THE ROLE OF FRICTIONAL WORK IN TRIBOLOGICAL BEHAVIOR OF POLYAMIDE 66 COMPOSITES CONTAINING RICE BRAN CERAMICS PARTICLES OR GLASS BEADS[I]

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ABSTRACT

In this study, we investigated tribological behavior of polyamide 66 (PA66) composites containing rice bran ceramics (RBC) particles or glass beads (GBs) under a wide range of contact pressures and sliding velocities, and discussed the role of the frictional work in the behavior. The volume fractions of the fillers were 8 and 26 vol%. The friction coefficients of pure PA66 showed the increasing tendency with the Pv values. In contrast, those of the PA66/RBC composites showed approximately no change, and those of the PA66/GB composites slightly decreased with increasing Pv value. The surface temperatures of the materials increased with increasing frictional work. The maximum temperature of pure PA66 and the PA66 composite with 26 vol% RBC particles exceeded 80 °C, which were higher than the glass transition temperature of PA66 resin. Pure PA66 exhibited a decrease in specific wear rate with increasing frictional work even as a change of the wear mode. This change was considered to be caused by softening of the resin because of high frictional work. In contrast, the specific wear rates of the PA66 composites with the RBC particles or GBs were much lower ($<0.5 \times 10^{-8}$ mm^2/N) compared with pure PA66 at low frictional work (<1.3 MJ/(m^2·s)). At high frictional work (>1.4 MJ/(m^2·s)), the PA66 composites with the RBC particles showed relatively high specific wear rates (0.6–1.0×10^{-8} mm^2/N) because of high surface temperature.

Keywords: sliding wear; frictional work; resin composite; rice bran ceramics particles; glass beads.

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INTRODUCTION

Hard particulate fillers have been used for thermoplastic resins to improve the mechanical and tribological properties [1–6]. In a previous study, the tribological properties of rice bran ceramics (RBC) filled polyamide 66 (PA66) composite and glass bead (GB) filled PA66 composite under dry conditions were investigated [7]. According to the results, the PA66/RBC and PA66/GB composites showed lower friction and wear compared with pure PA66. Furthermore, the wear volume of the PA66/RBC composite was lower than that of the PA66/GB composite. It was revealed that the fillers were effective to prevent from occurring plastic flows and roll-shaped-wear particles, which affected the wear.

On the other hand, resin materials usually have an application limit for the use of tribomaterials: their Pv value, which is the product of the contact pressure (P) and the sliding velocity (v) [8,9]. 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 values of resin materials are strongly related to their thermostability. The published Pv limit of PA66 resin is 0.09–0.11 MPa·m/s [9]. In general, resins exhibit poor thermostability

compared with those of metals and ceramics because they have low melting temperatures, low deflection temperatures under load, and low glass transition temperature. In tribomaterials, heating is caused by transmission of external supply sources and friction in the contact interface. The frictional heats are attributed to frictional work.

Therefore, clarification of the effect of frictional work on the tribological behavior of the PA66/RBC and PA66/GB composites is important in view of their practical usage, such as dry bearing. In this study, the friction and wear behavior of the PA66/RBC and PA66/GB composites were investigated under a wide range of Pv values, and the role of the friction work in the behavior was discussed.

EXPERIMENTAL DETAILS

Material Preparation

PA66 composites containing RBC particles or GBs were prepared by varying the volume fraction of the fillers. The volume fraction of the fillers were 8 and 26 vol%, which corresponded to 10 and 30 mass% for the RBC particles. The mean diameters of the RBC particles and GBs were 4.9 and 5.0 µm, respectively. The composite samples were manufactured by injection molding and cut into a pin shape: 3 mm × 2 mm × 20 mm (Fig. 1). The test surface was finished by polishing. A pure PA66 sample was prepared in the same process. The mechanical and thermal properties of the samples are listed in Table 1. The tensile strength of the PA66/RBC composites increased with increasing volume fraction. In contrast, that of the PA66/GB composites decreased. The glass transition temperature and melting temperature were approximately same values.

Table 1. The mechanical and thermal properties of the samples.

Sample	PA66/RBC (8 vol%) composite	PA66/RBC (26 vol%) composite	PA66/GB (8 vol%) composite	PA66/GB (26 vol%) composite	Pure PA66
Volume fraction of filler V_f, vol%	8	26	8	26	—
Young's modulus E, GPa	3.7	4.8	4.0	5.3	3.0
Tensile strength σ_t, MPa	81.4	83.8	71.7	69.5	74.3
Vickers hardness H_v, GPa	0.16	0.19	0.12	0.17	0.11
Surface roughness R_a, µm	0.1	0.1	0.1	0.1	0.1
Glass transition temperature T_g, °C	69.6	69.0	69.6	70.7	70.1
Melting temperature T_m, °C	259.5	262.1	259.2	259.0	262.3
Crystallinity α	39.5	39.7	36.8	43.0	43.7

Experimental Methods

To investigate the tribological behavior under a wide range of Pv values, we conducted friction tests using the pin-on-disk-type friction tester. The PA66/RBC composites, the PA66/GB composites, and pure PA66 were used as pin specimens. A disk specimen was made of austenitic stainless steel (JIS SUS304) with the surface roughness (R_a) of 0.1 µm. The normal loads (W) were 9.8, 14.7, and 19.6 N; thus, the apparent contact pressures (P) were 1.63, 2.45, and 3.27 MPa. The sliding velocities (v) were 0.2, 0.5, 1.0, and 2.0 m/s. The sliding distance was 2×10^3 m. The lubrication conditions were dry. Each test condition was repeated 3 times. A friction coefficient was calculated on the basis of friction torque using a torque meter. The wear volume of the pin specimens was calculated on the basis of mass loss measured with an electronic balance. A surface temperature of the pin specimens at 1.5 mm above the contact surface was measured using an infrared thermometer. The environmental temperature was 21.0±2 °C, and the relative humidity was 43.6±5%.
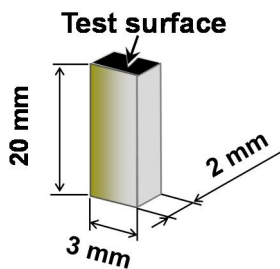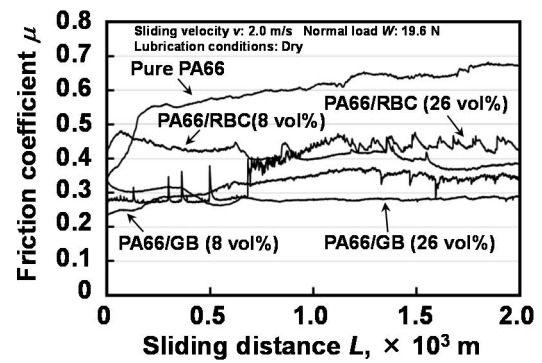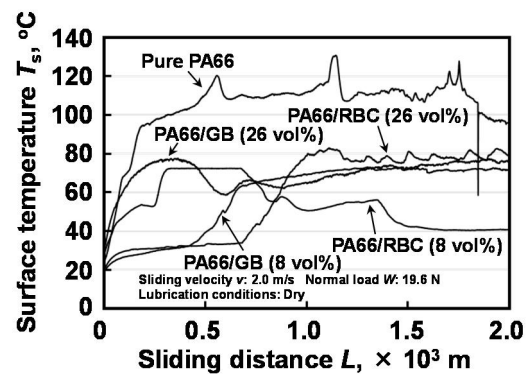

Figure 1. The schematic and the dimension of a pin specimen.
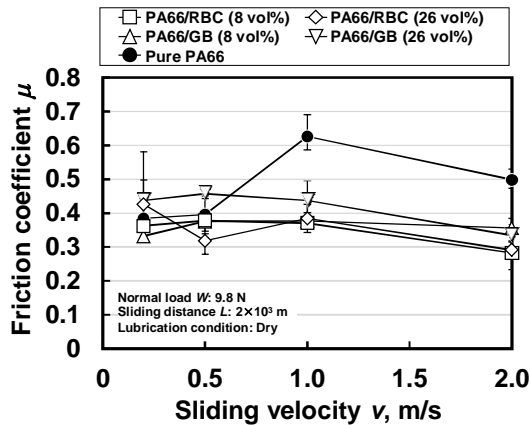

(a)   Friction coefficients


(b)   Surface temperatures

Figure 2. Representative variations in (a) friction coefficients and in (b) surface temperatures at 2.0 m/s of sliding velocity and 19.6 N of normal load.

RESULTS AND DISCUSSION

Figure 2 shows the representative variations in (a) the friction coefficients and in (b) surface temperatures at 2.0 m/s of sliding velocity and 19.6 N of normal load. The surface temperatures showed the approximately same tendency for the friction coefficients, irrespective of the materials. The friction coefficients and surface temperatures of pure PA66 were higher than the composites.
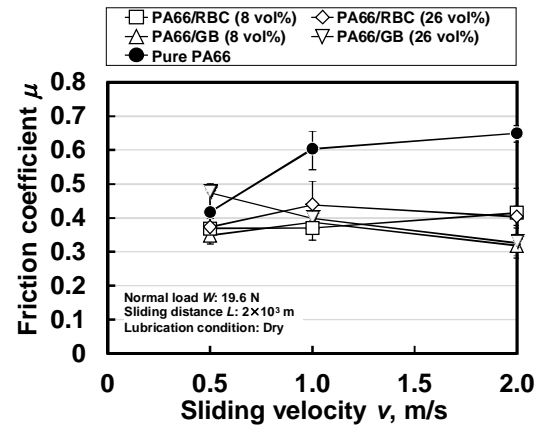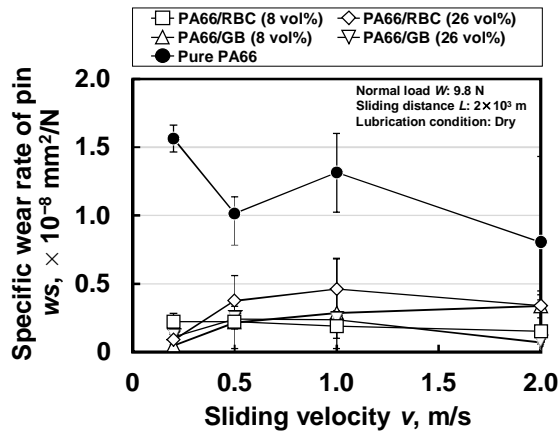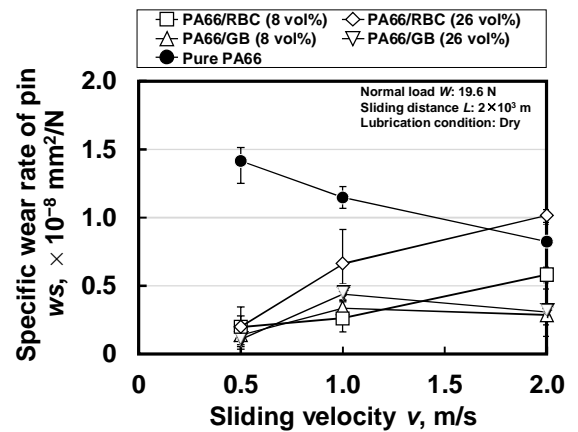
(a) Normal load W: 9.8 N (b) Normal load W: 19.6 N

Figure 3. The relationship between the friction coefficients and the sliding velocities.

(a) Normal load W: 9.8 N (b) Normal load W: 19.6 N

Figure 4. The relationship between the specific wear rates and the sliding velocities.

The relationship between the friction coefficients at 2×10^3 m and the sliding velocities was presented in Fig. 3. 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 coefficients of pure PA66 increased from 0.4 to 0.6 as the sliding velocity increased from 0.5 m/s to 1.0 m/s. Then, those decreased to 0.5 at 9.8 N of normal load. At 19.6 N, the coefficients increased. In contrast, the friction coefficients of the composites slightly decreased at 9.8 N of normal load. At 19.6 N of normal load, the coefficients of the PA66/RBC composite

slightly increased, and those of the PA66/GB composites slightly decreased.

The relationship between the specific wear rates and the sliding velocities is illustrated in Fig. 4. The specific wear rates of PA66 decreased with increasing sliding velocity at 9.8 N of normal load. On the other hand, the rates of the composites were smaller than those of pure PA66, irrespective of sliding velocity. At 19.6 N of normal load, pure PA66 exhibited the decrease in specific wear rate with increasing sliding velocity, and the PA66/RBC composites exhibited the increase. Thus, the wear properties were affected by both normal loads and sliding velocities.
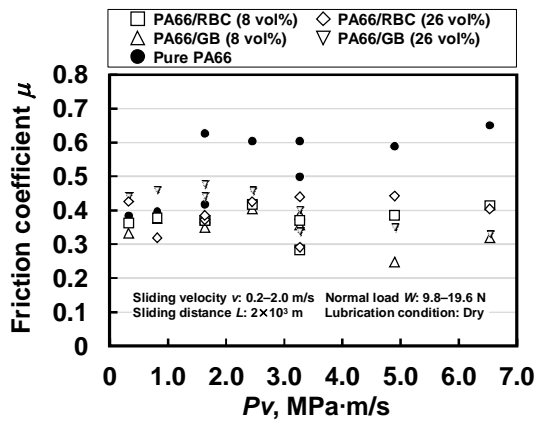
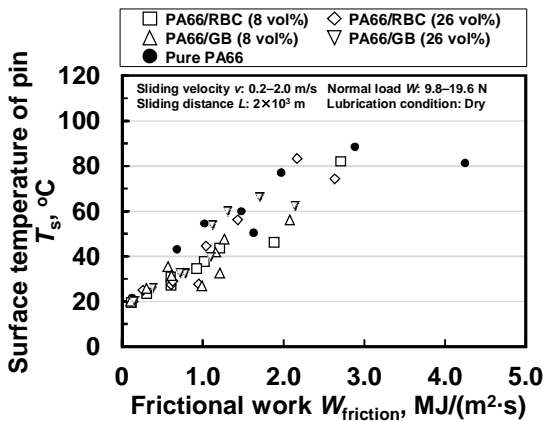Figure 5. The relationship between the friction coefficients and the Pv values.

Figure 6. The relationship between the specific wear rates and the frictional work.

Figure 7. The relationship between the surface temperatures of the pin specimens and the frictional work.

Figure 8. The relationship between the specific wear rates and the surface temperatures of the pin specimens.

Figure 5 presents the relationship between the friction coefficients and the Pv values. The friction coefficients of pure PA66 showed the increasing tendency with the Pv values. In contrast, the coefficients of the PA66/RBC composites showed approximately no change against increasing Pv value. Furthermore, the friction coefficients of the PA66/GB composites slightly decreased. These results indicated that the frictional work was different among the composites and pure resin at the same friction condition.

The frictional work per unit area per unit time ($W_{friction}$) can be calculated as follows:
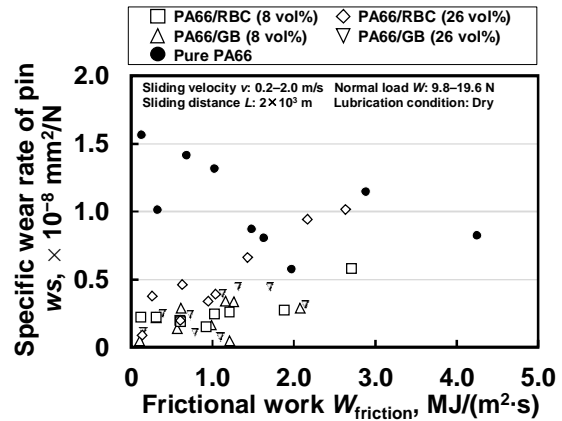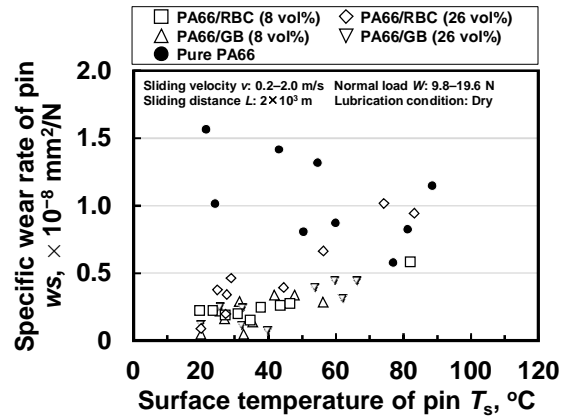
$$W_{friction} = \mu P v \qquad \text{(Eq 1)}$$

where μ represents the friction coefficient, P the apparent contact pressure and v the sliding velocity. The relationship between the specific wear rates and the frictional work is shown in Fig. 6. The wear behaviors as a function of the frictional work differed between the composites and pure PA66. Pure PA66 exhibited high specific wear rates ($>1.0 \times 10^{-8}$ mm^2/N) at low frictional work; these specific wear rates of the remained 0.6–1.1 $\times 10^{-8}$ mm^2/N at high frictional work. In contrast, the specific wear rates of the PA66 composites with GBs were low ($<0.5 \times 10^{-8}$ mm^2/N), irrespective of frictional work. For the PA66 composite with the RBC particles, the specific wear rates increased at high

frictional work; especially, those of the PA66 composite with 26 vol% RBC particles reached 1.0×10^{-8} mm^2/N.

The relationship between the surface temperatures of the pin specimens and the frictional work was illustrated in Fig. 7. As shown in the figure, the surface temperatures of the pin specimens increased with increasing frictional work up to 3.0 MJ/(m^2·s), irrespective of type of pin material. Thus, the increase of the surface temperature was caused by frictional heat generated by the frictional work. The frictional work of pure PA66 reached higher values than that of the other composites because their friction coefficients were higher at the same test conditions. The maximum temperature was approximately 90 °C, which exceeded the glass transition temperature of the PA66 resin.

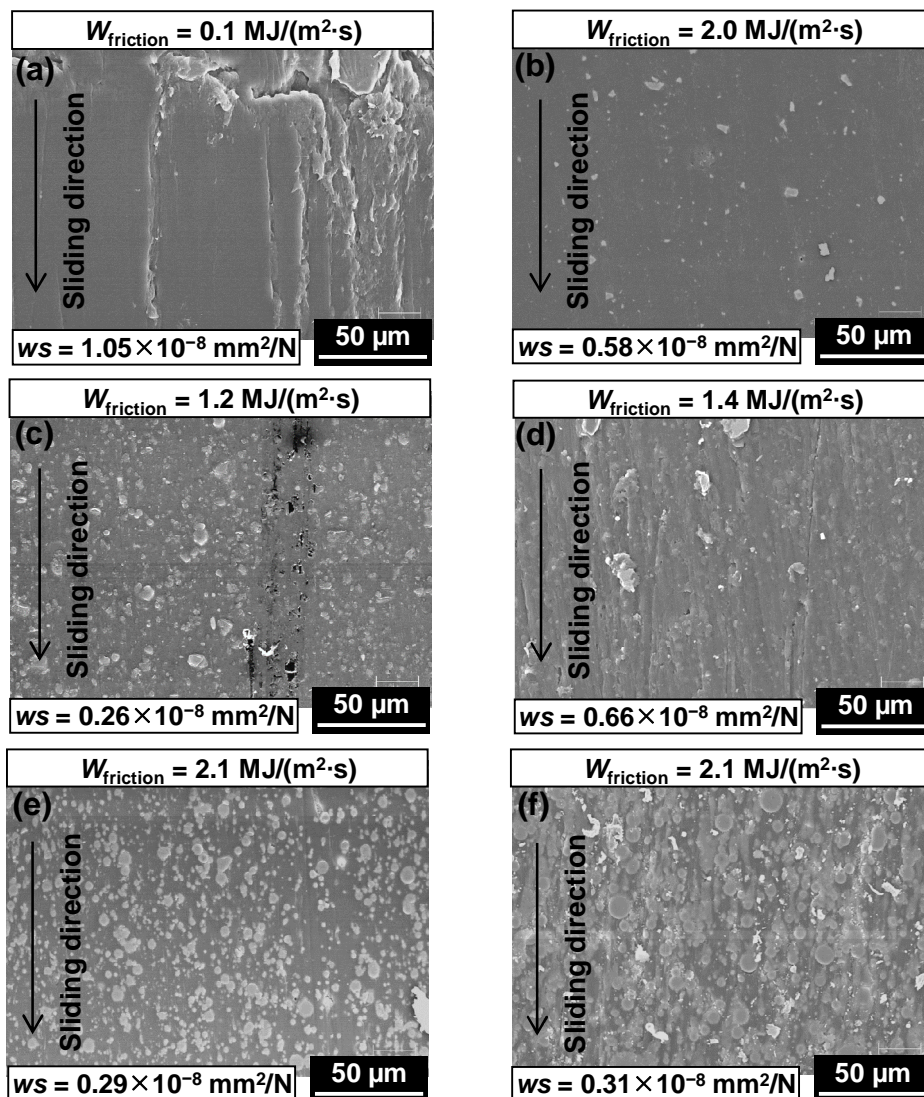*Figure 9. SEM images of the worn surfaces of the pin specimens: (a) pure PA66 at 0.1 MJ/(m²·s), (b) pure PA66 at 2.0 MJ/(m²·s), (c) PA66/RBC (8 vol%) at 1.2 MJ/(m²·s), (d) PA66/RBC (26 vol%) at 1.4 MJ/(m²·s), (e) PA66/GB (8 vol%) at 2.1 MJ/(m²·s), and (f) PA66/GB (26 vol%) at 2.1 MJ/(m²·s).*

Thus, the increase in the frictional work increased the surface temperature of the pin materials, and decreased the wear of pure PA66 or increased the wear of the composite filled with the hard particulate fillers. Fig. 8 presents the relationship between the specific wear rates and the surface temperatures. As shown in the figure, the specific wear rates of the composites were sufficiently smaller than those of pure PA66 at low temperature; the rates of pure PA66 decreased as the temperature increased, and those of the composite increased and reached the same level of pure PA66. Therefore, the effect of hard filler showed at low surface temperature.

Figure 9 shows SEM images of the worn surfaces of the pin specimens. For pure PA66, surface fractures were observed at 0.1 $MJ/(m^2 \cdot s)$. In contrast, smooth surface and fine wear particles were observed at 2.0 $MJ/(m^2 \cdot s)$. At high frictional work, softening of resin starts to occur since their temperatures exceed the glass transition temperature. Therefore, the wear mode of pure PA66 changed as the frictional work increased. On the other hand, no fracture or no removal of the RBC particles was observed on the PA66 composite with 8 vol% RBC particles at 1.2 $MJ/(m^2 \cdot s)$. This indicated that severe adhesion and plastic flows of PA66 were still prevented because of an anchor effect of the RBC particles. The effect of the RBC particles resulted in lower wear compared with pure PA66 up to 2.0 $MJ/(m^2 \cdot s)$. Similar morphology of the worn surface and wear behavior were shown for the PA66/GB composites in Fig. 5 (e) and (f). In contrast, flake-shaped-wear particles and narrow scratch marks were observed on the PA66 composite with 26 vol% RBC particles at 1.4 $MJ/(m^2 \cdot s)$, as shown in Fig. 5 (d). It was considered that removal of the RBC particles occurred, and, then, delamination of the resin matrix and abrasive wear by the removed particles resulted in high wear.

CONCLUSIONS

- The friction coefficients of the PA66/RBC composites showed approximately no change, irrespective of Pv value. Those of the PA66/GB composites slightly decreased with increasing Pv value.
- The surface temperatures of the pin specimens increased with increasing frictional work up to 3.0 $MJ/(m^2 \cdot s)$, irrespective of type of pin material.
- As the frictional work increased, the specific wear rates of pure PA66 decreased and those of the PA66 composite with 26 vol% RBC particles increased.
- The specific wear rates of the PA66/RBC and PA66/GB composites were lower ($<0.5 \times 10^{-8}$ mm^2/N) compared with pure PA66 at low frictional work (<1.3 $MJ/(m^2 \cdot s)$).

REFERENCES

[1] A. C. Garg, and Y. Mai, Failure Mechanisms in Toughened Epoxy Resins—A Review, Composites Science and Technology, 31 (1988) 179–223.
[2] J. Kim and Y. Mai, High Strength, High Fracture Toughness Fibre Composites with Interface Control—A Review, Composites Science and Technology, 41 (4) (1991) 333–378.
[3] K. Friedrich, Z. Lu and A. M. Hanger, Recent Advances in Polymer Composites' Tribology, Wear, 190 (1995) 139–144.

[4] A. P. Mouritz, K. H. Leong and I. Herszberg, A review of The Effect of Stitching on The in-Plane Mechanical Properties of Fibre-Reinforced Polymer Composites, Composites Part A: Applied Science and Manufacturing, 28 (12) (1997) 979–991.

[5] R. Chandra, S. P. Singh and K. Gupta, Damping Studies in Fiber-Reinforced Composites ― A Review, Composite Structures, 46 (1999) 41–51.

[6] K. Friedrich, Z. Zhang and A. K. Schlarb, Effects of Various Fillers on The Sliding Wear of Polymer Composites, Composites Science and Technology, 65 (15-16) (2005) 2329–2343.

[7] K. Shibata, T. Yamaguchi and K. Hokkirigawa, Improvement of Tribological Properties of Thermoplastic Resin by Using Rice Bran Ceramics Particulate as Wear-Resistant Fillers, Proceedings of NordTrib 2012, (2012) USB flash drive.

[8] J. K. Lancaster, Estimation of The Limiting PV Relationships for Thermoplastic Bearing Materials, Tribology, 4 (2) (1971) 82–86.

[9] J. K. Lancaster, Dry bearings: A Survey of Materials and Factors Affecting Their Performance, Tribology, 6 (6) (1973), 219–251.