축예하중을 가한 알루미늄/복합재료 동시경화 샤프트의 비틀림 피로 특성

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Torsional Fatigue Characteristics of Aluminum/Composite Co-Cured Shafts with Axial Compressive Preload

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Key Words: thermal residual stress, co-cure, hybrid shaft, compressive preload, torsional fatigue.

ABSTRACT

Long shafts for power transmission should transmit torsional load with vibrational stability. Hybrid shafts made of unidirectional fiber-reinforced composite and metal have high fundamental bending natural frequency as well as high torque transmission capability. However, thermal residual stresses due to the coefficient difference of thermal expansion of the composite and metal are developed so that the high residual stresses decrease fatigue resistance of the hybrid shafts, especially at low operating temperatures. In this work, axial compressive preload was given to the shaft in order to change the residual stresses. Static and fatigue torsional tests were performed and correlated with stress analyses with respect to the preload and service temperature.

1. INTRODUCTION

Power transmission shafts with high rotating speed such as automotive propeller shafts, should satisfy required static torque capacity, torsional fatigue strength, and fundamental bending natural frequency. Since long shafts made of conventional materials cannot satisfy these design values simultaneously, hybrid co-cured shafts composed of aluminum and composite was developed [1]. However, the co-cure joining induces thermal residual stresses due to large difference of CTE (Coefficients of Thermal Expansion) of aluminum and composite, which affect the fatigue strength of the hybrid shaft, more seriously at subzero service temperature.

In this study, the aluminum/composite co-cured shafts were manufactured with axial compressive preload to reduce the residual stresses and their torsional static and fatigue characteristics were investigated at room and subzero service temperatures. Experimental results from the torsional fatigue test were correlated with the calculated residual stresses with respect to the compressive preload and service temperature.

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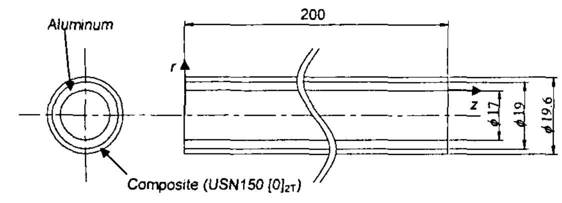

Fig. 1 Co-cured hybrid shaft specimen (Units in mm).

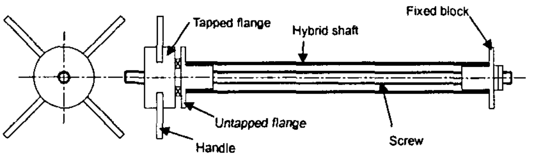

Fig. 2 Assembly drawing of the compressive jig and the hybrid shaft.

Table 1. Mechanical properties of the composite

Longitudinal modulus, E_c	131.6 GPa
Longitudinal CTE, α_c	-0.9×10^{-6}/°C
In-plane shear modulus, G_c	6.12 GPa
Ply thickness	0.150 mm

Table 2. Mechanical properties of the aluminum tube

Elastic modulus, E_a	72 GPa
Shear modulus, G_a	27 GPa
CTE, α_a	23.0×10^{-6}/°C
Ultimate tensile strength, S_u	275 MPa
Tensile yield strength, S_y	241 MPa

2. SPECIMENS

The hybrid shaft specimens were manufactured by co-curing unidirectional carbon fiber epoxy composite prepreg USN150 (SK Chemicals, Korea) to aluminum tubes (6063-T6). Fig. 1 shows the dimensions of the hybrid shaft specimen and the mechanical properties of the composite and the aluminum were shown in Tables 1 and 2. To control the thermal residual stresses, an axial compressive preload was given to the hybrid shaft by a steel compressive jig similar to a vise shown in Fig. 2. Then co-cure operation was followed in an autoclave under 0.6 MPa at 125°C.

3. ANALYSIS OF RESIDUAL STRESSES

The co-cure operation of the aluminum/composite hybrid shaft induces thermal residual stresses due to large CTE difference of the materials. The aluminum tube expands without constraint by the composite part as the temperature rises until cure of the composite initiates at 125°C. After co-cure bonding the composite part to the aluminum tube, the hybrid shaft is cooled down to the room temperature of 25°C. Since the CTE of the cured composite material is almost zero in the axial direction, the co-cured interface constrains shrinkage of the aluminum tube. Then tensile and compressive residual stresses in the axial direction are developed in the aluminum and the composite, respectively. The calculated axial residual stresses were 63.7 MPa in the aluminum and −198 MPa in the composite from the axial force equilibrium equation and condition of equal axial strain of the materials. Since the high tensile residual stress is detrimental to fatigue strength of metallic materials [2] and the aluminum tube transmits most of the torsional load subjected to the hybrid shaft, fatigue strength of the hybrid shaft may decrease much compared to that of a pure aluminum shaft.

Therefore, a manufacturing method of hybrid shafts with axial compression given by the steel compressive jig was developed to eliminate the thermal residual stresses [3]. Because the zero residual stresses might not be the optimal for fatigue strength and the residual stresses vary with the service temperature, in this work, the amount of axial compressive preload was adjusted to control the axial thermal residual stress. The amount of axial compressive preload was represented by compressive displacement which was the relative axial displacement between the compressive jig and the aluminum tube before curing. The axial residual stresses in the aluminum at room and subzero service temperatures were calculated by simple equations from mechanics of materials for several compressive displacements as shown in Fig. 3. Also this simple calculation considering only axial residual stresses was validated by finite element analysis of the hybrid shaft.

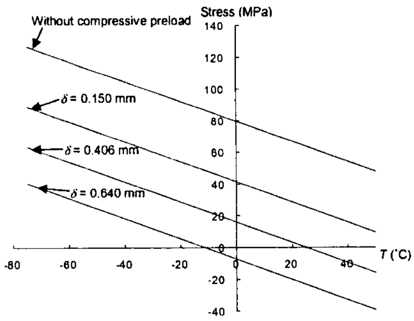

Fig. 3 Calculated axial residual stress in the aluminum.

4. EXPERIMENTAL

The torsional fatigue tests of the hybrid shaft specimens with respect to the compressive displacement were performed at room temperature, 25°C, and subzero temperature, –24°C, with a hydraulic type Instron 8032 torque tester (Instron Corp., USA). The stress ratio and test frequency were –1 and 10 Hz, respectively. Applied torque amplitude was varied to construct S-N curves.

The first fracture was occurred at the aluminum tube because the *GJ* value of the aluminum tube is much higher than that of the composite layer so that most of applied torque is transmitted by the aluminum tube.

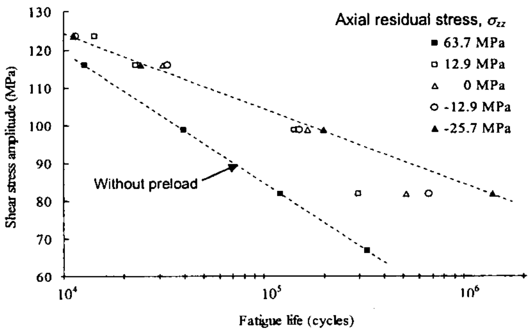

Fig. 4 S-N curve of hybrid shafts with different residual stresses at room temperature.

Fig. 4 shows S-N curves of the hybrid shafts with several axial residual stresses in the aluminum at room temperature. The axial residual stress was calculated from the compressive displacement and the shear stress amplitude represents the shear stress in the aluminum due to the applied torque amplitude. The experimental results at room and subzero temperatures were compared in Fig. 5 and Fig. 6, which shows fatigue life under repeated torque of ±43 Nm with respect to the compressive displacement and calculated axial residual stress in aluminum, respectively.

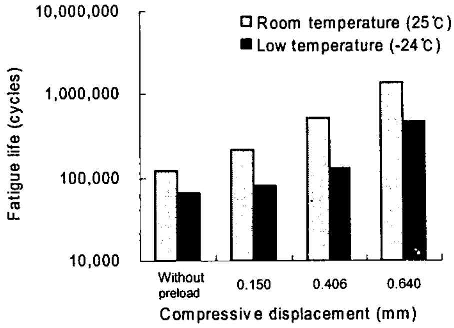

Fig. 5 Fatigue life with respect to the compressive displacement under torque amplitude of 43 Nm.

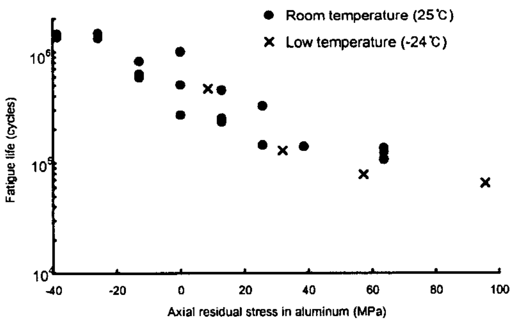

Fig. 6 Fatigue life with respect to the axial residual stress under torque amplitude of 43 Nm.

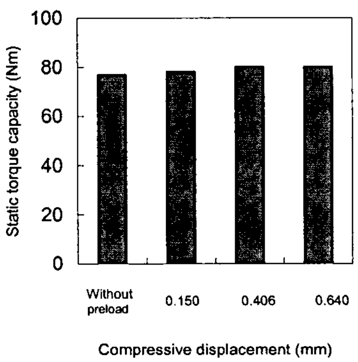

Fig. 7 Static torque capacity with respect to the compressive preload.

The torsional static test with respect to the compressive displacement was also performed at room temperature and results are shown in Fig. 7. There was little effect of preload on the static torque capacity.

5. DISCUSSIONS

From the fatigue test of hybrid shafts composed of aluminum and carbon fiber composite with different residual stresses as shown in Fig. 4, the fatigue life was increased by the axial compressive preload which decreased the axial residual stress in the aluminum tube. When the applied shear stress increased such a level that it dominates the axial residual stress, the improvement of fatigue life due to the decrease of the axial tensile residual stress by the compressive displacement became lower like the static case in Fig. 7. These phenomena well agree with the general fatigue model of metallic materials shown in Fig. 8 [4]. The fatigue life at subzero temperature was much lower than that at room temperature as shown in Fig. 5, because the residual stress increases as the temperature decreases. But the fatigue life at both test temperatures with respect to the axial residual was similar as shown in Fig. 6.

At the room temperature, the fatigue life of the hybrid shaft manufactured with the compressive displacement of 0.76 mm (1.4×10^6 cycles) was 2.5 times longer than the fatigue life of a monocoque aluminum shaft (5.7×10^5 cycles) and 12 times longer than the fatigue life of the hybrid shaft manufactured without compressive preload (1.2×10^5 cycles).

For the application of the hybrid shaft at low temperatures, the amount of preload may be adjusted. For example, with the compressive displacement of 0.64 mm at the subzero temperature, the fatigue life is 4.7×10^5 cycles, which is comparable to the fatigue life of the monocoque aluminum shaft.

In conclusion, it was found that the fatigue resistance of the hybrid co-cured shaft can be improved both at room and subzero service temperatures by axial compressive preload to give low axial residual stress in the aluminum part.

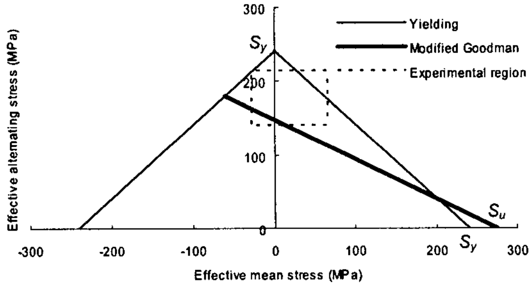

Fig. 8 Constant-life diagram.

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REFERENCES

(1) Cho, D. H., Lee, D. G., and Choi, J.H., "Manufacture of One-Piece Automotive Drive Shafts with Aluminum and Composite Materials," *Composite Structures*, Vol. 38, 1997, pp. 309-319.

(2) Fuchs, H. O. and Stephens, R. I., *Metal Fatigue in Engineering*, John Wiley & Sons, New York, 1980, pp. 233-240.

(3) Cho, D. H. and D. G. Lee, "Manufacturing of Co-Cured Composite Aluminum Shafts with Compression during Co-Curing Operation to Reduce Residual Thermal Stresses," *Journal of Composite Materials*, Vol. 32, 1998, pp. 1221-1241.

(4) Stephens, R. I., Fatemi, A., Stephens, R. R., and Fuchs, H. O., *Metal Fatigue in Engineering*, John Wiley and Sons, 2001, pp. 74-79.