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Correlations between the abrasive wear, fatigue, and tensile properties of filler-dispersed polyamide 6

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ABSTRACT

The abrasive wear, fatigue, and tensile properties of polyamide 6 (PA6) dispersed with titanium carbide particles, aluminum borate whiskers, and vapor-grown carbon fibers were determined. Moreover, the correlation between them was investigated using the equation $W_s=(gf)/(kH)$, where W_s is the wear rate, g is the shape factor of the abrasive particles, f is the fracture probability, k is a constant, and H is the microhardness. The value of $1/f$ represents the number of deformation cycles imposed by the abrasive particles until a local fracture occurs at the material surface. At a low sliding velocity, a correlation was observed between $1/f$ and the low stress fatigue life. At a high sliding velocity, f approached unity and a correlation was found between the wear rate and the tensile fracture work, which is in agreement with the Ratner–Lancaster plot.

1. Introduction

Materials wear through various mechanisms such as adhesive, abrasive, surface fatigue, fretting, and corrosive wear. Abrasive wear occurs when a hard rough surface or hard particles slide on a material and plow grooves on its surface, which can cause 10^6 times more material loss than adhesive wear [1]. Polymers are used under abrasive wear conditions in applications that require flexibility, corrosion resistance, and good processability [2,3]. For these applicatons, it is often desired to improve the wear resistance without causing a reduction in the elastic modulus. For example, the filaments used for paper-making belts are exposed to severe abrasive wear conditions because of contact with other parts of the paper-making machine and simultaneously subjected to high tension when the belts are driven at high speed. It is therefore necessary for these filaments to have a high elastic modulus to ensure dimensional stability in addition to high wear resistance.

The wear resistance of a bulk polymer is proportional to the product of its tensile strength and elongation at break (Ratner–Lancaster plots) [4–6]. Lhymn also reported that the wear resistance of polymers dispersed with fillers is proportional to the tensile modulus or the hardness [7]. Therefore, it is expected that if the tensile modulus and strength of polymers are increased because of the dispersion of fillers, their wear resistance should also increase. The results of a number of studies on the friction and wear properties of polymers dispersed with high hardness inorganic whiskers and particles [8–11], and those dispersed with nano-sized particles [10–16] have indeed indicated that in some cases wear resistance can be increased by dispersing fillers [9–12,14,15]. However, in other cases, the wear resistance is reduced even when the elastic modulus and hardness are increased [16]. Therefore, investigation of other mechanical properties such as fatigue is needed to determine their influence on the wear properties of filler-dispersed polymers.

In a previous study [17], the friction properties of the abrasive wear for polyamide 6 (PA6) dispersed with various inorganic fillers were investigated and the influence of viscoelasticity on the friction coefficient was analyzed using the abrasive wear model proposed by Irisawa et al. [11,12]. This model represents the friction coefficient and wear rate as a function of the stress required for sliding an abrasive particle, the microhardness, the probability that the material will detach as wear debris per one sweep of an abrasive particle, and the shape factor of the abrasive particle. Among these parameters, the probability that the material will detach per one sweep of an abrasive particle is considered to be related to the fatigue property of the material. In the present study, therefore, the anisotropy in the abrasive wear property and the correlation between the abrasive wear, fatigue, and tensile properties of various PA6 composites were investigated.

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2. Experimental

2.1. Materials

The PA6 and PA6 composite films used for this study were the same as those used in a previous study [17]. The matrix was PA6 (Unitika, M1040) with a glass transition temperature of 48.5 °C and a melting temperature of 223 °C. The fillers 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 diameters of 1, 0.1–1, and 0.15 μm and aspect ratios of 1, 10–50, and 10–500, respectively. The high-aspect ratio fillers (ABW and VGCF) exhibited preferential orientation parallel to the film plane due to the flow of the molten polymer during hot pressing [17].

2.2. Wear testing

Wear tests were conducted using a wear tester with a rotating drum covered with abrasive paper. This test method was originally developed to determine the wear properties of filaments [10], and the filaments can be worn without causing rotation around the filament axis. The friction coefficient (μ) and the average wear rate ($<W_s>$), which is the average of the wear rate (W_s) during the wear test, were determined as described previously [17]. In the present study, the influence of the filler orientation on the wear properties of the composite films was investigated by conducting wear tests on both the film surfaces and edges, as shown in Fig. 1. These test geometries are henceforth referred to as surface wear and edge wear.

The specimens used for the surface wear tests were 114 mm long, 2 mm wide, and 0.55 mm thick, and the thickness was decreased by wear. The specimens used for the edge wear tests were 114 mm long, 0.5 mm wide, and 0.55 mm thick, and the width was decreased by wear. Abrasive papers of grades #320, #800, and #2000 (JIS R 6001), which are coated with SiC particles with average diameters of 40.0, 14.0, and 6.7 μm, respectively, were used for the wear tests. The specimens were hung on the rotating drum and pushed against the abrasive paper by connecting, using string, one end of the specimen to a load cell and the other end to a weight. The masses of the weights were 120 and 30 g for the surface and the edge wear tests, respectively. The sliding velocity was varied between 0.81 and 5.38 m s^{-1}. For the surface wear tests, the wear time was adjusted to maintain a constant sliding distance for each grade of abrasive paper [17]. For the edge wear tests, a shorter wear time of 180 s was chosen in order to avoid elongation and break of the specimens. During the wear tests, water at 20 °C was poured at a rate of 4 L min^{-1} in order to remove the wear debris and prevent an increase in temperature due to the heat of friction. Prior to testing, the specimens were conditioned by soaking in water for 24 h.

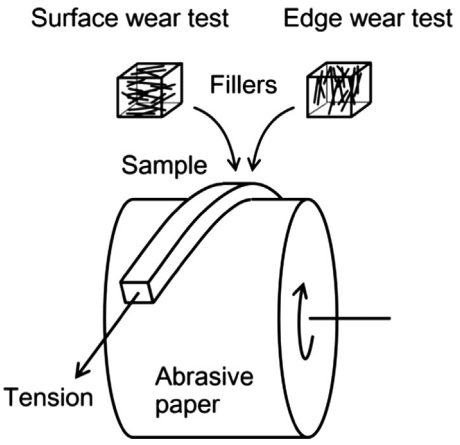

Fig. 1. Schematic illustrations of the surface wear test and edge wear test.

2.3. Fatigue testing

Fatigue tests were performed on single-surface-notched specimens in dry air (relative humidity of 5%) using a fatigue tester (FRS20, Asashi Seisakusho Co.) by applying a biased sinusoidal stress wave and measuring the number of cycles requried to cause fracture (fatigue life). The sinusoidal stress wave had a stress ratio (minimum stress (σ_{min})/maximum stress (σ_{max})) of 0.1 and a frequency of 20 or 90 Hz, where the latter frequency was used to determine the fatigue life at a low stress level in an acceptable time period. Specimens with different cross-section sizes were used depending on the frequency in order to avoid resonance (20 Hz: 10 mm long (gage length), 0.55 mm thick, and 5 mm wide with a notch to a depth of 0.25 mm in the thickness direction; 90 Hz: 10 mm long (gage length), 0.55 mm thick, and 3 mm wide with a notch to a depth of 0.45 mm in the thickness direction). The surface notches were introduced using a razor blade. The specimens were dried in a vacuum oven heated at 80 °C for 24 h before the tests.

It has been reported that the fatigue life of thermoplastic polymers such as polyamide 6,6 and polyamide 6 decreases with increasing test frequency when the fatigue life is determined by thermal failure [18,19]. The thin specimens used in the present study allowed the heat generated during the cyclic loading to be rapidly released, thus avoiding thermal failure as confirmed by the fact that the fatigue life did not vary with respect to the test frequency under the present test conditions.

2.4. Tensile testing

Tensile tests were performed using a tensile testing machine (Orientec, RTC-1350A). The tensile modulus was determined using a rectangular specimen 50 mm long (gage length), 0.55 mm thick, and 10 mm wide at a strain rate of 2% min^{-1}. The tensile strength and the elongation at break were determined using a dumbbell-shaped specimen specified by JIS K-7162-1BB at a strain rate of 83% min^{-1}. The specimens were stored in a desiccator and dried at 80 °C for 24 h in a vacuum oven before the tensile tests. For each composition of the composite films, 5 determinations were performed, and the average values are shown.

3. Results and discussion

3.1. Tensile and fatigue properties

Fig. 2 shows the tensile modulus, tensile strength, and elongation at break for the PA6 and PA6 composite films. With increasing filler content, the tensile modulus increased while the tensile strength and elongation at break decreased. These results are attributed to the fact that the fillers resist the applied stress in the low strain region but undergo debonding from the PA6 in the high strain region, which causes defect formation.

In general, the fatigue life consists of two periods: crack initiation and gradual crack growth up to specimen failure. The crack initiation period is dominant in the fatigue life of unnotched specimens under low stress levels, whereas the crack growth period is dominant in the fatigue life of notched specimens. In addition, the stress states in the specimens notched on the surface and at the end differs under tensile stress. Specifically, the surface notch tends to produce a near plane strain state and causes brittle