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AXIOMATIC DESIGN OF COMPOSITE HEMISPHERICAL BEARING

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ABSTRACT

Composite hemispherical bearings (CHB) are employed for the suspension of high mobility tracked vehicles to transfer the compressive load from the connecting rod to the piston in an in-arm suspension unit. During the compressive load transmission, the connecting rod journal rotates on the surface of CHB like a ball and socket joint. Although carbon-PEEK composite materials have been mainly used for the conventional CHB due to their high compressive strength as well as low friction coefficient, they are frequently failed by the surface cracks generated during the manufacturing process of hemispherical shape at lower cycles than its required endurance life. Therefore, in this paper, the axiomatic design approach was employed to develop a new CHB with enhanced endurance life.

Keywords[1]: composite, hemispherical, bearing, ISU, suspension

1 INTRODUCTION

Carbon fabric reinforced composites are currently being employed for heavy duty bearings subjected to high pressure as well as oiless environment since they have non-seizure characteristics and self-lubricating properties [1]. An example of the heavy duty carbon fabric composite bearings is the hemispherical bearing for the military tracked vehicles. The weight reduction of military vehicles has been a great concern to improve the mobility and operational cost of tracked vehicles. As an effort to reduce the vehicle weight, road-arms and hydropneumatic suspensions were combined into one.

The combined road-arm and suspension is called as the in-arm suspension unit (ISU). One of the key technologies for the ISU is to use composite hemispherical bearings (CHBs). The CHB transfers the compressive load from the connecting rod to the piston in the ISU. In addition to the compressive load transmission, the connecting rod journal rotates on the surface of CHB like a ball and socket joint. Carbon - PEEK (poly ether ether ketone) composites have been used because they should endure the maximum compressive pressure larger than 200 MPa with the intrinsic low friction coefficient. However the conventional CHB is failed often earlier than the intended life due to the surface cracks generated by the machining operation during the manufacturing of hemispherical shape.

The functional requirements of CHB are "to have a low friction between the CHB and the connecting rod," "to endure the required dynamic compressive load," and "to dissipate the heat generated on the bearing surface," without increasing manufacturing cost. These functional requirements are not easy to satisfy simultaneously with conventional CHB designs due to the coupling between the dynamic compressive load and the dissipation of heat generation. Therefore, in this paper, the axiomatic design approach was employed to develop a new CHB with enhanced endurance life with high heat dissipation. For these purposes, the concept of composite-metal hybrid bearing was employed for the CHB design to reduce the manufacturing cost as well as to enhance the endurance life. The newly designed CHB satisfies the two design axioms of 'Independence Axiom' and 'Information Axiom' [2].

2 FRs and DPs of CHB

In a connecting rod and piston assembly as shown in Figure 1, the CHB is located between a connecting rod and piston. When a roadwheel moves up and down, the compressive force is applied to the CHB by the connecting rod. The maximum bearing stress on the CHB during normal operation is about 200 MPa, which requires a bearing material with large through-thickness compressive strength (TTCS) such as carbon fabric-PEEK (poly ether ether ketone) composite whose TTCS is about 600 MPa. Figure 2 shows the cross-sectional shape of the conventional CHB. Conventional CHBs are manufactured by machining of a thick carbon fabric-PEEK or carbon fabric-phenolic composite plate to create the hemispherical shape. Each ply of the composite laminate lies almost perpendicular by the central axis, which is the loading direction of the connecting rod. The machining process for CHB with CNC milling machines is not only costly because of the severe wear of cutting tools but also produces many cracks and delaminations on the surface of the CHB [3]. In order to solve the difficulties in the manufacturing process of CHB, the axiomatic design approach was employed.

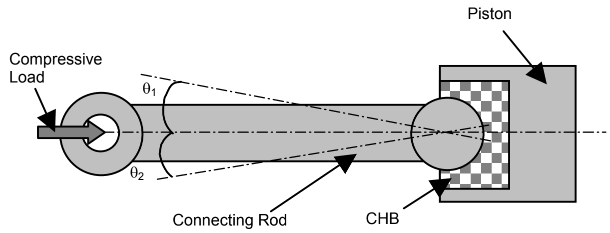


Figure 1 Schematic diagram of a CHB in a connecting rod and piston assembly

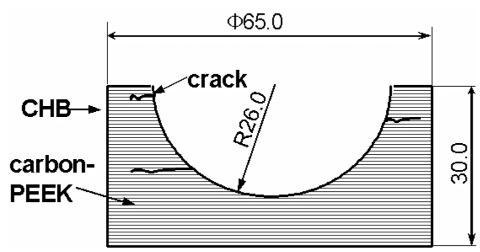


Figure 2 Conventional CHB

The functional requirements of the composite hemispherical bearing (CHB) are

FR_1 = Have a low friction between the CHB and connecting rod.
FR_2 = Endure the required dynamic compressive stress (200 MPa, 6.0 x 105 cycles).
FR_3 = Dissipate heat generated on the bearing surface.

To be competitive with the conventional CHB, the cost of the newly developed CHB should be lower than the conventional CHB. Therefore, the constraint for the new CHB design may be dictated as follows.

C = Minimize the manufacturing cost of the CHB.

Three DPs for satisfying these FRs are stated as

DP_1 = Self-lubricating material
DP_2 = Structural Integrity
DP_3 = Thermal conductivity of CHB

The design equation for the conventional CHB may be written as

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & X \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (1)$$

3 AXIOMATIC DESIGN OF A NEW CHB

To meet the FR_1, self-lubricating material should be chosen. Although there are many self-lubricating polymeric materials including PTFE (polytetrafluoroethylene), they have low compressive strength. For example, the compressive yield strength of PTFE is only about 15 MPa. Therefore, carbon fiber reinforced polymeric composite material maybe a candidate for DP1 because they have compressive strength much higher than 200 MPa.

3.1 DECOMPOSITION OF FR_2 AND DP_2 BRANCH

To be competitive with the conventional CHB, the cost of the newly developed CHB should be lower than the conventional CHB. Therefore, the constraint for the new CHB design may be dictated as follows. Since the configuration of a CHB is limited by the dimension of the piston and connecting rod, there is little freedom to change the size of CHB to reduce the stress level. Therefore, decompositions of FR_2 and DP_2 branch were performed considering surface crack and residual stress generated during manufacturing process of CHB and material strength. The decompositions of FR_2 and DPs for satisfying the decomposed FRs are stated as

FR_{21} = Reduce the surface cracks.
FR_{22} = Increase the compressive strength.
FR_{23} = Reduce the residual stress of the CHB.
FR_{24} = Reduce wear.

DP_{21} = Manufacturing process.
DP_{22} = Metallic support.
DP_{23} = Coefficient of thermal expansion.
DP_{24} = Wear rate of CHB material.

The design equation for the CHB may be written as

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ x & 0 & X & 0 \\ x & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{Bmatrix} \quad (2)$$

Since the design matrix is half triangular, the new CHB composite materials can be realized. As shown in the design matrix of Equation (2), the generation of surface cracks is much dependent on the machining process such as milling to generate the hemispherical shape. Therefore, a new design concept for CHB without machining was proposed using co-cure bonding of the composite on the metallic support as shown in Figure 3.

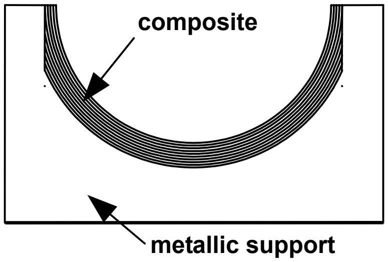


Figure 3 Schematic drawing of the new CHB

In the new design, the CHB is designed as a hybrid composite structure consisting of composite bushing and metallic support. The composite bushing is made of carbon fabric-phenolic prepreg. The two parts are joined by co-cure process as shown in Figure 4; (a) Carbon fabric-phenolic prepregs are loaded between a pair of molds, (b) The prepregs are pressed between the molds at elevated temperature, but lower than curing temperature, (c) Edges of the formed prepregs are trimmed, (d) The formed prepregs are fully cured into the composite busing which is bonded to the surface of the metallic support.

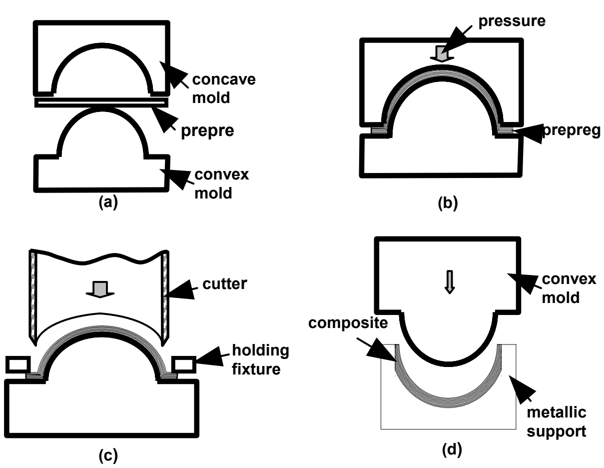


Figure 4 Manufacturing process for the new CHB

In this work, DP_{22} was investigated experimentally because the through-thickness compressive strength (TTCS) of carbon-phenolic composite material has not been investigated deeply in spite of its importance in designing heavy duty composite bearing. Zhang [4] observed that the TTCS of unidirectional carbon-epoxy composite was in the range of 171 MPa - 194 MPa depending on the specimen width, while the TTCS of cross ply laminate increased up to 1,000 MPa. But, he did not investigate the effects of stacking sequence on the TTCS of fabric reinforced composite. The TTCS was measured for the two different composite materials, such as PAN based carbon fabric-phenolic composite and rayon based carbon fabric-phenolic composite with respect to four different of stacking sequences for each material. The designations of the laminates are shown in Table 1.

[Table 1] Designations of the laminates

material / stacking sequence	PAN based carbon fabric-phenolic composite	Rayon based carbon fabric-phenolic composite
$[0]_{2n}$	PZ	RZ
$[0/90]_n$	PC	RC
$[\pm 45]_n$	PA	RA
$[(-45/0/45/90)_s]_{n/2}$	PQ	RQ

In addition to the designation in Table 1, two letters 'S' and 'T' were used to represent the 12 mm thick specimen, and the 24 mm thick specimen, respectively. For example, RAS specimen is 12 mm thick [±45]n rayon based carbon-phenolic composite laminate. The TTCS was measured by applying a pressure on the specimen through the steel collars contacting the specimen. During the loading, the strains on the four sides of the specimen were measured to observe the bending effect, which was proved negligible. The horizontal line represents the average TTCS, and the vertical line represents $\pm 3\sigma$ standard deviations.

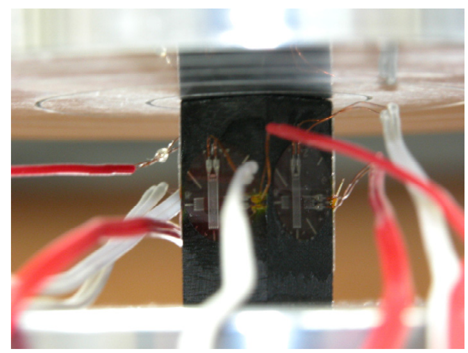
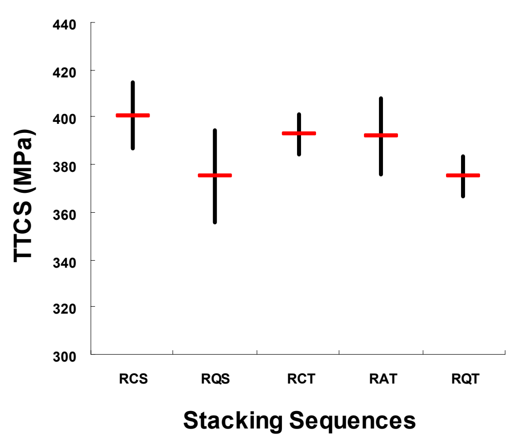
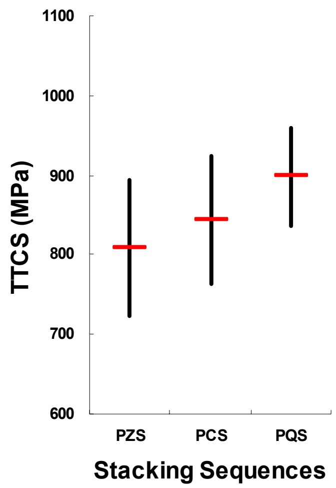


Figure 5 Through-thickness compression specimen



(a) rayon based composite

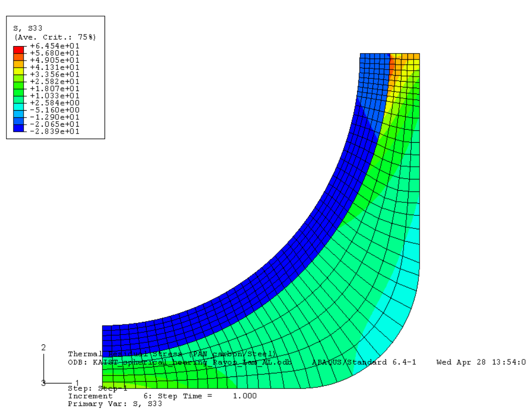


(b) PAN based composite

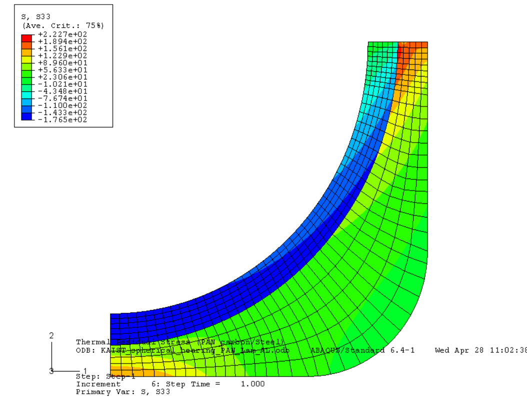
Figure 6 TTCS of carbon fabric-phenolic composite

All the laminates of Table 1 satisfied the requirement of the TTCS for CHB. However the cross ply and the quasi-isotropic stacking sequences are chosen for the rayon based composite and the PAN based composite, respectively to increase the compressive load capability of the CHB.

Residual stress may occur in co-cured hybrid composite bearings. Therefore, the residual stresses were analyzed through finite element analysis for the stacking sequences determined considering TTCS. In the analysis, the quadratic quadrilateral (type CAX8) elements in ABAQUS Ver. 6.4 (Hibbitt, Karlsson & Sorensen, Inc.) with axisymmetry were used. As shown in Figure 7, the residual stresses, when the temperature decrease between the adhesive curing and room temperature was 135 ℃, were relatively small compared with the material strength.



(a) rayon based carbon fabric-phenolic composite



(b) PAN based carbon fabric-phenolic composite

Figure 7 Residual stress of the hybrid composite spherical bearing

In order to investigate the effect of stacking sequence and fiber type on the wear characteristics of carbon-phenolic composite, wear tests were performed for the several materials in Table 1 under the test conditions of P•V = 0.8 MPa•m/sec (P = 13.4 MPa, V = 0.06 m/sec). The specification of endurance life requirement of CHB is that the wear depth should be smaller than 1.5 mm after 40 hour use. Even though there was some scattering in the data, the PAN based carbon fabric-phenolic composites gave better result than the rayon based material in terms of wear rate as shown in Figure 8.

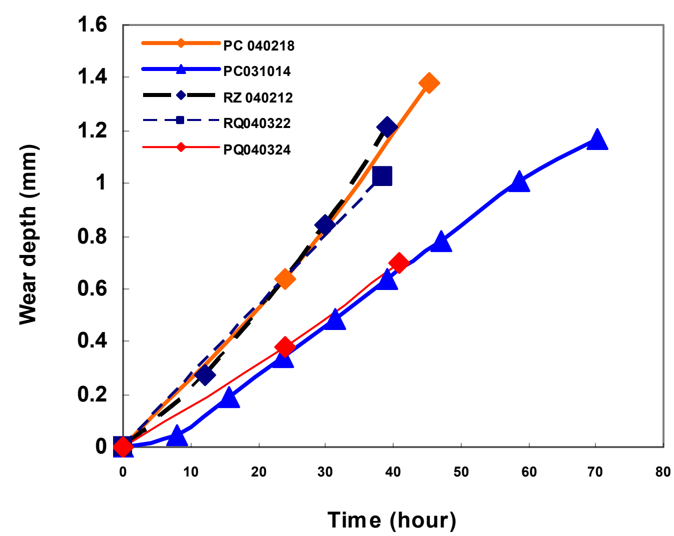


Figure 8 Wear test results for various carbon fabric composites

3.2 DECOMPOSITION OF FR3 AND DP3 BRANCH

FR_3 and DP_3 can be decomposed as follows.

FR_{31} = Increase the thermal conductivity of composite bushing material.
FR_{32} = Shorten the heat path.

DP_{31} = Thermal conductivity of composite material
DP_{32} = Thickness of composite material

The design equation for the impact beam may be written as

$$\begin{Bmatrix} FR_{31} \\ FR_{32} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{31} \\ DP_{32} \end{Bmatrix} \qquad (3)$$

Since the design matrix is diagonal, the new CHB can be realized. The through-thickness thermal conductivity, K, of carbon fabric-phenolic composite laminates was measured using NETZSCH LFA 447 Nanoflash (Netzsch Instruments, Inc.), in which the thermal diffusivity, α was measured. K was obtained by the following equation using the measured thermal diffusivity and specific heat.

$$K = \alpha \rho C_p \qquad (4)$$

where,

ϱ = bulk density
C_p = specific heat

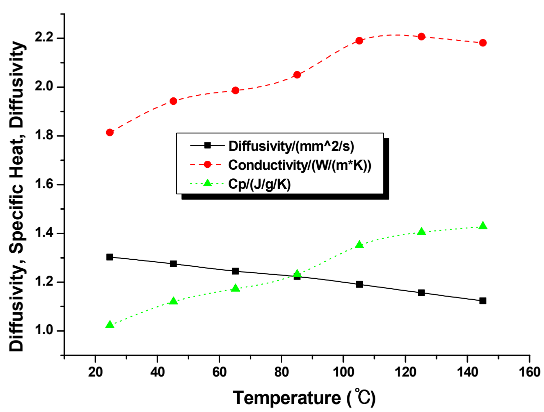


Figure 9 Thermal conductivity measurements

As shown in Figure 9, the through-thickness thermal conductivity value of rayon based carbon fabric-phenolic composite was between 1.8 and 2.2 W/mK, which is two order lower than the thermal conductivity of aluminum, which is 200 W/mK. Therefore, to decrease the thickness of the composite bushing in CHB is effective to increase thermal conductivity of CHB. To enhance the load bearing capability of the new hybrid CHB, a thick metallic ring such as aluminum was employed, as shown in Figure 10.

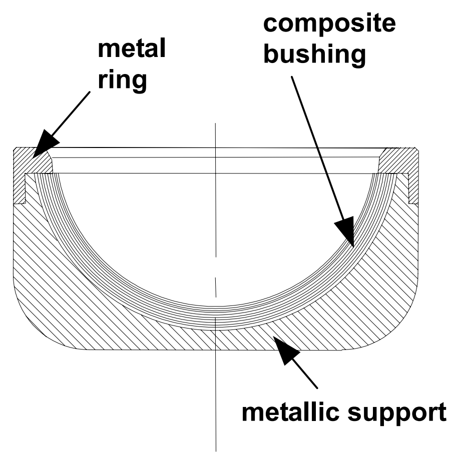


Figure 10 Newly developed CHB with increased thermal dissipation

4 FABRICATION OF THE CHB AND TEST

The newly developed CHB was fabricated by the molding process without machining the hemispherical shape as shown in Figure 4. One of the prototypes is shown in Figure 11. It also satisfied the dimensional tolerance of 50 μm. To test the endurance life of the prototype of CHB, an endurance test apparatus was designed by the axiomatic design approach as shown in Figure 12.

Figure 11 Prototype of the newly developed CHB

The functional requirements of the endurance life test apparatus for CHB are

FR_1: Apply the compressive load on the CHB
FR_2: Rotate the ball of con-rod in the socket of the CHB

Two DPs for satisfying these FRs are stated as

DP_1: Hydraulic Jack
DP_2: Pneumatic Actuator

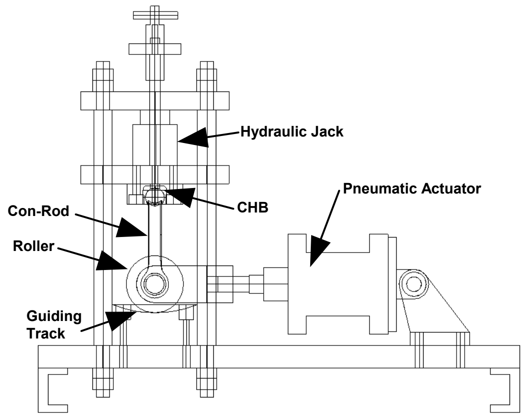


Figure 12 Apparatus for the endurance life test of CHB

5 DISCUSSIONS

In this research, hybrid composite hemispherical bearings (CHB) for high mobility tracked vehicles were designed using the axiomatic design approach. The hemispherical shape of new CHB was fabricated by molding without machining process, which will improve its endurance compared with the conventional CHB whose hemispherical shape was fabricated by milling operation. It also satisfied the dimension tolerance. The endurance life of the prototype of CHB will be tested using the test apparatus for the endurance life, which was also designed by the axiomatic design approach.

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