Friction and Wear Behavior of Polyamide 66 Composites Filled with Rice Bran Ceramics under a Wide Range of Pv Values

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Hard particulate fillers are used to improve the mechanical and tribological properties of thermoplastic resins. In this study, we investigated the fundamental tribological behavior of polyamide 66 (PA66) resin composites containing rice bran ceramics (RBC) particles at a wide range of pressure-velocity (Pv) values under dry conditions. Irrespective of Pv value, PA66/RBC composite exhibited relatively low friction coefficients (0.4), whereas the friction coefficients for pure PA66 increased. In addition, the PA66/RBC composite better prevented an increase in the surface temperature compared with pure PA66 at high Pv values. To distinguish the effect of the flowability of the resin, surface temperatures normalized by the glass transition temperature were defined. The specific wear rates of pure PA66 changed with the normalized surface temperature because the wear mode transited. Low specific wear rates ($< 0.3 \times 10^{-8} \text{ mm}^2/\text{N}$) were obtained for the PA66/RBC composite without the transition of the wear mode against the normalized surface temperature. These wear rates were reduced by 55-86% compared with those of pure PA66.

Keywords: resin composite, hard particulate filler, friction, sliding wear, Pv value, normalized surface temperature

1. Introduction

Various types of fillers are utilized to improve mechanical properties of thermoplastic resin materials [1-8]. Solid lubricants can add low friction and low wear to the resins because of the formation of lubricative transfer films [9,10]. Occasionally, the solid lubricants cause relatively high wear because of the lack of transfer films [11,12]. Particulate fillers are sometimes useful for improving the mechanical and tribological properties of resin materials [13].

Hokkirigawa et al. developed rice bran ceramics (RBC), which was a hard porous carbon material [14]. RBC has a low friction coefficient and high wear resistance. Therefore, RBC particles have been considered as a particulate filler with low friction and wear. The previous study clarified that the thermoplastic resin/RBC composites exhibited lower friction and higher wear resistance compared with those of pure resins [15]. The increased hardness by the RBC particles prevented the severe wear accompanied by the surface plastic flow, which resulted in prevention of significant increase of the contact area. Another study revealed that the wear resistance of polyamide 66/RBC (PA66/RBC)

composites improved as the amount of small sized RBC particles increased [16]. Thus, the tribological behaviors, particularly the wear resistance, of thermoplastic resins improve when RBC particles are used as a filler material. However, those behaviors were obtained at a limited sliding condition.

For the use of tribomaterials, resin materials usually have an application limit: their Pv value, which is the product of the contact pressure (P) and the sliding velocity (v) [17]. When the Pv value reaches a certain limit of a resin, severe or catastrophic wear occurs, which is accompanied by softening, melting, carbonizing, or degradation of the resin because of frictional heat. The critical Pv value of resin materials is strongly related to their thermostability.

Therefore, investigation of the tribological behavior of thermoplastic resin/RBC composites under a wide range of Pv values is important in view of their practical usage. In this study, the friction and wear behavior of PA66/RBC composites under a wide range of Pv values was investigated, and the difference in wear mode between the composite and pure PA66 was discussed using normalized surface temperature.

Fig. 1 Schematic of the manufacturing processes of the PA66/RBC composites

2. Experimental details

2.1. Material preparation

The mean diameter of RBC particles (Sanwa Yushi Co. Ltd., Japan) was $4.9\ \mu\text{m}$, and they were anisotropic in shape [18]. Their surfaces were not treated with any coupling agent. Figure 1 shows a schematic of the manufacturing process of a PA66/RBC composite. The RBC particles were compounded with pure PA66 by kneading at the volume fraction of 8 vol%. Finally, the

form was cut into a pin shape with dimensions of $3\ \text{mm} \times 2\ \text{mm} \times 20\ \text{mm}$. One side of the pin specimen with $3\ \text{mm} \times 2\ \text{mm}$ was used as a flat test surface. Therefore, the apparent contact area was $6\ \text{mm}^2$. A pure PA66 sample was also prepared for comparison.

The mechanical and thermal properties of the PA66/RBC composite are reported in Table 1. As shown in the table, the Vickers hardness, Young's modulus, and tensile strength of the composite increased compared with those of pure PA66.

Table 1 Mechanical and thermal properties of the PA66/RBC composite

Sample	PA66/RBC composite	Pure PA66
Density ρ , g/cm^3	1.19	1.13
Young's modulus E , GPa	3.7	3.0
Tensile strength σ_T , MPa	81.4	74.3
Vickers hardness H_V , GPa	0.158	0.111
Surface roughness R_a , μm	0.1	0.1
Thermal conductivity λ , $\text{W}/(\text{m}\cdot\text{K})$	0.27	0.24
Glass transition temperature T_g , $^\circ\text{C}$	70	70
Melting temperature T_m , $^\circ\text{C}$	260	262
Crystallinity α , %	40	44

Fig. 2 Schematic of the pin-on-disk-type friction tester

2.2. Experimental methods

To investigate the friction and wear properties under a wide range of normal loads and sliding velocities, friction tests were performed using the pin-on-disk-type friction tester shown in Fig. 2. A friction coefficient was calculated from torque measured using a torque meter coupled to the stage. The PA66/RBC composite and pure PA66 were used as pin specimens. Disk specimen was made of stainless steel (JIS SUS304), and their test surfaces were finished by polishing, which resulted in the surface roughness (Ra) of $0.1\ \mu\text{m}$. The experimental conditions are presented in Table 2. The sets of normal load and sliding velocity were selected as the Pv values gradually increased. An infrared thermometer was set near the stage of the friction tester to measure surface temperatures of the pin specimens. The spot diameter of the thermometer was $1.2\ \text{mm}$, and the thermometer had a focus guide as a square area with $2\ \text{mm} \times 2\ \text{mm}$ by a red light-emitting diode. To avoid a contact risk between the rotating stage and the thermometer, the center of the measurement point was set at $1.5\ \text{mm}$ above the contact

surface. The wear volume of each pin specimen was calculated from mass loss measured with an electronic balance.

3. Results and discussion

Figure 3 shows the representative variations of friction coefficients at $2.0\ \text{m/s}$ of sliding velocity and $19.6\ \text{N}$ of normal load. The value of Pv in the figure was the highest among the overall experimental conditions ($6.53\ \text{MPa}\cdot\text{m/s}$). The friction coefficient for the PA66/RBC composite slightly decreased with increasing sliding distance. In comparison, pure PA66 showed a rapid increase in friction coefficients and exhibited high values (> 0.6).

Figure 4 shows the representative variations of surface temperature at $2.0\ \text{m/s}$ of sliding velocity and $19.6\ \text{N}$ of normal load. The behavior of surface temperatures as function of sliding distance was similar to that of friction coefficients. The surface temperature of the PA66/RBC composite increased, but then decreased with increasing sliding distance. The surface

Table 2 Experimental conditions

Normal load W , N	9.8				14.7		19.6		
Apparent contact pressure P , MPa	1.63				2.45		3.27		
Sliding velocity v , m/s	0.2	0.5	1.0	2.0	1.0	2.0	0.5	1.0	2.0
Sliding distance L , m	2000								
Lubrication condition	Dry								
Environmental temperature T_e , °C	20.7±2								
Environmental humidity RH, %	43.6±5								
Number (N) of tests under the same condition, times	3

Fig. 3 Typical variations in friction coefficients as functions of the sliding distance at 2.0 m/s and 19.6 N

Fig. 4 Typical variations in surface temperatures as functions of the sliding distance at 2.0 m/s and 19.6 N

temperature of pure PA66 increased and exhibited high values ($> 80^{\circ}\text{C}$).

Figure 5 illustrates the relationship between the friction coefficients obtained at 2×10^3 m and the Pv values. The error bars indicate the maximum and minimum values of friction coefficient among the results collected under the same experimental conditions, and the plots show the average values. The friction coefficient for pure PA66 was high (≥ 0.6) when the Pv values exceeded $2.5 \text{ MPa}\cdot\text{m/s}$. In contrast, the friction coefficients of the PA66/RBC composite exhibited approximately no change and was relatively low (0.4), irrespective of the Pv value.

Figure 6 shows the relationship between the surface temperature obtained at 2×10^3 m and the Pv value. The surface temperature increased with increasing Pv value, irrespective of the material. Pure PA66 exhibited surface temperatures higher than glass transition temperature

(70.1°C) when the Pv values exceeded $3.3 \text{ MPa}\cdot\text{m/s}$. The surface temperatures of the PA66/RBC composite were lower than those of pure PA66 when the Pv values exceeded $1.5 \text{ MPa}\cdot\text{m/s}$. As shown in Fig. 5, the PA66/RBC composite exhibited lower friction coefficients compared with pure PA66 throughout the test. Therefore, frictional heat of the composite was smaller than that of pure PA66.

Figure 7 illustrates the relationship between the specific wear rates of the pin and the Pv values. The wear behaviors of the PA66/RBC composite and pure PA66 as function of the Pv value differed. Pure PA66 exhibited high specific wear rates ($> 1.0 \times 10^{-8} \text{ mm}^2/\text{N}$) at low Pv values; these wear rates decreased with increasing Pv value and remained 0.5×10^{-8} – $1.0 \times 10^{-8} \text{ mm}^2/\text{N}$. In contrast, the specific wear rate of the PA66/RBC composite was low ($< 0.3 \times 10^{-8} \text{ mm}^2/\text{N}$), irrespective of the Pv value. The reduction of specific wear rate for the PA66/RBC composite was 55–86% compared with pure

Fig. 5 Relationship between the friction coefficients and Pv values

Fig. 6 Relationship between the surface temperatures and Pv values

Fig. 7 Relationship between the specific wear rates and Pv values

PA66.

As shown in Fig. 6, the surface temperature for each material increased with increasing Pv value. Therefore, softening phenomena may occur at high Pv values. In particular, the flowability of the resin can increase rapidly when the temperature of the resin exceeds its glass transition temperature.

To distinguish the effect of the flowability of the resin, surface temperatures normalized by the glass transition temperature were defined. The normalized surface temperature is the ratio between the measured surface temperature (T_s) and the glass transition temperature of each material (T_g). Figure 8 illustrates the relationship

between the specific wear rates of the pin specimens and the normalized surface temperatures, and SEM images of the worn surfaces of the pin specimens. As shown in the figure, pure PA66 exhibited high values of specific wear rates ($> 1.0 \times 10^{-8} \text{ mm}^2/\text{N}$) when the normalized surface temperature was less than 0.86. According to the SEM image, adhesive wear was considered to be dominant for pure PA66 under the test conditions. When the normalized surface temperature exceeded 0.86, the specific wear rate decreased and remained $0.5 \times 10^{-8} - 1.0 \times 10^{-8} \text{ mm}^2/\text{N}$ with massive plastic flows. Unavoidable softening would occur on pure PA66 at these friction conditions. In contrast, the PA66/RBC composite exhibited low specific wear rates ($< 0.3 \times 10^{-8} \text{ mm}^2/\text{N}$) with shallow and mild scratch marks without the transition of the wear mode against the normalized surface temperature.

The results of this study were limited because the measured surface temperature of the pin specimen might not present the temperature at the pin-disk interface: the interface temperature will obviously be higher than that of the measured temperature. Therefore, the practical temperature of the contact interface would exceed the glass transition temperature of the material in more test conditions. Thus, the wear mode of pure PA66 started to transit at the surface temperature lower than the glass transition temperature (86% of T_g).

Finally, the friction and wear behavior of the PA66/RBC composite is summarized in Fig. 9. In brief, pure PA66 exhibited high wear and relatively low friction at low Pv values ($T_s < T_g$), or medium wear and high friction at high Pv values ($T_s \geq T_g$). In contrast, the

Fig. 8 Relationship between the specific wear rates and normalized surface temperatures, and SEM images of the worn surfaces of the pin specimens

Fig. 9 Distribution of the specific wear rates and friction coefficients under the overall experimental conditions

PA66/RBC composite exhibited low wear and relatively low friction under the overall experimental conditions.

4. Conclusions

- (1) The friction coefficient (0.4) of the PA66/RBC composite was relatively low, irrespective of Pv value.
- (2) The increase of the surface temperature of the PA66/RBC composite was low compared with that of pure PA66 at high Pv values. The surface temperature of the PA66/RBC composite did not exceed the glass transition temperature.
- (3) The wear mode of the PA66/RBC composite did not transit against increasing Pv value. Therefore, low specific wear rates ($< 0.3 \times 10^{-8} \text{ mm}^2/\text{N}$) were obtained for the composite, irrespective of Pv value. The wear rates of the composite were 55-86% less than those of pure PA66.
- (4) The PA66/RBC composite is capable to be used as a high-wear-resistant tribo-material under a wide range of Pv values compared with using pure PA66.

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