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Effect of wear debris on the tribological characteristics of carbon fiber epoxy composites

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Abstract

Wear debris generated on the sliding surface of carbon composite bearings should be removed quickly for stable sliding movement because it induces severe damage on the contact surface. In order to remove the wear debris generated, composite bearing specimens with many micro-grooves on their surfaces were fabricated using a newly developed molding method.

The wear characteristics of carbon/epoxy composites with micro-grooves were investigated by dry sliding test with respect to applied pressure and compared to those of carbon/epoxy composites without micro-grooves. Using the measured friction coefficient and wear rate, a model for the effect of wear debris on the friction and wear of carbon composites was proposed.

Keywords: Composites; Friction; Wear; Micro-grooves; Wear debris; Fiber breakage

1. Introduction

The carbon fiber is composed of many laminated graphite planes, which endows it with self-lubricating characteristics. Consequently carbon fiber reinforced polymer composites have been widely used for bearing materials especially in unlubricated environment to exploit the self-lubricating characteristics of carbon fiber [1–4]. Although the friction coefficients of thermoset polymers such as epoxy and phenol are usually higher than those of thermoplastics such as polytetrafluoroethylene (PTFE) and high-density polyethylene (HDPE), the carbon/thermoset polymer matrix composites are popular in bearing material, especially for high load capability bearings because thermoset polymers have better mechanical properties as well as adhesion characteristics to the carbon fiber [5].

There have been many researches on the tribological behavior of composite surfaces under un-lubricated sliding condition. It has been known that the carbon fiber which is composed of laminated graphite layers is worn out gradually by breakage of fibril when subjected to solid sliding, and the thermoset matrix is worn out by delamination wear due to accumulated damage [6]. The produced wear debris plows the sliding surface (i.e. abrasive wear), and causes large friction and wear of sliding surface, which is a well-known model for the effect of wear debris [6].

Sung and Suh [7] investigated the effect of fiber orientation on the friction and wear of carbon fiber reinforced polymeric composites, in which they found that the friction and wear of composites were minimum when the fiber direction was perpendicular to the sliding surface at low applied pressure. However, the composite surface whose fiber is aligned with the sliding surface is preferable at high applied pressure because the exposed carbon fiber can gouge into the counter surface when the fiber direction is not parallel to the sliding surface, which may initiate severe wear or seizure [8].

The fact that the friction coefficient of carbon fiber polymer composites is minimum at low applied pressure when the fiber direction is perpendicular to the sliding surface is contrary to intuition because the slip between the graphite layers in the carbon fiber might occur easily when the shear traction is parallel to the fiber direction. The large friction coefficient of carbon fiber composites at high pressure when the fiber direction is parallel to the sliding surface may be caused by wear debris produced

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during sliding operation, which has not been explained in the previous models.

Suh and Sin [9] found that the friction increased exponentially as the plowing depth of wear debris increased. Sin et al. [10] found that the abrasive wear coefficient decreased as the abrasive grit diameter decreased and converged on the sliding wear coefficient when the abrasive grit diameter was smaller than 1 μm.

Therefore, the wear debris may affect the friction and wear characteristics of composite surfaces, only when its size is larger than the roughness of contact surface. Since almost all the wear debris produced during sliding operation is submicron size, the wear debris may not increase the friction and wear of composite surface sufficiently. Therefore, the previous models for the effect of wear debris on the friction and wear characteristics cannot be applied effectively to the wear characteristics of carbon fiber polymer matrix composites.

Lee et al. [11] investigated the effect of wear debris on the carbon/epoxy composites during sliding operation, from which it was found that the compacted wear debris induced severe fiber bending, which was followed by fiber breakage.

In this work, the friction coefficients and wear rates of carbon fiber epoxy composite specimens with and without micro-grooves were measured with respect to applied pressure using a pin-on-disk type wear tester to investigate the effect of wear debris on the tribological characteristics of composite surface. Then a model for the effect of wear debris on the friction and wear of composites was proposed based on the observed surfaces of composite specimens.

2. Specimen and experimental setup

Table 1 lists the mechanical properties of carbon fibers, epoxy matrix, and their unidirectional composites (USN150, SK Chemicals, Korea), which were used to fabricate wear specimens. Fig. 1 shows the newly developed fabricating process of a micro-grooved mold and composite specimens with many micro-grooves. The micro-grooved mold was fabricated by stacking two different thickness plates as follows: after the precision stamping of plates of different thicknesses, the thick plates (200 μm thickness) and the thin plates (100 μm thickness) whose width was 250 μm larger than that of the thick plate were stacked alternatively in order to fabricate the mold with repeated ridges and grooves by fastening the stacked plates with guide plates and bolts.

The grooved specimens were molded under two different pressure conditions: 0.7 MPa in an autoclave with vacuum applied, and 20 MPa in a hot press without vacuum, resulting the fiber volume fractions, $V_f = 0.67$ and $V_f = 0.82$, respectively. Fig. 2 shows the photographs of cross-sectional view and plan view of the grooved specimen fabricated, in which the fiber direction was parallel to the side areas of grooves.

Fig. 3(a) shows the schematic diagram of a pin-on-disk type wear tester. The shear force on the specimen was measured by strain gages bonded on the specimen holder in Fig. 3(b), and the strain data was obtained using an amplifier through an analog-to-digital converter. The dimensions of the grooved specimen

Table 1
Mechanical properties of carbon fibers, epoxy matrix, and their unidirectional composites (USN 150, SK Chemicals, Korea)

Carbon fiber	
Tensile modulus (GPa)	235
Poisson's ratio	0.20
Tensile strength (MPa)	4400
Density (kg/m^3)	1770
Epoxy matrix	
Tensile modulus (GPa)	2.5
Poisson's ratio	0.38
Tensile strength (MPa)	34–83
Density (kg/m^3)	1200
Composites	
Tensile modulus (GPa)	
$V_f = 0.67$	158
$V_f = 0.82$	193

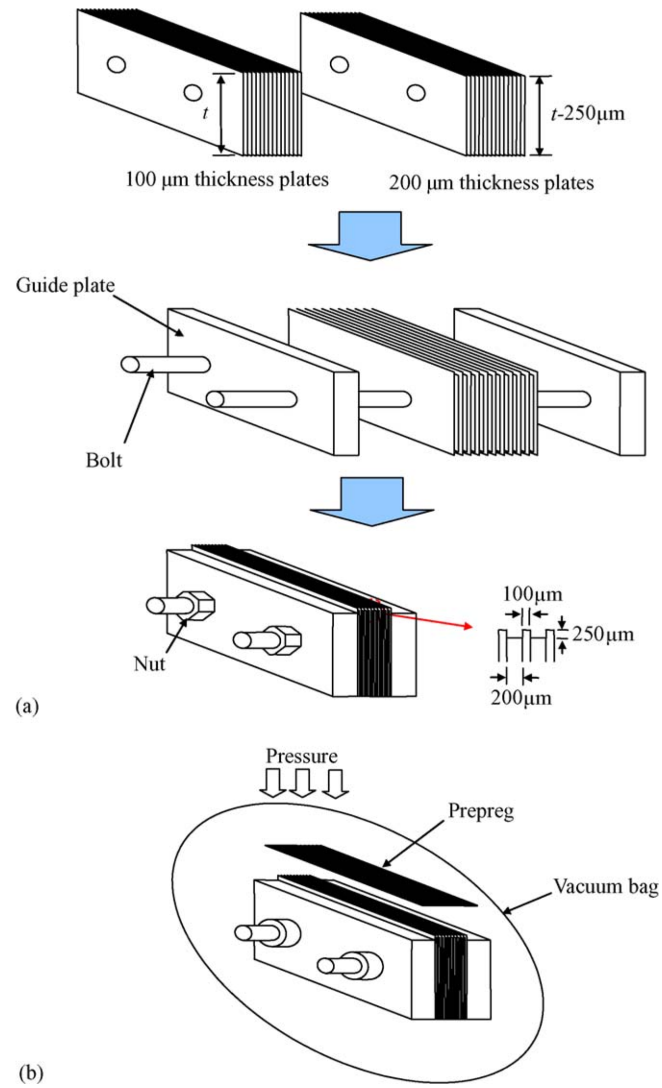

Fig. 1. Fabricating process for the grooved mold and specimens with micro-grooves: (a) fabrication method for the mold; (b) molding process for the composites with many micro-grooves.