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Influence of viscoelasticity on friction coefficient of abrasive wear for filler-dispersed polyamide 6

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ABSTRACT

The friction and wear properties of polyamide 6 dispersed with titanium carbide particles, aluminum borate whiskers and vapor-grown carbon fibers have been investigated in relation with the filler type, the filler content, the roughness of abrasive paper and the sliding velocity. The results have been analyzed based on an abrasive wear model using an expression $\mu=(g\sigma_s)/(kH)$ where μ is the friction coefficient, g is the shape factor of the abrasive particle, σ_s is the stress required for sliding the abrasive particle, $k=1.08$ and H is the microhardness. The PA6 and the composite films showed abrasive wear except for the ABW/PA6 and TCP/PA6 films worn with a fine abrasive paper which showed adhesive wear. For abrasive wear, the decrease in the roughness of abrasive paper and the increase in the sliding velocity both increased the storage modulus due to viscoelasticity. This led to the decrease in the penetration depth and g. As a result, the friction coefficient of the PA6 and the composite films decreased. On the other hand, the filler type and the filler content influenced the friction coefficient through the changes in σ_s and H.

1. Introduction

The wear of materials is caused by various mechanisms: adhesive, abrasive, surface fatigue, fretting and corrosive wear and the combination of these. Among these mechanisms, the abrasive wear occurs when a hard rough surface or hard particles slide on a material and plow grooves in it. The abrasive wear can cause 10^6 times larger material loss than the adhesive wear when compared for the same material [1]. Polymers are used under abrasive wear conditions where the properties characteristic to polymers such as flexibility, corrosion resistance and good processibility are of importance [2,3]. In some applications of polymers under severe abrasive wear conditions, there is a demand for improving the wear resistance without sacrificing elastic modulus. For example, the filaments for paper-making belts are in contact with other parts of the paper-making machine and exposed to severe abrasive wear conditions. Simultaneously, these filaments should have a high elastic modulus for assuring the dimensional stability against the tension which arises when the belts are driven at a high speed.

Elastomers are known to possess a good abrasive resistance whereas their elastic modulus is rather low [4,5]. The elastic modulus of polymers can be increased by incorporating with fillers. There have been extensive studies on the friction and wear properties of polymer-matrix composites filled with high hardness inorganic whiskers and particles [6–9] and nano-sized particles [8–14]. In some cases, the wear resistance of polymers was improved by dispersing fillers [7–10,12,13] while in other cases it was reduced even though the elastic modulus and the hardness were increased [14]. It is expected that these experimental results can be reasonably interpreted based on a model of abrasive friction and wear proposed by Irisawa et al. [9,10]. They have represented the friction coefficient and the wear rate under abrasive wear conditions using the fundamental parameters such as the hardness, stress required for sliding the abrasive particles (yield stress), fracture probability and shape factor of the abrasive asperity. Based on this model, the influences of the fillers on the friction and wear properties of polymers can be related to the changes in these fundamental parameters.

For elastomers, the friction coefficient when sliding against a hard rough surface can be represented as the sum of the adhesion and the deformation component if interaction between these two components can be neglected. The adhesion and deformation components are in proportion to E''/p^r and $E''p^n/(E')^{n+1}$, respectively, where E' is the storage modulus, E'' is the loss modulus, p is the normal pressure, r is an exponent with a value close to 0.2 and n is an exponent not less than unity [15]. The variation in the moduli E' and E'' with temperature and deformation velocity causes the variation in the friction coefficient. As a result, the temperature-time superposition for the viscoelasticity is also valid

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for the friction coefficient of elastomers. A master curve of the friction coefficient versus log(sliding velocity) relationship covering a wide range of sliding velocity at a given reference temperature has been obtained by shifting the curves of the friction coefficient measured at various temperatures, for example, for acrylonitrile–butadiene rubber sliding against wavy glass [16]. For crystalline polymers such as polytetrafluoroethylene (PTFE) and high density polyethylene (HDPE), master curves of the friction coefficient under adhesive wear condition have been obtained [17,18]. For a semicrystalline polymer, polyamide 6 (PA6), a master curve of the friction coefficient under adhesive wear condition has been obtained from the curves measured by changing the sliding velocity [19]. In this case, however, deviation from the master curve arose as the time elapsed after the sliding velocity was changed due to the change in friction mechanisms. It is expected that the friction coefficient of the polymer-matrix composites is also influenced by the viscoelastisity to a greater or lesser extent.

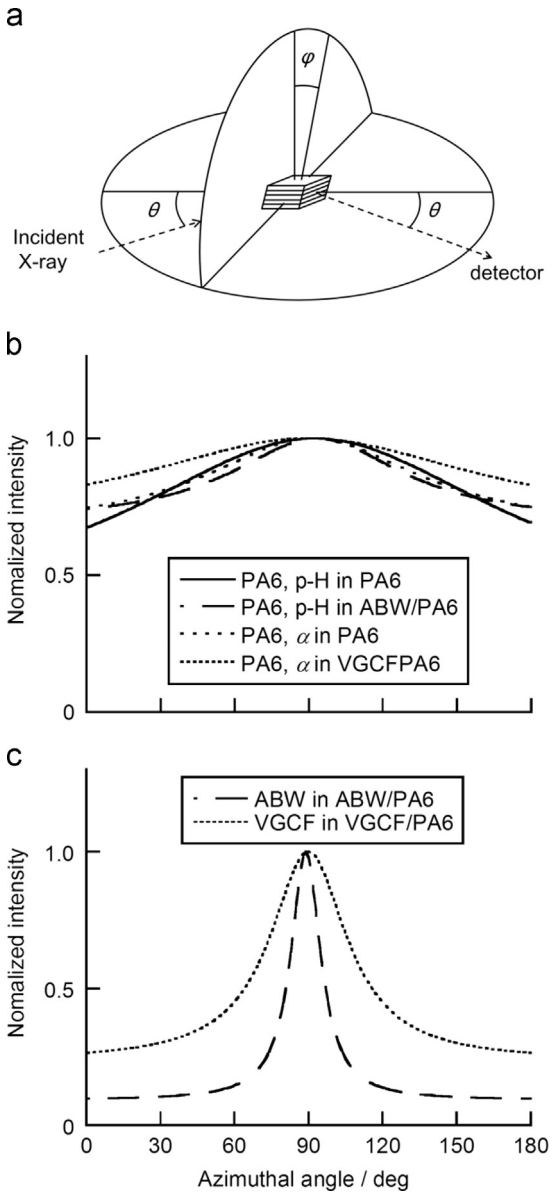

Fig. 1. (a) Schematic illustration of WAXD measurements. Azimuthal WAXD profiles of (b) PA6 and (c) ABW and VGCF in PA6 and composite films. Diffractions measured were 001 diffraction of PA6 pseudohexagonal (p-H) phase in PA6 and ABW/PA6 films, 200 diffraction of PA6 α phase in PA6 and VGCF/PA6 films, 120 diffraction of ABW in ABW/PA6 film and 002 diffraction of VGCF in VGCF/PA6 film. Weight fraction of fillers was 5.0 wt%.

In the present study, the friction and wear properties of the composites using PA6 matrix and various fillers have been analyzed based on the model proposed by Irisawa et al. [9,10]. The advantage of this model in the present study is that it does not assume any particular shape of the abrasive particle such as cone, paraboloid of revolution and sphere, and it can take into account the fracture probability. The wear tests have been carried out by contacting the specimen to the abrasive papers with different asperities at various sliding velocities and the influences of the viscoelasticity of the composites have been investigated. This paper focuses on the friction properties and the wear properties will be reported in another paper.

2. Experimental

2.1. Materials

The matrix used for the composite films was PA6 (Unitika, M1040) with the glass transition temperature of 48.5 °C and the melting temperature of 223 °C. The fillers used were titanium carbide particles (TCP, INHANCE), aluminum borate whiskers (ABW, Shikoku chemical, TNN-3267) and vapor-grown carbon fibers (VGCF, Showa Denko, VGCF-S) with the diameters of 1, 0.1–1 and 0.15 μm, the aspect ratios of 1, 10–50 and 10–500 and the densities of 4.9, 3.0 and 2.2 g cm^{-3}, respectively.

The composite films were prepared from the compound pellets of PA6 with fillers at 5 wt% loading and the neat pellets of PA6 as follows: the compound pellets and the neat pellets were dried at 80 °C for 24 h in a vacuum oven and blended so that the weight fraction of fillers in the blend varied between 0 and 5 wt%. The blend was hot-pressed at 250 °C into a film and immediately quenched in contact with two steel plates cooled with water at room temperature. The film was cut into small pieces and stirred in order to enhance dispersion of fillers in PA6. Then, the pieces were hot-pressed into the film again with the same procedure as described above. These film forming-cutting cycles were repeated and the film obtained at the third hot-pressing was used for measurements. The same process history was imposed on the neat PA6 film.

The prefered orientation of the fillers and the PA6 matrix in the composite film was investigated with the wide-angle X-ray diffraction (WAXD) using a diffractometer (Rigaku, CN4036A2), a position-sensitive proportional counter and a CuKα radiation. The X-ray beam was incident on the edges of the stacked films and the diffraction profile was measured as a function of the azimuthal angle, φ, at the peak diffraction angles under a symmetric transmission geometry where the azimuthal angle was defined to be 90° for equatorial direction (Fig. 1(a)). The peak diffraction angles were 21.7° for the 001 diffraction of PA6 pseudohexagonal phase, 20.1° for the 200 diffraction of PA6 α phase, 16.5° for the 120 diffraction of ABW and 26.0° for the 002 diffraction of VGCF. Fig. 1(b) and (c) shows the azimuthal WAXD profiles of the PA6 and the composite films normalized to the maximum intensities. It is found that PA6 crystallites have almost random orientation in the PA6 and the composite films. For the fillers with high aspect ratios such as ABW and VGCF, on the other hand, the preferred orientation in parallel to the film plane was developed due to the flow of molten polymer during hot-pressing. The half-width at half-maximum of the azimuthal diffraction profile was 7.3° and 18.9° for ABW and VGCF in the composite films, respectively.

2.2. Wear test

The wear tests were performed on the surface of the composite films 0.55 mm thick cut into the sizes of 114 mm long by 2 mm wide. These specimens were made to contact with an abrasive paper wrapped on a rotating drum of a wear test apparatus developed for