCTION

The materials for bearings such as fluid-film or rolling element bearings require several properties: low friction, low wear rate, and long life. While many engineering materials may be used for bearing materials, final selection for the optimum bearing material is commonly based on judgment as to the most essential material properties, type of application, and cost.

Although white metal was mainly used due to its superior compatibility with steel shafts, ability to embed foreign particles, and unique ability to adapt to misalignment, the major problem of white metal journal bearing used in large marine vessels is the seiziure between the journal and the bearing when the lubricant film is broken under heavy load, or low velocity applications, or start and stop periods. To solve the seizure problem, polymers are widely used in the parts of bearings, gears, and oil sealings because the friction coefficient of polymers is much low compared to that of metallic materials due to their self-lubrication properties [1]. Phenolics among several plastic materials are largely used for bearing materials because the phenolics operate satisfactory with steel or bronze journals when lubricated with oil, water, or other liquids without seizure. However, the low mechanical strength, low thermal conductivity and large thermal expansion of phenolics limit the wide applicability for bearings like other polymer bearings. In order to overcome these inferior properties of polymers, reinforcements in either fiber or powder form are usually embedded in polymers to make composites.

Several investigations on composite materials for journal bearings have been carried out. Most of them, however, are related to the metal composite or PTFE liner. Sharma investigated bearing characteristics of cast ZA-27 (zinc aluminum) /graphite particle composite materials with graphite particle content varying from 1-6 wt. % under lubricated, semi-dry, and dry conditions [2], in which the composite bearings were able to run up in the regimes of boundary lubrication without seizure. Zhang manufactured three kinds of metal-plastic multilayer composite journal bearings, which were composed of a steel backing, a middle layer of sintered porous bronze and a surface layer of polytetrafluoroethylene (PTFE) filled with Pb or Cu_2O powders [3].

The manufacturing method of journal bearings is also an important engineering factor, which determines manufacturing cost as well as performance of the product.

White metal lining journal bearings are usually manufactured by centrifugal casting, in which a permanent mold is rotated about its axis at high speeds (300 to 3000 rpm) as the molten metal is poured. The molten metal is centrifugally thrown towards the inside mold wall, where it solidifies after cooling. Irregular inner surface should be machined for accurate dimensions, which costs much for large journal bearings. While, composite journal bearings can be manufactured by filament winding, which produces precise inside surface if an accurate mandrel for winding is used.

In this work, the feasibility of carbon fiber reinforced phenolic composites for large journal bearings was investigated by the axiomatic design method [4]. Also the manufacturing methods for the hybrid composite journal bearing composed of composite and metal were developed. Using the measured material properties, the stress analysis of a large journal bearing was performed using finite element method to assess the reliability of the composite journal bearing.

2 AXIOMATIC DESIGN OF THE HYBRID COMPOSITE JOURNAL BEARING

Axiomatic design was employed to solve the design problem of the conventional journal bearing.

The objective of this study is to design and manufacture journal bearings with high strength, high hygrothermal stability, better tribological behavior such as low wear rate and low friction coefficient than the white metal, and low manufacturing and maintenance cost. the highest level of FR and DP were defined as follows;

FR: Enhance the mechanical properties and hygrothermal characteristics of the journal bearing.

DP: Bearing material and dimensions of the journal bearing

C_1: Dimensional constraint (Minimum film thickness)
C_2: Maintenance
C_3: Cost

Mechanical properties include strength, wear rate, and friction coefficient in the sliding direction. Composite journal bearings in marine applications should also sustain the high stress caused by hygrothermal expansion. Under high load and low velocity applications of composite journal bearing to large vessels, severe wear may occur on the bearing surface. Therefore, journal bearing materials should have low wear rate. When the direct contact between the journal and bearing occurs, heat generated by friction should be dissipated easily because polymeric composite materials usually have low mechanical properties at high termperature.

In addition to good mechanical properties and hygrothermal characteristics, the journal bearing should satisfy several other strict constraints; minimum film thickness between the journal and bearing. The typical clearance range for journal bearing is dictated as follows [5].

$$0.02 \text{ mm} \le h_{min}=(c-\Delta c)(1-\varepsilon) \le 0.03 \text{ mm} \qquad (2.1)$$

where, c: radial clearance

Δc: dimensional change of radial clearance

ε: eccentricity ratio

The above dimensional constraint includes mechanical and hygrothermal expansions.

Therefore, the highest level of the FRs and DPs may be decomposed as follows.

FR_1: Support the compressive stress caused by hygrothermal expansion.
FR_2: Reduce wear rate.
FR_3: Dissipate the heat generation.
FR_4: Minimize the dimensional change by hygrothermal effect.

DP_1: High strength and stiffness of carbon fiber
DP_2: Self lubricating characteristic
DP_3: Thermal conductivity and bearing thickness
DP_4: Hybrid bearing composed of composite and metal

C_1: Radial clearance should be included in the typical range.
C_2: Maintenance should be possible.
C_3: Manufacturing cost should be reduced.

In order to support the high compressive stress and buckling load, the compressive strength and stiffness of the material should be high. Also, in order to cope with severe tribological environments, the material should have the self lubricating characteristic. Carbon fibers are the most widely used advanced fibers which have high specific stiffness, strength and good tribological behavior. Phenolics among several types of polymers for bearing materials are largely used because the phenolics operate satisfactory with steel or bronze journals when lubricated with oil, water, or other liquids. They have also good resistance to seizure and dimensional stability. Therefore, the characteristics of carbon fiber reinforced phenolic composite material were selected as DP_1, DP_2 and DP_3. Even though phenolics have good dimensional stability in the high temperature, the thickness of the composite should decrease to reduce the hygrothermal stress and to increase the heat dissipation capability, if a metallic back up material is used to support thin composite material, which is a hybrid composite material. Therefore, the hybrid journal bearing composed of thin composite layer and backing metal was selected as DP_4. Eq. 2.2 shows the master design matrix of the journal bearing. Stiffness (DP_1) of carbon fiber also affects the dimensional change (FR_4) of the journal bearing. Also, the self lubricating characteristic (DP_2) of the composite material affects dimensional change (FR_4). However, these effects are small because the dimensional change of the journal bearing is dominated by the thickness of the composites and back up metal, consequently, the relationship was expressed as lower case *x*.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ x & x & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \qquad (2.2)$$

This design is decoupled design because the master design matrix is expressed as a lower triangular matrix. Since this design problem is a decoupled design, the hybrid composite journal bearing can be designed based on the axiomatic design principle.

3 MECHANICAL PROPERTIES

Two types of fiber reinforced composites such as unidirectional asbestos fiber reinforced phenolic composite and carbon fiber reinforced phenolic composite were studied. The asbestos fiber reinforced phenolic composites have been employed in large stern journal bearings for supporting the propeller shaft of a ship because they have the highest performance per price among the composites although the health hazard of this material is recently a great concern. The large asbestos fiber reinforced phenolic composite bearings are usually manufactured by winding asbestos fibers with resin or resin precursor impregnated on a mandrel, followed by curing at elevated temperatures. The carbon fiber reinforced phenolic composites studied in this work were 8-harness satin weave. The fiber was PAN (Polyacrylonitrile) based T300 and the matrix was resol-type phenolic. A carbon fiber reinforced phenolic composite was prepared by laying up prepregs and curing them with the suggested cure cycle. Table 1 shows the composite mechanical properties in the circumferential direction, each of which was averaged from the five tested values.

Table 1 Mechanical properties of two composite materials in the circumferential direction

	Carbon/phenolic	Asbestos/phenolic
Compressive strength (MPa)	220	86.2
CTE (10^{-6}/°C)	1.23	7.19
Swelling (%)	0.01	0.03

From theses results, it was found that properties of carbon fiber reinforced phenolic composite were better than those of asbestos fiber reinforced phenolic composite in every respect.

4 WEAR TESTS OF COMPOSITE MATERIALS

The composite plate was cut and machined to produce hexahedral shape of size 5 mm × 5 mm × 6 mm as shown in Fig. 1. The wear tests were performed using a pin-on-disk type arrangement shown in Fig. 2. The steel plate was 240mm in diameter and 12 mm in thickness. The composite specimens were slid against the steel plate at several different speeds and load. The friction forces of the specimens were measured by a strain-gage bridge which was bonded on the specimen holder. The wear volume of the composite was calculated by the weight loss measurement. The weight loss of the composite specimen was measured by an electronic balance with 0.1mg resolution.

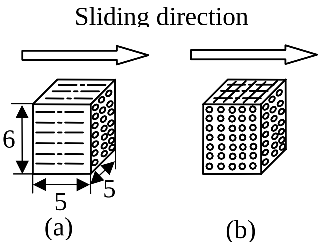


Fig. 1 Specimen [mm] for wear test with sliding direction; (a) asbestos phenolic, (b) carbon phenolic.

For each test, the surface of the steel plate was polished to a roughness of about 0.2 μm. The *PV* value (*P*: pressure, *V*: speed) of 2.0 MPa·m/s was used, which was similar to the operating condition of large vessels.

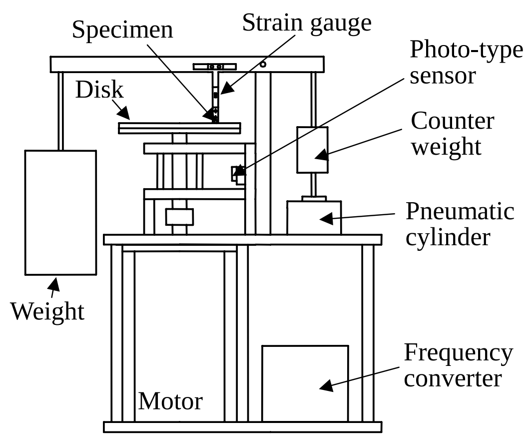


Fig. 2 Schematic diagram of the pin-on-disk type wear tester.

The wear volumes of the carbon phenolic and asbestos phenolic composite specimens were measured as a function of sliding time at two different *P*'s and *V*'s with constant *PV* value of 2.0 MPa·m/s. As shown in Fig. 3, significant differences in wear volume between the two materials were observed. The wear volume of carbon fiber reinforced phenolic composites was little changed with respect to load and velocity, but the wear volume of asbestos fiber reinforced phenolic composites increased much with respect to load and velocity. Also the pressure was more dominant factor for the wear volume of asbestos fiber reinforced phenolic composites than the speed at the constant *PV* value. When the pressure increased and speed is decreased, the wear volume increased as shown in Fig. 3 and the wear surface of this condition was rougher than the other conditions as shown in Fig. 4(a), (b). This implies that the large void of asbestos fiber reinforced phenolic composites directly influenced much the wear behavior of the composite.

If the stress due to the friction force exceeded the shear strength of specimen, a crack initiated and propagated along the void of the specimen, which plucked off the specimen as shown in Fig 4(a), which caused large wear volume.

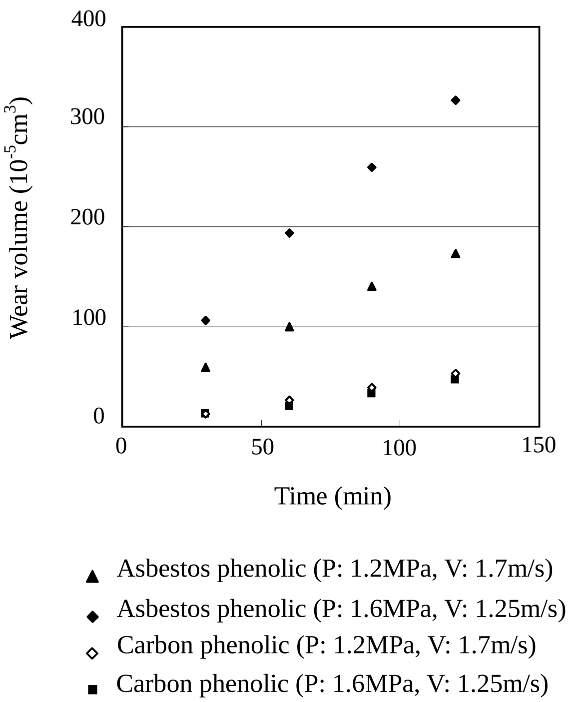
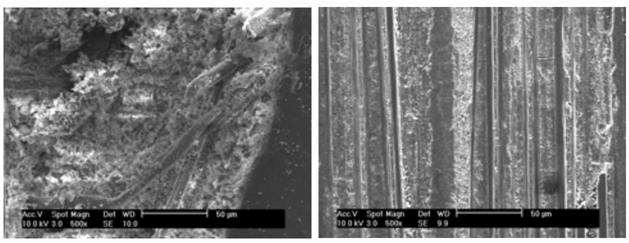


Fig. 3 Wear volume of the carbon phenolic and asbestos phenolic composites with respect to sliding time at the constant PV value.

For the carbon fiber reinforcement phenolic composites, the wear volumes were less than those of the asbestos reinforced phenolic composites at the constant *PV* because of the self lubricating capability and high conductivity of carbon fiber. Fig. 4(b) shows the fiber fracture and material in the adherent membrane. When the two sliding surfaces came into contact, asperities of the softer surface were easily deformed and some were fractured by the repeated loading action. These repeated loading action caused crack nucleation under the very near surface and further loading and deformation caused cracks to extend and propagate, joining neighboring ones. The cracks propagated along the week part, i.e., interface between fiber and matrix, where the fiber fracture occurred by repeated loading.



(a) (b)

Fig. 4 Wear surface of the two composite materials. (a) Asbestos phenolic (P: 1.6MPa, V: 1.25m/s), (b) Carbon phenolic (P: 1.6MPa, V: 1.25m/s).

The friction coefficients of two materials were obtained under the constant normal force of 40 N at the speed of 1.25 m/s by dividing the friction force by the vertical force as shown in Fig. 5. The dry mean friction coefficients of the asbestos fiber reinforced phenolic and the carbon fiber reinforced phenolic composite were 0.27 and 0.16, respectively. The low friction coefficient of the carbon phenolic composite is due to the lubricating action of carbon fibers. The friction coefficients of carbon phenolic composite in the initial transient state were higher than those in the steady state because the material adherent in the membrane reduced the friction in the steady state [6]. In case of asbestos fiber reinforced phenolic composite, the material adherent in the membrane was discontinuous and non uniform as shown in Fig. 4(a). Because of low interfacial strength between asbestos fiber tows, the fiber bundles were peeled off during sliding so that a roll-like wear debris was produced, which caused large wear volume.

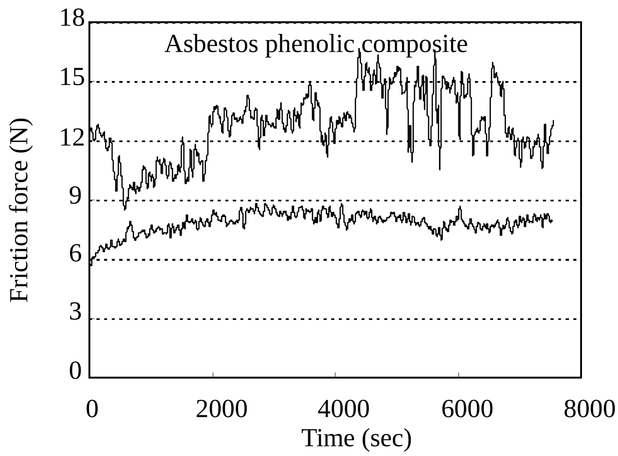


Fig. 5 Friction force of composite specimens with respect to sliding time

(normal pressure: 1.6MPa, velocity: 1.25m/s).

5 DESIGN OF THE HYBRID COMPOSITE JOURNAL BEARING

5.1 DESIGN PROCESS

The thickness of the asbestos fiber reinforced phenolic journal bearing should be larger than 45 mm to prevent the buckling of composite bearing due to large CTEs and swelling due to oil absorption in addition to the interference fitting. In the actual running, the journal bearings made of asbestos phenolic composite were reported to be failed by these factors.

In this work, a hybrid journal bearing was suggested to solve the above problems with axiomatic design. When the carbon fiber phenolic composite with back up material is employed for the bearing material, 4 mm thickness is enough because of its high modulus. Since the maximum compressive stress in the composite journal bearing occurs in the hoop direction, so the warp direction of carbon fiber reinforced fabric composite (DP_1) is aligned to the hoop direction of journal bearing. The manufacturing method for the hybrid composite journal bearing with RTM (Resin Transfer Molding) is illustrated in Fig. 6.

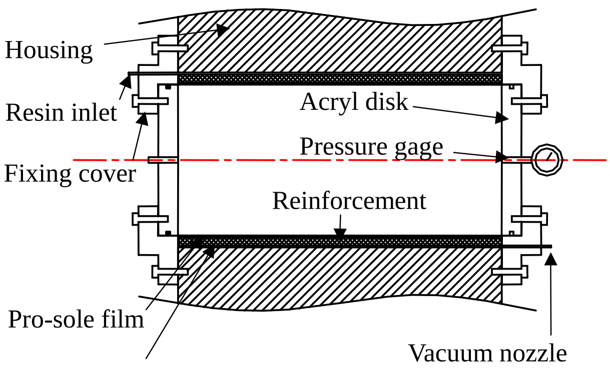


Fig. 6 Manufacturing method for the hybrid composite journal bearing with RTM.

The manufacturing cost (C_4), which is an important constraint can be reduced much by employing the RTM (Resin Transfer Molding) method, which is depicted as follows.

1. Prepare the carbon fiber tubular reinforcement with a pressure bag (such as Pro-sol film) inside.
2. Insert the reinforcement into the metal housing.
3. Close the sides of the metal housing with an acrylic disk.
4. Pressurize the inside bag to make the reinforcement stick to the metal housing.
5. Inject phenolic resin into the reinforcement.
6. Pressurize and depressurize several times to help the phenolic resin impregnate the reinforcement.
7. Blow hot air in the tube to complete the cure of the resin.

5.2 STRESS ANALYSIS OF THE COMPOSITE JOURNAL BEARING

Using the material properties, the stress and strain distributions in the composite journal bearing were calculated by finite element method under the assumed operating conditions that the temperature and pressure of the composite bearing were equal to the mean values of the lubrication oil. In case of actual journal bearings, the temperature and pressure continuously change, therefore, they are locally different. In this study, however, the nominal bearing pressure and mean temperature rise were used to investigate the macroscopic deformation of composite bearing. The mean temperature rise was calculated by adding the two contributions: the actual mean temperature rise of the oil film and the equivalent temperature rise to give the same dimensional change due to bearing swelling caused by oil absorption.

$$\Delta T_{total} = \Delta T_{film} + \Delta T_{swelling} \tag{5.1}$$

where, ΔT_{film} = Temperature rise of oil film,

$\Delta T_{swelling}$ = Equivalent temperature rise by swelling

The equivalent temperature rise of 42°C due to swelling was obtained by dividing the swelling strain with the CTE of the composite. The mean temperature rise of oil film obtained by finite difference method was 10°C under the average pressure of 0.6MPa. Therefore, the estimated total average temperature rise was 52°C. Since the steel housing was thick with thickness 45 mm and most heat generated in the oil film flew out through the side leakage of oil due to the higher heat capacity of oil, the steel housing was assumed as a rigid body. Another key assumption of this analysis was the perfect bonding between composite and steel backing.

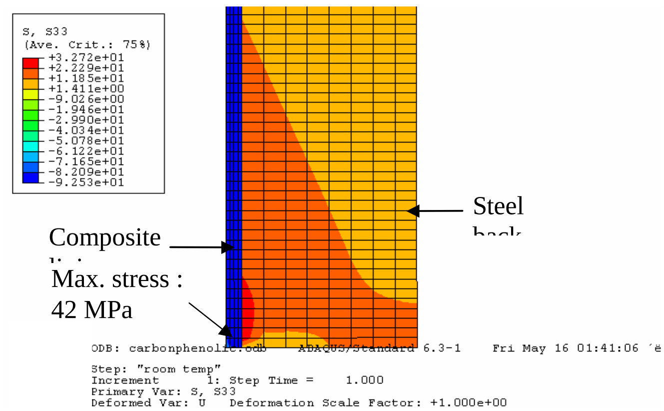


Fig. 7 Stress distribution in the hoop direction of hybrid composite journal bearing.

The FE-analysis results show that the maximum compressive stress of 42 MPa in the hoop direction occurs at the edge of composite bearing as shown in Fig. 7. Since this value is much lower than the compressive strength of the composite (220 MPa in the hoop direction), the composite bearing was safe.

6 CONCLUSION

In this work, the axiomatic design approach was used to design the hybrid composite journal bearing made of carbon fiber reinforced phenolic to solve the seizure problem of white metal lining journal bearing and hygrothermal residual stress with interference fitting of asbestos phenolic journal bearing. The wear characteristics of the carbon fiber reinforced phenolic composites and the asbestos fiber reinforced phenolic composites were superior to those of the asbestos phenolic composite. The dry friction coefficient of carbon fiber reinforced phenolic was about 60% of the asbestos fiber reinforced phenolic at the same *PV* value. Therefore, the hybrid composite journal bearing may solve the problems of conventional journal bearings such as white metal lining and polymeric journal bearings.

7 ACKNOWLEDGEMENTS

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