This paper is part of the Proceedings of the 2nd International Conference on
High Performance and Optimum Design of Structures and Materials (HPSM 2016)
www.witconferences.com

Study of friction and abrasion properties of wood plastic composites

K. Araki, G. Hamabe, Y. Sano, T. Kume & T. Tanaka
Graduate School of Science and Engineering, Doshisha University, Japan

Abstract

The eco-friendly composites containing PA11 and CP were investigated in order to apply to the functional parts (e.g. sliding parts) in this study. Mechanical properties and tribology properties of PA11 composite were compared with PLA composite or POM. The specimens were prepared by the mixing process using a co-rotating twin-screw extruder and the moulding process using an injection-moulding machine. As a result, both properties of PA11/CP30wt% were reached the each target values. It was related to the Vickers hardness of the PA11/CP composite that the wear loss of the composite when the friction-and-wear test had carried out under a general test condition. It was improved due to suppressing the sliding heat generation that the friction-and-wear property of PA11 composite including high-CP content, because the heat conductivity of composite was low value.
Keywords: PA11, cellulose, PLA, POM, tribology property, mechanical property, sliding heat generation, heat conductivity.

1 Introduction

In recent years, more and more plastic materials have been used as functional parts [1–3]. In particular, polyacetal (POM) is often used as the sliding parts [4]. Plastic sliding parts require several characteristics; noise reduction, dry operation, light weight, cost reduction, and so on. Moreover, if the part is equipped with these characteristics in a well-balanced way, it has general versatility. On the other hand, as a measure for the depletion of fossil resources and environmental problems, the study on bioplastics has flourished in recent years. For plastic sliding parts, it can be presumed that the oil-based plastics will be replacing the bioplastics. Polylactic acid (PLA) is a representative example of bioplastics. However, in order to use

WIT Transactions on The Built Environment, Vol 166, © 2016 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM160381

sliding parts, PLA has several problems; low heat resistance, lowering strength as a result of hydrolysis, and so on [5].

Therefore, we focused on polyamide 11 (PA11) among bioplastics because PA11 has some excellent characteristics, such as heat resistance, impact resistance, wear resistance, and so on. By complexation with PA11 and reinforcing material in order to improve the mechanical properties and tribology properties, we examined whether applicable to sliding parts. Previous work on the PA11 composite has shown that the tribology properties of PA11 increased with increasing the elastic modulus of PA11 [6]. Therefore, cellulose was taken notice of because it is a biomass material which can be expected to improve elastic modulus when used as a filler. Among cellulose, cellulose powder (CP) was reported the improvement of mechanical property when used as a filler in a thermoplastic composite [7].

The purpose of this study is to examine the potential of PA11-based bio-composites as sliding parts. We made the PA11-based composites including CP in order to improve mechanical properties and tribology properties. The properties were investigated by changing the CP content. Furthermore, the composites were compared with PLA composites or POM; this is the target value.

2 Experimental

2.1 Materials

Three types of resins used in the paper were as follows: PA11, PLA, and POM. Meanwhile, CP was used as a filler in the experiments.

PA11 (Rilsan®B grade) was purchased from ARKEMA Co., Ltd. (France). PLA (REVODE110 grade) was purchased from Zhejiong Hisun Biomaterials Co., Ltd. (China). POM (Lupital f20-03 grade) was purchased Mitsubishi Engineering-Plastics Co., (Japan). CP (KC FLOCK W-100GK grade) used as a biomass reinforcement was purchased from Nippon Paper Industries Co., Ltd. (Japan). The average diameter of CP was 37 μm (reference values). CP was added to PA11 composites or PLA composites. The amount of CP was one of the following: 10wt%, 30wt%, and 50wt%. For example, "PA11/CP10wt%" means the PA11 composite including 10wt% CP. The PA11 and the CP were dried at least for 24h at 80°C in a hot-air oven before mixing step. On the other hand, the PLA was dried at least for 3h at 90°C in a vacuum oven before mixing step.

2.2 Composite preparation

The compounding process was performed using a co-rotating twin-screw extruder (ZSK18 MEGAlab, Coperion GmbH, Germany) having a screw outer diameter of 18mm and a barrel length of 720 mm (L/D=40). PA11 or PLA pellets and CP were premixed before the mixing. During melt-mixing, the premixed materials were fed simultaneously into the hopper by volumetric feeder. The screw configuration is shown in Figure 1. The configuration included a kneading zone of five kneading elements with standard (45°) and neutral (90°) staggering angles. The screw rotational speed was kept constant at 150 rpm. The set temperatures for barrel are shown in Table 1. On the mixing of PLA/Cellulose composite, the set temperatures continuously became lower toward the top end of the barrel in order to protect from thermal decomposition of PLA. All composite materials were cooled down in a water bath and pelletized after the extrusion process. After that, the materials were dried at least for 24h at 80°C in a hot-air oven in order to remove the moisture by the cooling process.

Table 1: Temperature conditions for the mixing of the pellets and the CP.

	Heating zone (°C)						
	1	2	3	4	5	6	7
PLA/CP	200	200	200	200	200	200	200
PA11/CP	180	175	175	170	170	165	165
Flow direction	→	→	→	→	→	→	→

Figure 1: Screw configuration of the co-rotating twin-screw extruder designed with conveying and kneading elements.

2.3 Specimen preparation

The specimen making process was performed using a single screw injection-moulding machine (PLASTER ET-40V, TOYO Machinery & Metal Co., Ltd, Japan). Table 2 shows injection-moulding conditions. The tensile specimens were type A1 in the Japanese Industrial Standards (JIS) K 7139. Specimens for friction-and-wear test were made cut from plates having a thickness of 4mm. The friction-and-wear specimens conforming to JIS K 7218A were used.

Table 2: Parameters of injection-moulding when making the specimens.

	PA11/CP	PLA/CP
Screw rotation speed (rpm)	150	100
Back pressure (MPa)	2.7	4.0
Holding pressure (MPa)	30	25
Cylinder temperature (°C)	200	210
Mold temperature (°C)	70	40
Injection speed (mm/sec)	50	50
Holding time (sec)	10	8
Cooling time (sec)	40	120

2.4 Composite characterisation

2.4.1 Vickers hardness test

The Vickers hardness of the composites were measured according to JIS Z 2244. The Vickers hardness test was performed using a digital Vickers hardness tester (VMT-7, Matsuzawa Co., Ltd, Japan). The tests were carried out 10 times measurement for each composite at a load of 10kgf.

2.4.2 Tensile test

The tensile properties of the composites were measured according to JIS K 7162. The tensile tests were carried out using a universal testing machine (Auto Graph AG-100kN, Shimadzu Co., Japan) at room temperature. PA11 composite and POM were measured with crosshead speed of 5mm/min. On the other hand, PLA composite were measured with crosshead speed of 1mm/min because it breaks at a lower strain. The evaluation values set an average of the results for tests run on at least five specimens.

2.4.3 Friction-and-wear test

The friction coefficient and the specific wear rate of the composites were measured by the ring-on-disk method according to JIS K 7218A. The friction-and-wear test was carried out using a friction-and-wear testing machine (EFM-III-E, A&D Co., Ltd, Japan). The test was carried out under two different conditions as shown in the Table 3. Condition 1 is a general test condition can be used for sliding parts such as office automation equipment. By contrast, condition 2 is a more hard condition can be used for sliding parts such as a bearing. Mating sliding member was used a carbon steel S45C having a surface roughness Ra of 0.20-0.60 μm. The friction coefficient, μ, was calculated by Equation (1):

$$\mu = \frac{F \cdot R}{P \cdot r} \tag{1}$$

where, f[N] is a frictional force acting between the specimen and the mating sliding member, P[N] is the test load, F[N] is the force in the direction of rotation of the specimen, R[mm] is the distance between the centre distance of the specimen and the frictional force detector, r[mm] is the average radius of the specimen.

The specific wear rate, V_{SA}[$\times 10^{-6}$ $mm^3/(Nm)$], was calculated by Equation (2):

$$V_{SA} = \frac{V}{P \cdot L} = \frac{W}{\rho \cdot P \cdot L} \tag{2}$$

where, V[mm^3] is the specimen wear loss, L[km] is the total sliding distance, W[g] is the weight change quantity of the specimen, ρ[g/cm^3] is the density of the specimen.

The friction-and-wear test was also carried out under the air-cooled condition in order to investigate the influence of a sliding heat generation. The testing parameters at this time as well as condition 2 were used. The air cooling was carried out by the method, which the test machine had the wings by the cooling fan (SF-45D, Suiden Co., Ltd, Japan). The air volume of the cooling fan was 186 mm^3/min.

Table 3: Parameters of the friction-and-wear test under two different conditions.

	Condition 1	Condition 2
Surface pressure (MPa)	1	6
Sliding speed (mm/sec)	150	50
Test temperature (°C)	Room temperature	
Test time (hour)	3	

2.4.4 Measurement of heat conductivity

The heat conductivity, λ[W/(mK)], of the PA11 composites were calculated by Equation (3):

$$\lambda = \alpha \times C_p \times \rho \tag{3}$$

where, α[m^2/sec] is the thermal diffusivity, C_p[J/(kg·K)] is the specific heat capacity, ρ[Kg/ m^3] is the density of the specimen. The thermal diffusivity was measured by a flash method using a xenon flash analyser (LFA 467 Hyperflash, Netzsch, Germany). The measured temperature of the thermal diffusivity was 125°C, which is the working temperature of PA11. The specific heat capacity was measured by a differential scanning calorimetry method using a smart thermos analysis system (TA7000, Hitachi High-Tech Science Co., Japan). The density was measured by an Archimedes method using an electronic densimeter (SD-200L, Alfa Mirage Co., Ltd, Japan).

3 Results and discussion

3.1 Vickers hardness properties

The result of Vickers hardness test of PA11 composite including CP is shown graphically in Figure 2. It was found that the Vickers hardness of PA11 tended to increase with increasing CP content. In particular, the Vickers hardness of the PA11 composite adding 50wt% CP was approximately twice value of the one of the pure PA11. Also, the friction-and-wear test conducted this time is presumed to be the wear type called "abrasive wear". Abrasive wear means the wear type in which the projections of hard side dig up the materials of soft side [8]. Because the pure PA11 and PA11/CP composites are because softer than the mating sliding member, S45C. The relation between the Vickers hardness and the wear loss during an abrasive wear is a relationship of inverse ratio as shown in Equation (4) [9]:

$$V = \frac{K \cdot W \cdot L}{H} \tag{4}$$

where, V is the specimen wear loss, K is the wear coefficient, W is the load, L is the friction distance, H is the hardness of the material. From the above equation, it is presumed to lead to decrease wear loss with increasing material hardness. Therefore, it is expected that the wear loss of the PA11 composite adding 50wt% CP which showed the highest Vickers hardness, is most reduced.

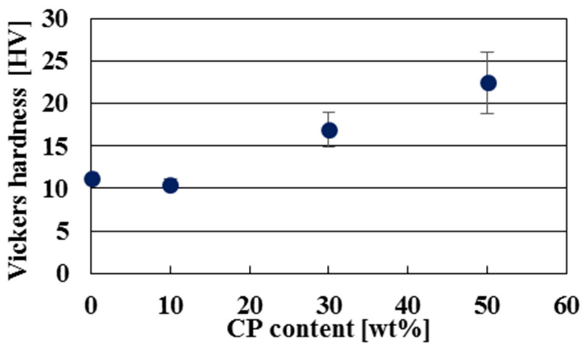


Figure 2: Vickers hardness of PA11 composites as a function of CP content.

3.2 Tensile properties

The result of both tensile strength and elastic modulus of PA11 or PLA composites including CP is shown graphically in Figure 3. Note that the mechanical properties of PLA composite may become the big values compared to the other composite, because the crosshead speed of PLA composite was slower than the one of the other composites. Figure 3 shows that the tensile strength and elastic modulus of PA11 or PLA composites tended to increase with increasing CP content. It can be said that CP have the effect as a reinforcing material of PA11 or PLA. The elastic modulus of PLA composite including low-CP content showed a good value. However, the increase rate of the elastic modulus of PA11 composites to the CP content was higher than the one of PLA composites. Furthermore, from Figure 3, the peak value of the tensile strength was considered the PA11 or PLA composite added amount of CP is in the range of 30wt% to 50wt%. The reason is considered to be due to decrease in the elongation at break. Figure 3 shows that the tensile strength and elastic modulus of PA11 composites including more than 30wt% CP exceeded the target value (POM).

3.3 Friction-and-wear properties under condition 1

The friction coefficient and the specific wear rate of the composites were measured by the friction-and-wear test under condition 1, a general test condition. The result of specific wear rate of PA11 composite including CP is shown graphically in

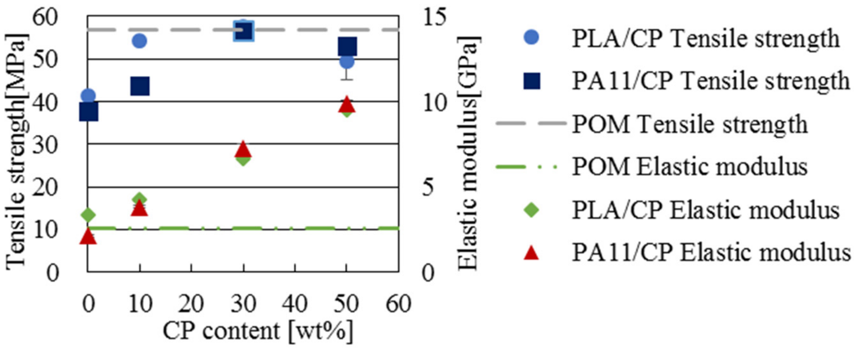


Figure 3: Tensile strength and elastic modulus of composites as a function of CP content.

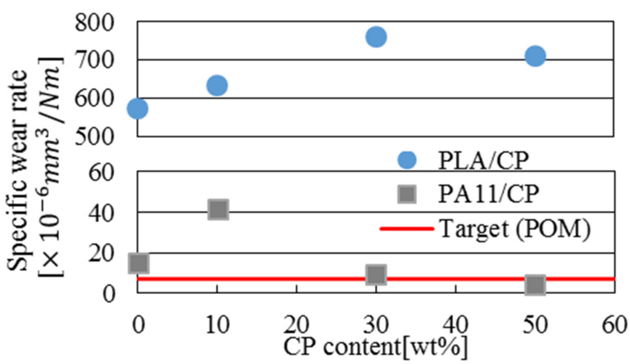


Figure 4: Specific wear rate of composites under condition 1 as a function of CP content.

Figure 4. Furthermore, the result of friction coefficient of composites including CP is shown graphically in Figure 5. It is desired that the both values (specific wear rate and friction coefficient) are lower, because the application for members receiving the continuous sliding was assumed. As can be seen from Figures 4 and 5, both values of PA11 composites adding more than 30wt% CP were good values. In particular, the values of PA11/CP50wt% exhibited excellent values than the target value (POM). In the preceding section, we talked about the influence the improvement of mechanical properties are given to the reduction of the wear loss. For this reason, the CP inside PA11 composites exhibits a reinforcing effect, thereby the mechanical properties were increased, and as a result it is considered that friction-and-wear characteristics were improved. The friction coefficient of the PLA composite was the same as the other of PA11 composite. However, the PLA composite showed the specific wear rate ten or more times worse than the other of PA11 composite. It is suspected that the specific wear rate of PLA

composites got worse because the composites were softened by the sliding heat generation. The heat resistant of PLA composites is lower than the other of PA11 composites. Therefore, it is likely that the temperature of PLA composites was upper than the heat distortion temperature of PLA.

Figure 6 shows microscope images of the wear surface of the PA11 composites. According to Figure 6, although pure PA11 noticeable wear marks by mating sliding member, it was found that the wear marks decreased with increasing CP content. However, the rod-shaped abrasion powder was observed in PA11/CP10wt%. For this reason, Stick-slip phenomenon had occurred in PA11/CP10wt%, as a result the specific wear rate and the friction coefficient had been worse [10].

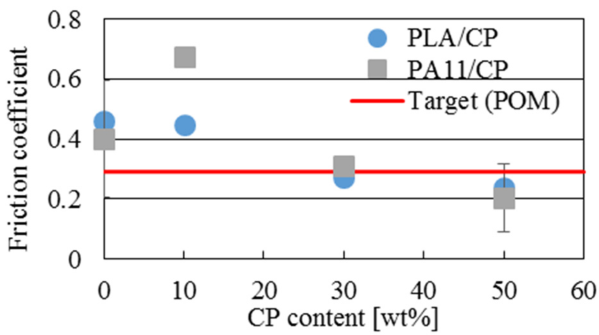


Figure 5: Friction coefficient of composites under condition 1 as a function of CP content.

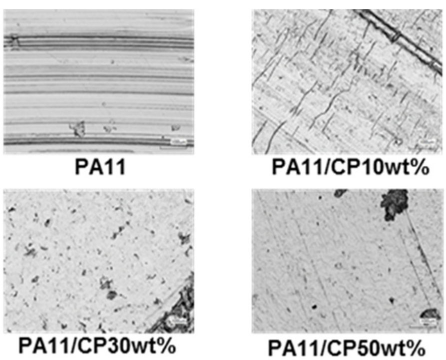


Figure 6: Micrographs of wear surfaces of PA11 composites under condition 1.

3.4 Friction-and-wear properties under condition 2

The friction coefficient and the specific wear rate of the composites were measured by the friction-and-wear test under condition 2, a hard test condition more than condition 1. The result of specific wear rate and friction coefficient of PA11 composite including CP is shown graphically in Figure 7. Pure PA11 and PA11/CP10wt% were not able to clear the test under condition 2. As can be seen from Figure 7, both values (friction coefficient and specific wear rate) of PA11/CP30wt% were achieved POM, on the other hand, the values of PA11/CP50wt% got worse.

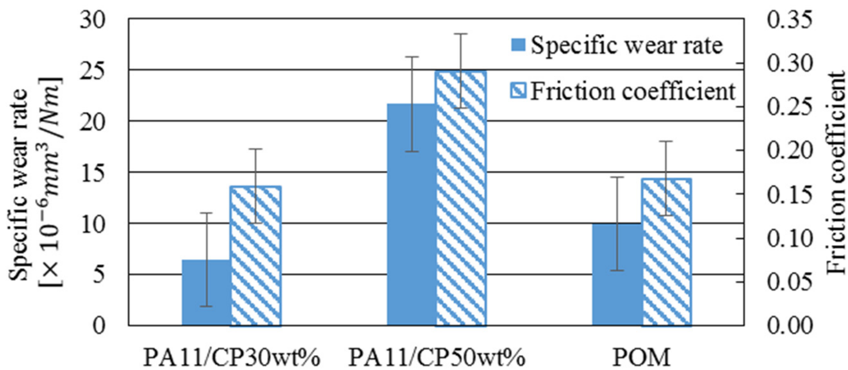
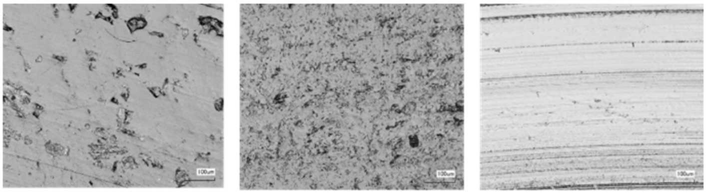


Figure 7: Specific wear rate and friction coefficient of composites under condition 2.

Figure 8 shows microscope images of the wear surface of the PA11 composites. According to Figure 8, in comparing the wear surface of PA11/CP30wt%, it was found that the one of PA11/CP50wt% is rough. It is suspected that both values (friction coefficient and specific wear rate) of PA11/CP50wt% got worse because the composite was softened by the sliding heat generation. During the friction-and-wear test, the highest temperature of the mating sliding member was about 105°C under the condition of PA11/CP30wt%, and the other was about 130°C under the condition of PA11/CP50wt%. Due to a heat distortion temperature of pure PA11 is about 145°C, it is likely that the temperature of PA11/CP50wt% has reached the heat distortion temperature of the matrix, PA11. The reason that the difference of the temperature of the mating sliding member was explained as follows: many holes called "rumen" exist in the CP as a natural fibre. Since a thermal conductivity of the internal of the rumen is low, the thermal conductivity of the PA11 composite decreased with increasing CP content [11]. As this result the temperature difference between PA11/CP30wt% and PA11/CP50wt% occurred due to the sliding heat generation generated on the sliding surface had become difficult to escape.

As stated earlier, it is considered that a Vickers hardness has a significant influence over a wear loss when an abrasive wear (as shown in Equation (4)). However, it was found that the difference of thermal conductivities has also a significant influence over a wear loss due to the sliding heat generation cannot be ignored when both a pressure of the sliding surface and a sliding speed.



PA11/CP30wt% PA11/CP50wt% POM

Figure 8: Micrographs of wear surfaces of PA11 composites under condition 2.

3.5 Thermal conductivity measuring

In the preceding section, it was noted that the difference of thermal conductivities between PA11/CP30wt% and PA11/CP50wt%. Thermal conductivities of the PA11 composites were measured in order to confirm this prediction. As a result of the measuring, the thermal conductivity of PA11/CP30wt% was 0.413 W/(mK), and the other of PA11/CP50wt% was 0.385 W/(mK). It was found that the thermal conductivity of PA11/CP50wt% was lower than PA11/CP30wt%. As discussed previously, it confirmed that the sliding heat generation generated on the sliding surface of PA11/CP50wt% had become difficult to escape. For this reason, the friction-and-wear property of PA11/CP50wt% under condition 2 got worse.

3.6 Friction-and-wear properties under the air-cooled condition

The friction-and-wear test under the air-cooled condition was carried out in order to prevent the sliding heat generation. The several values of PA11/CP50wt% under the non-cooled condition and then under the air-cooled condition were compared. The specific wear rate and the friction coefficient are compared in Figure 9. The microscope images of the wear surface are compared in Figure 10. The highest temperature of the mating sliding member reduced until about 80°C when the test of PA11/CP50wt% under the air-cooled condition, despite the other was about 130°C when the test of PA11/CP50wt% under the non-cooled condition. According to Figure 9, a 77.8% improvement in the specific wear rate and a 22.2% improvement in the friction coefficient were shown by suppressing sliding heat generation. According to Figure 10, it was observed that the smoothly sliding surface because the temperature of the sliding surface was lower than the heat distortion temperature from the result of suppressing the sliding heat generation. As these results, it was found that the friction-and-wear property was improved due to suppressing the sliding heat generation.

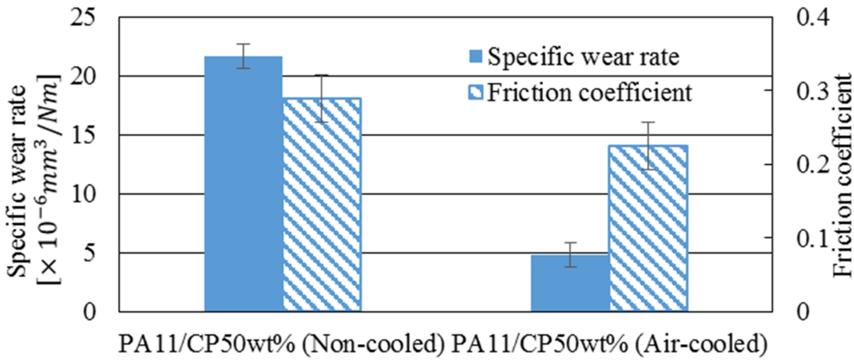


Figure 9: Comparison of specific wear rate and friction coefficient of composites under the condition of the non-cooled and the air-cooled.

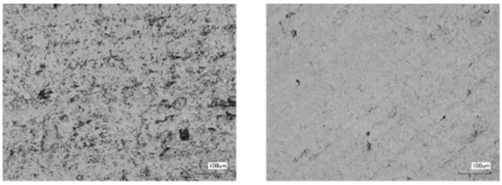


Figure 10: Comparison of micrograph of composites under the condition of the non-cooled and the air-cooled.

4 Conclusion

In order to apply eco-friendly composites to the sliding parts, we made that eco-friendly composite containing PA11 and CP. Furthermore, it was compared with PLA composite or POM; this is a target value. As a result of the friction-and-wear test, it was found that PA11 composite including cellulose had the friction-and-wear performance, which was able to be a substitute for POM. The results we obtain are as follows:

1) The tensile strength and the elastic modulus of PA11 composites tended to increase with increasing CP content. In particular, these properties of PA11/CP30wt% were reached the target values.
2) It was related to the Vickers hardness of the PA11/CP composite that the wear loss of the composite when the friction-and-wear test had carried out under a general test condition, because the wear form called abrasive wear was occurred in the test.
3) It was improved due to suppressing the sliding heat generation that the friction-and-wear property of PA11 composite including high-CP content, because the heat conductivity of composite was low value.

Acknowledgements

This work was financially supported by the Program for the Strategic Research Foundation at Private Universities, 2013-2017, MEXT of Japan. The authors wish to thank Y. Miki for his support in the friction-and-wear test and S. Uemura for his support in measuring specific heat capacity.

References

[1] Chang, L., Zhang, Z., Zhang, H. & Schlarb, A. K., On the sliding wear of nanoparticle filled polyamide 66 composites. *Composites Science and Technology*, **66**, pp. 3188-3198, 2006.
[2] Meng, H., Xie, G. Y., Yang & R., Friction and wear behavior of carbon nanotubes reinforced polyamide 6 composites under dry sliding and water lubricated condition. *Composites Science and Technology*, **69**, pp. 606-611, 2009.
[3] Xian, G., Walter, R. & Haupert, F., Friction and wear of epoxy/TiO_2 nanocomposites: Influence of additional short carbon fibers, *Composites Science and Technology*, **66**, pp. 3199-3209, 2006.
[4] Nagai, M. & Morimoto, K., Enpura-kei ko-bunnshi toraibo materiaru, *Seikei-Kakou*, **25(2)**, pp. 63-67, 2013.
[5] Sato, K., Takeda, K. & Ishikawa, Y., Thermostability and toughness of aramid fiber filled polylactic acid composites. *Seikei-Kakou*, **23(3)**, pp. 175-180, 2011.
[6] Minagawa, T., Takeuchi, T., Arao, Y. & Tanaka, T., Tribological performance of nanocomposites made of environmental harmony type thermoprastic resin. Proc. of *The 5th International Conference on Manufacturing, Machine Design and Tribology*, eds. Jeong, H. & Nitta, I., Korea, p. 27, 2013.
[7] Technical information; Nippon Paper Industries Co., Ltd., www.nipponpapergroup.com/products/chemical/fanctional_chemical/kcflock.html
[8] Chige, H., Ko-bunshi no masatsu-mamou tokusei, *Idemitsu technical report*, **33(3)**, pp. 87-92, 1990.
[9] Uchiyama, Y., Friction and wear of plastics, *Thermosetting resin*, **10(1)**, pp. 10-24, 1989.
[10] Oda, T., Stick slip study for slip friction resin material, *Koyo engineering journal*, **151**, pp. 57-63, 1997.
[11] Takagi, H., Baiobe-su fukugouzairyou gijyutsu, *Seikei-kakou*, **24(8)**, pp. 449-454, 2012.