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Low Friction Coefficient Property of Super Fiber-Reinforced Composites

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Abstract

This paper focuses on using the high strength and low friction coefficient properties of 'super fibers', such as ultra-high molecular weight polyethylene, to develop high performance fiber-reinforced composites with low friction coefficient properties. Dyneema SK60 (an ultra-high molecular weight polyethylene fiber) and three other representative high performance fibers (super fibers), are optimized in combination with an epoxy resin polymer matrix and compression molding to produce new low friction composites. As a result, for the developed four super fiber-reinforced composites, an obvious difference of friction coefficient properties was observed. The friction coefficients of composites across the fiber lay-up were generally lower than those of specimens cut along the direction of the fiber lay-up with a significant fiber direction dependence. The Dyneema fiber-reinforced composite exhibited the lowest and most stable friction coefficient properties. This low friction coefficient may be attributed to a phenomenon of 'reticular residue effect' as the most likely cause. The fiber mass fraction of the composites contributed a significant amount to the anti-friction properties of the materials: samples with a higher fiber mass fraction had a lower friction coefficient. These results indicated that the developed composites described here, with high strength and low friction coefficients, are expected to find wide application in the field of anti-friction parts and energy saving.

Keywords

Low friction coefficient, super-fiber, fiber-reinforced composite, mechanical property

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1. Introduction

Engineering design focuses on maximizing speed and reducing both size and weight to improve mechanical efficiency and save energy. Hence, there is a demand for improved low friction coefficient materials for mechanical parts. High-speed and high-capacity devices require an increased slipping point at high surface pressures. The friction performance at the consequent high surface pressures of traditional white metals has reached a physical limit in such applications. This is evidenced by surface damage from adhesion and sintering phenomena as the heat generated from friction cannot dissipate quickly enough. Moreover, in high-precision applications, such as optical instruments and superconductor coil bobbins [1], precision can be lost or the article damaged due to thermal expansivity from frictional heat. There are clearly increasing requirements for reliable, high-performance, low friction coefficient materials. Polymer-based composites are expected to have suitably low friction coefficients, high strength, low density, low noise, chemical resistance and self-lubricating properties.

Polymer-based bearing materials have been described in the literature [2] as early as the 1930s, and in more recent years, polymer anti-friction materials have found application in fields such as automobile and electrical appliance manufacture. Polytetrafluoroethylene (PTFE) has the lowest friction coefficient of any solid-state material. However, it is not entirely suitable for anti-friction applications because of high abrasion losses, low strength, and low stiffness. There are a few unreinforced PTFE applications, but the polymer is more frequently compounded with reinforcing fibers or inorganic fillers.

Ultra-high molecular weight high-density polyethylene (UHMWHDPE) is a typical anti-friction polymer material [3] with not only a low friction coefficient and high resistance to abrasion loss but also excellent anti-friction properties. The material is used in the manufacture of mechanical parts in diverse applications such as ski parts and artificial hip joints [4] despite its low mechanical strength and low thermal conductivity. However, UHMWPE can be drawn into a high performance fiber that has excellent specific tensile strength and stiffness properties coupled with low density. In addition, importantly for the work described in this paper, the coefficient of friction is low, and the strength and thermal conductivity are high [5, 6]. These fibers are made by a special manufacturing process [7]. These fibers also have good water-resistance and impact-resistance properties [8]. However, despite this, research on the friction properties of UHMWPE fiber-reinforced composites is not highly advanced. This paper describes the development of friction materials with low friction coefficients and high strengths to exploit the inherent characteristics of UHMWPE and high-performance fibers.

In this paper, we have selected four types of 'super fibers' [9] (defined as high-performance fibers with strength >2 GPa and Young's modulus >50 GPa). The fibers are optimally combined with an epoxy resin polymer matrix to produce high performance fiber-reinforced composite with the expectation of low friction coefficients. The UHMWPE fiber Dyneema SK60 [8] and three other high-performance fibers were examined: Zylon HM (a high strength PBO fiber) [8], Technora T241J [10] (a high-tenacity para-aramid fiber) and Torayca T800HB [11] (a high-performance carbon fiber). The work described here focuses on the development of high strength and low friction coefficients using super fiber-reinforced composites and clarifying the friction mechanism for practical industrial applications such as anti-friction parts and energy savings.

2. Experimental

2.1. Materials

Four types of reinforcing fibers were used to produce low friction coefficient composites: Dyneema SK60, Zylon HM, Technora T241J and Torayca T800HB. Table 1 lists the mechanical properties of the fibers [12].

Dyneema SK60 (Dyneema, a registered trademark of Toyobo Co. Ltd., in Japan) is a typical ultra-high molecular weight polyethylene fiber with a specific tensile strength of up to fifteen times that of steel. It is less dense than water and is extremely durable and resistant to moisture, UV light and chemical attack. Particularly, Dyneema has good anti-friction properties coupled with exceptional thermal conductivity [13], and was therefore selected for the work described in this paper.

Three types of reinforcing fibers were selected for comparison. Zylon HM (Toray Co. Ltd.) is a typical high strength PBO (poly-*p*-phenylenebenzobisoxazole) fiber [8]. Technora T-241J (Teijin Co. Ltd.) is a strong para-aramid fiber. It shows little loss of strength even when abraded, flexed and stretched. Torayca® T800HB (Toray Co. Ltd.) is a high performance polyacrylonitrile (PAN) type carbon fiber with excellent mechanical properties (high specific strength and specific stiffness) that also displays the notable characteristics of carbon, namely, minimal deformation due to thermal effects, heat and chemical resistance and self-lubrication.

The epoxy resin (bisphenol-A, JER 827, Japan Epoxy Resins Co. Ltd.) is used as the matrix for four types of composites including DFRP with a saturated aliphatic cyclic acid anhydrous type (HN5500, Hitachi Chemical Co. Ltd.) and accelerator curing agent of imidazole (EK BMI-12, Japan Epoxy Resin Co. Ltd.). The diameter of Dyneema filament is about 12 μm [13].

Table 1.
Fibers with high strength and high Young's modulus

	UHMWPE fiber	PBO fiber	Aramid fiber	Carbon fiber
Strength (MPa)	2200–4800	5800	2400–3500	2000–7200
Young's modulus (GPa)	70–175	180–270	55.7–147	230–700
Density (g/cm^3)	0.97–0.98	1.54–1.56	1.39–1.45	1.74–1.97

2.2. Fabrication

Compression molding [14] was used to fabricate the composites. The pre-wetted fiber pack was placed in the mold and compressed to final form. The excess resin escaped through top and bottom vents. The composite was heated and then cured in the mold for about 2 h, and then the mold temperature was raised to 130°C for 2 h to post-cure the molding. The hardening and curing process was controlled using a thermo-controller (SOFW-450, Asone Co. Ltd.). In this paper, the Dyneema composite will be referred to as DFRP (D means Dyneema, and FRP means fiber-reinforced plastic, 56 wt%), Zylon (59 wt%) composite, Technora (aramid fiber, 76 wt%) composite and Torayca (carbon fiber, 73 wt%) composite will be referred to as ZFRP, AFRP and CFRP, respectively. Figure 1 shows the four sample unidirectional composite specimens and an unreinforced epoxy sample.

2.3. Measurement

The frictional properties of the fiber-reinforced composites were measured using a Friction Player FPR-2100 friction tester (RHESCA Co. Ltd.) with a pin (ball)-on-disk (Fig. 2). The sliding friction coefficients were measured under a specified load.

The specimens were textured to give a uniform friction surface using grades of emery paper from #400 to #2000. The ball (SUS304, 3/16 inches in diameter) was mounted on the head of the pin and the specimen placed on the disk stage of the pin (ball)-on-disk friction tester, and the tests were run under specified loads of about 4.9, 9.8 or 19.6 Newton (N) with close contact between the ball and specimen, equivalent to a linear velocity of 250 mm/s. The frictional force in real-time and the friction coefficient between the ball and specimen were calculated and recorded graphically by computer. The experiments were run in air at room temperature (about 25°C) for about 1800 s. The grinding marks on both the ball and the spec-

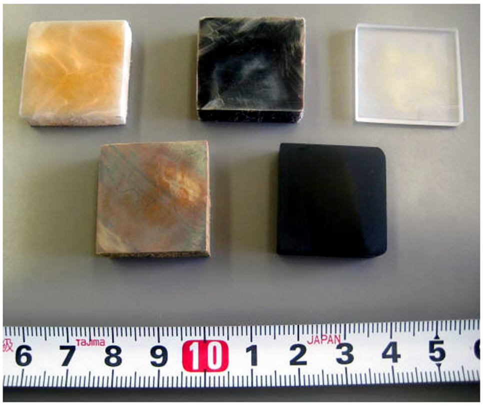

Figure 1. Specimens (from left to right) of DFRP, ZFRP, AFRP, CFRP and unreinforced epoxy resin. This figure is published in color on http://www.brill.nl/acm

imen on the disc were observed by optical microscope (VH-Z100R, Keyence Co. Ltd.) to analyze surface wear.

3. Results

3.1. Friction Coefficient Properties of Fiber-Reinforced Composite

The frictional properties across the fiber lay-up and along the fiber lay-up (Fig. 3) were measured. Figure 4 shows the change in friction coefficient with time for the four types of fiber-reinforced composites at room temperature. In Fig. 4, the average friction coefficient of DFRP across the fiber lay-up is about 0.07, and the average friction coefficient of DFRP along the fiber lay-up is about 0.12. Similarly, the average friction coefficients of ZFRP, AFRP and CFRP across the fiber lay-up and along the fiber lay-up are listed in Table 2. The fluctuation of the friction coefficient across the fiber lay-up for DFRP is much smaller than that along the fiber lay-up

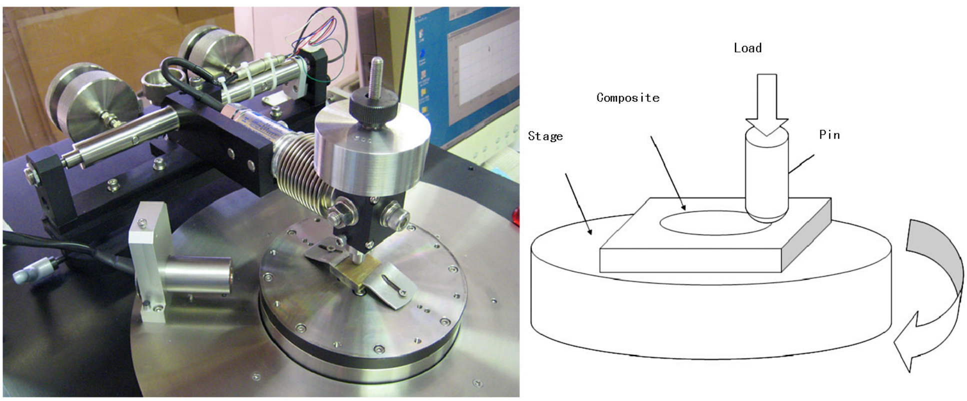

Figure 2. Equipment and schematic diagram of friction experiment. This figure is published in color on http://www.brill.nl/acm

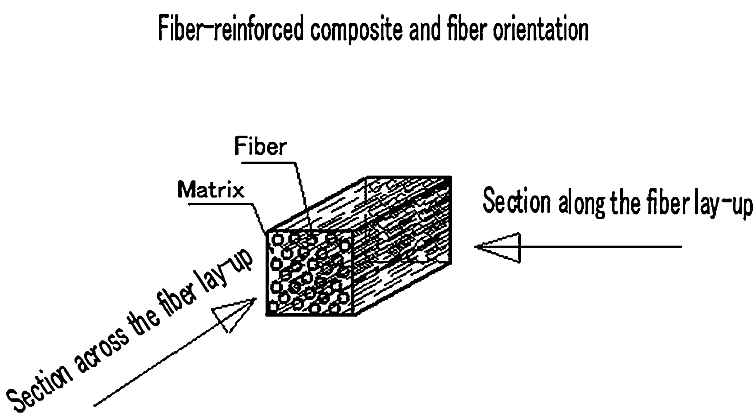

Figure 3. Fiber-reinforced composite and fiber orientation.

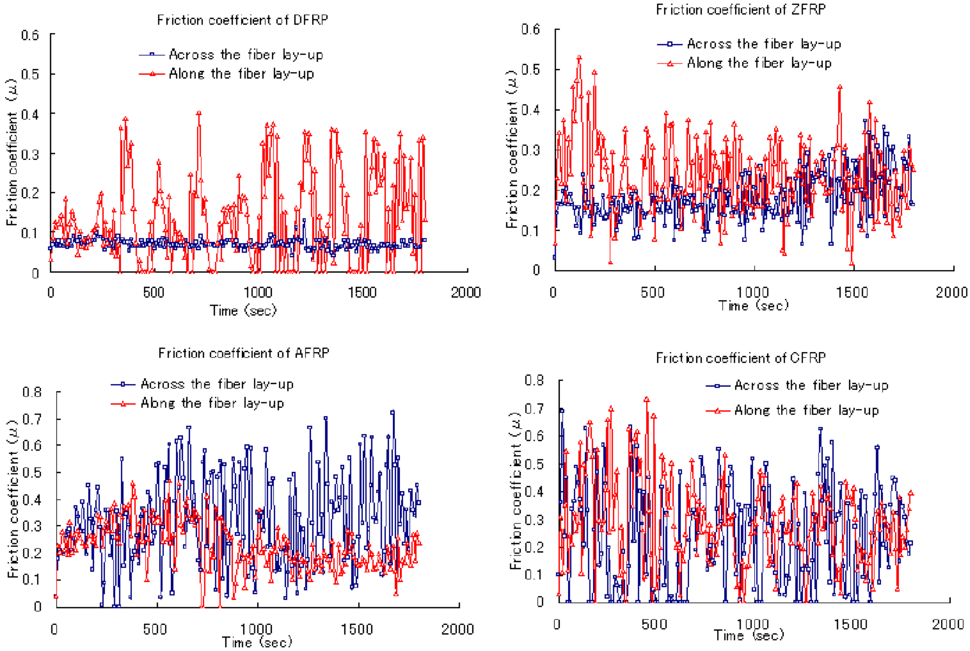

Figure 4. Friction coefficients of DFRP, ZFRP, AFRP and CFRP. This figure is published in color on http://www.brill.nl/acm

Table 2.
Friction coefficient of DFRP, ZFRP, AFRP and CFRP

Orientation	DFRP	ZFRP	AFRP	CFRP
Across the fiber lay-up	0.07	0.18	0.32	0.26
Along the fiber lay-up	0.12	0.23	0.24	0.30

and also smaller than for the other three materials. This may be attributed to the particular property of Dyneema filament, which will be discussed in Section 4.5.

Figure 5 shows a real-time graph of the friction coefficient of the epoxy resin used as matrix in the fiber-reinforced composites. The mean friction coefficient of the epoxy resin is 0.36, far greater than that of the fabricated composites, so the reinforcement fibers in composites play a major role in reducing friction.

3.2. *Microscopic Observation of the Grinding Marks*

The specimens used in the sliding friction experiments were observed by optical microscope. Figure 6 shows the impressions of the pin-ball on the wear surfaces of DFRP, ZFRP, AFRP and CFRP. In the micrographs, impressions of the pin-ball are clearly visible in the wear surface of the fiber cross-section in all specimens. The

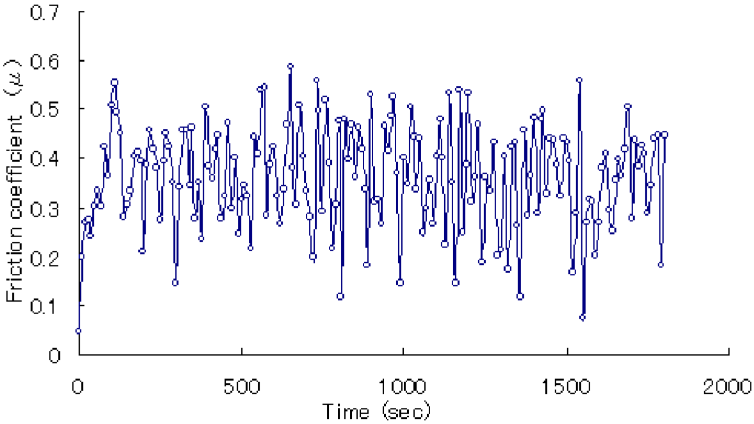

Figure 5. Friction graph of epoxy resin. This figure is published in color on http://www.brill.nl/acm

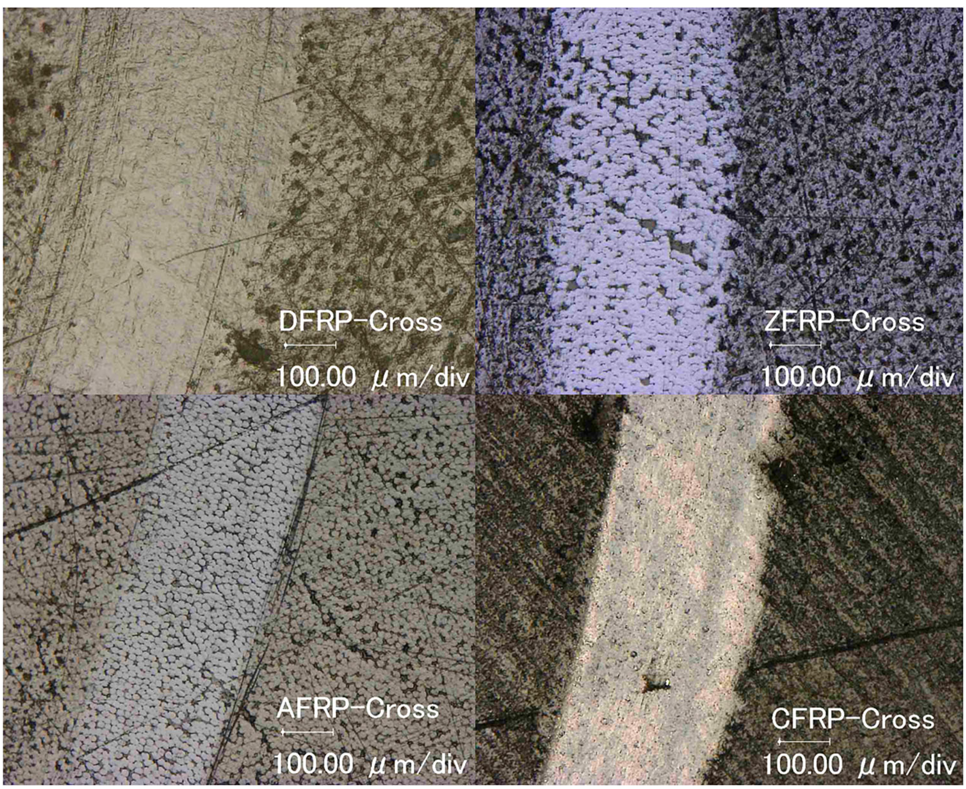

Figure 6. Impression of DFRP, ZFRP, AFRP and CFRP across the fiber lay-up showing the cut ends of the fibers. This figure is published in color on http://www.brill.nl/acm

DFRP specimen shows shallow impressions on the wear surfaces of both fiber cut ends and fiber long axis sections (Fig. 7).

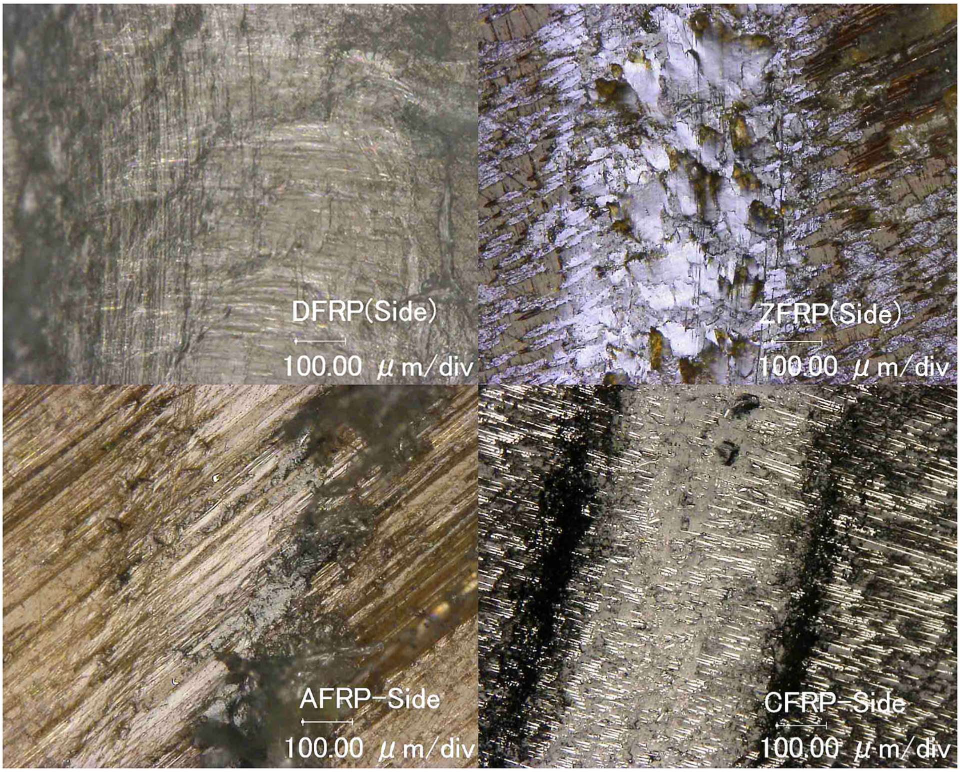

Figure 7. Impression of DFRP, ZFRP, AFRP and CFRP along the fiber lay-up. This figure is published in color on http://www.brill.nl/acm

3.3. Microscopic Observation of the Pin-Balls

Figure 8 shows the wear of the pin-ball between the ball and fiber cross-section of DFRP, ZFRP, AFRP and CFRP. The CFRP shows circular wear patterns typical of friction experiments. In contrast, in the DFRP, ZFRP and AFRP specimens, the wear patterns are not perfect circles. The DFRP, ZFRP and AFRP samples show relatively good friction performance. This is particularly true of the DFRP sample which only left only a slight scar on the ball, showing the least wear of all the samples. Therefore, the results show the same wear trends on both the pin-ball and the fiber-reinforced composite.

4. Discussion

4.1. Comparison of Friction Coefficient Properties across the Fiber Lay-up

Figure 9 shows the friction coefficient across the fiber lay-up of DFRP, ZFRP, AFRP and CFRP at room temperature. The mean friction coefficient of DFRP across the fiber lay-up is about 0.07, the lowest friction coefficient of the four samples. The value of the friction coefficient is much smaller than for the other three materials:

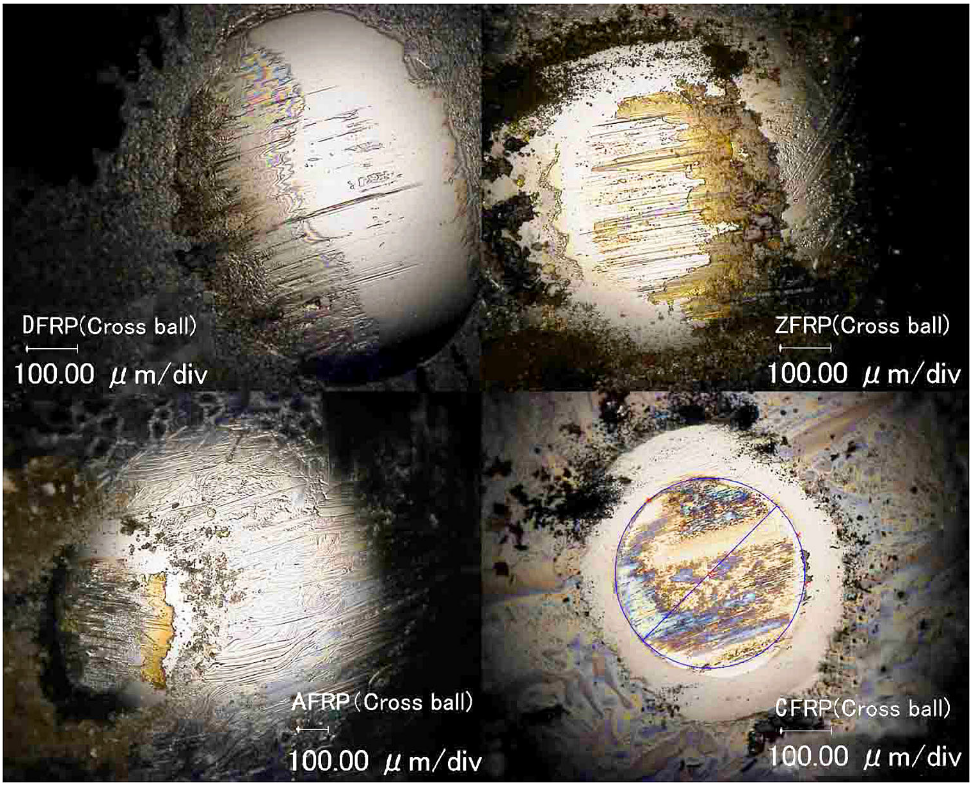

Figure 8. Wear on the ball caused by DFRP, ZFRP, AFRP and CFRP. This figure is published in color on http://www.brill.nl/acm

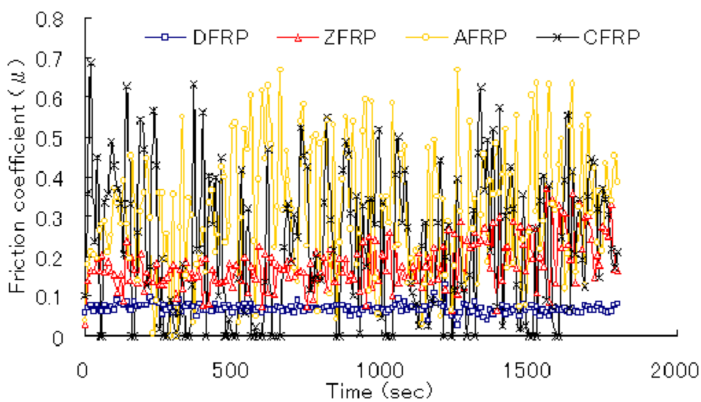

Figure 9. Friction coefficients measured across the fiber lay-up. This figure is published in color on http://www.brill.nl/acm

one-third of the ZFRP ($\mu = 0.18$), one-fifth of the AFRP ($\mu = 0.32$) and one-fourth of the CFRP ($\mu = 0.26$). When friction was observed over a long period of time, fluctuations in the friction coefficient for DFRP across the fiber lay-up are minimal,

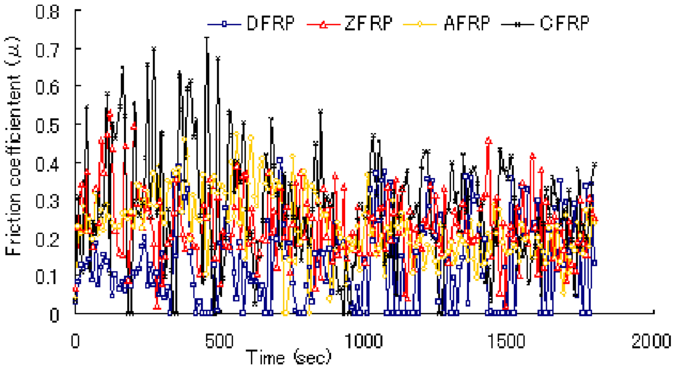

Figure 10. Friction coefficients along the fiber lay-up. This figure is published in color on http://www.brill.nl/acm

showing no trend of increased friction coefficient, while the other three types show great fluctuations and a trend of increased friction coefficient is seen in ZFRP.

4.2. The Comparison of Friction Coefficient Properties along the Fiber Lay-up

Figure 10 shows the friction coefficient along the fiber lay-up of DFRP, ZFRP, AFRP and CFRP. The average friction coefficient of DFRP along the fiber lay-up is about 0.12, the lowest friction coefficient of the four samples. The value of the friction coefficient of DFRP is about half that of the ZFRP ($\mu = 0.23$) and AFRP ($\mu = 0.24$) and less than half that of CFRP ($\mu = 0.30$). The other three specimens also showed a relatively low coefficient of friction, indicating that these super-fiber-reinforced composites have a low overall friction coefficient, when measured both across the cut ends of the fibers and in the direction of the fiber lay-up. However, it should be noted that the average friction coefficient across the cut ends of the fibers was lower than that measured in the direction of the fiber lay-up.

4.3. Effect of Friction Coefficient Properties due to Changes in Fiber Mass Fraction

To clarify the effect of some material factors on friction coefficient properties, the DFRP is chosen as a representative one for super fiber-reinforced composites since its friction coefficient is lowest. The DFRP composite samples were prepared with various mass fractions to examine the effect on friction performance. Figure 11 shows friction coefficients measured across the fiber lay-up of DFRP with Dyneema fibers of 40, 50 and 56 wt%. A force of about 4.9 N on the pin (ball) and a linear velocity of 250 mm/s between the ball and DFRP were used.

The samples of DFRP with higher fiber mass fractions showed lower friction coefficients, and less friction coefficient fluctuation (Fig. 11). Table 3 lists the mean friction coefficients of three mass fractions of DFRP. The trends in the friction coefficients related to change in fiber mass fractions shown in Fig. 12 suggest a linear reduction relationship for the contribution of the fiber mass fraction of Dyneema fibers to the anti-friction properties of the materials.

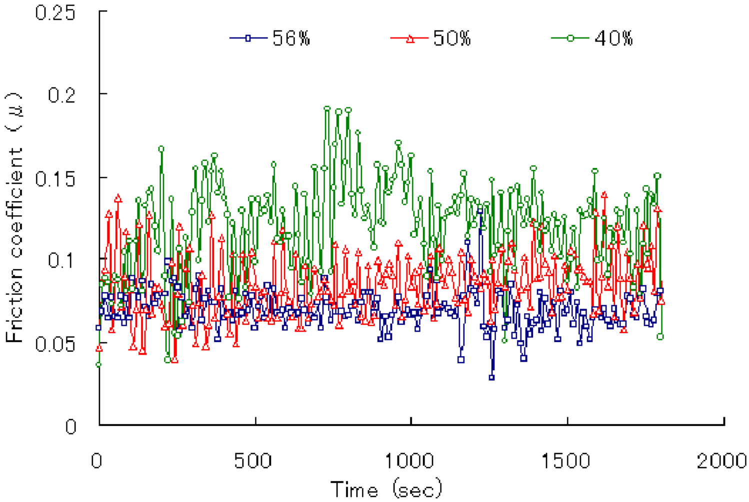

Figure 11. Variation of friction coefficient of DFRP with fiber mass fraction. This figure is published in color on http://www.brill.nl/acm

Table 3.
Mean friction coefficient of DFRP by fiber mass fraction

Fiber mass fraction (wt%)	40	50	56
Mean friction coefficient	0.12	0.09	0.07

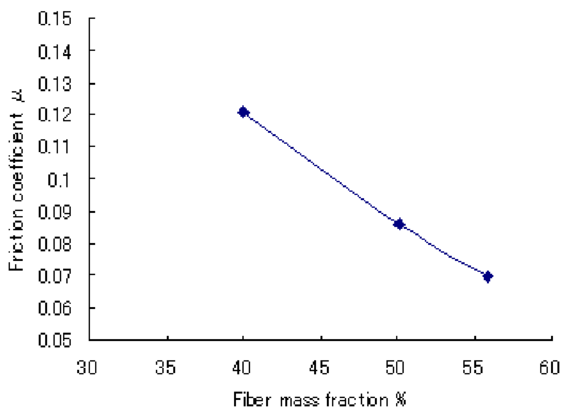

Figure 12. Trend of friction coefficient by fiber mass fraction. This figure is published in color on http://www.brill.nl/acm

4.4. Effect of Friction Coefficient Properties due to Variation in Load Between Pin (Ball) and Specimen

The friction coefficients of super fiber-reinforced composites vary with load between the pin (ball) and the specimen. Figure 13 shows the friction coefficient

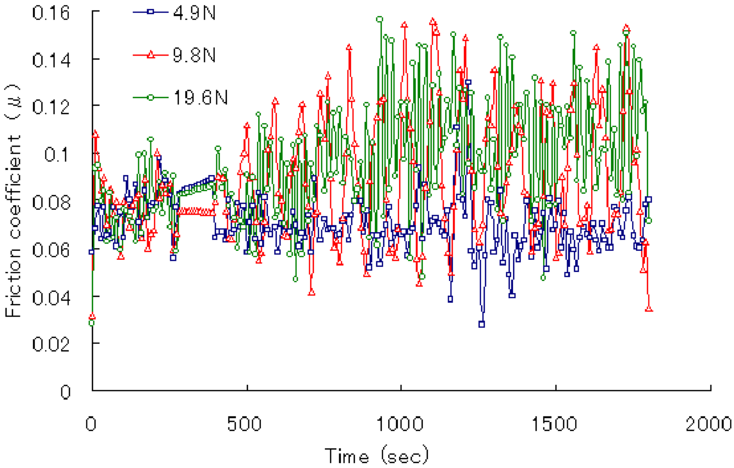

Figure 13. Friction coefficient of DFRP under various loads. This figure is published in color on http://www.brill.nl/acm

across the fiber lay-up of DFRP (56 wt%) under loads of 4.9, 9.8 and 19.6 N at a linear velocity of 250 mm/s between the pin-ball and specimen. Figure 13 suggests that an increase of the friction coefficient and friction coefficient fluctuation is related to the load between pin-ball and specimen.

4.5. The Mechanism of DFRP with Low Friction Coefficient

Ultra-high molecular weight polyethylene fiber (Dyneema) consists of long-chain linear molecules [12] with little short-chain branching, indicating that less frictional resistance may be expected than from low-molecular-weight polyethylene, which consists of short chains and has many branches in the molecule.

Figure 14 shows a photo micrograph of DFRP taken across the fiber lay-up. In the photograph, the white reticulate portion is a cross-sectional view of the fibers (a general cross-sectional view of the fiber is the round mark in the right photo) and the epoxy resin between fibers. The fibers of Dyneema and the matrix are illustrated in Fig. 14(left), and the image of thin bright curves represents the shape of the cross-section after compression molding. Ultra-high molecular weight polyethylene fiber has better friction performance than epoxy resin, so epoxy resin wears faster than the fibers (Fig. 15 shows that the wear measured on the epoxy resin sample is about five times the depth of the wear measured on the DFRP sample). The measurements were made using a Tokyo Seimitsu Co. Ltd., Surfcom 480A tracing driver surface texture-measuring instrument. This indicates that the matrix wears away faster than the fibers, and therefore the contact friction surface will gradually decrease to only the reticular section of fibers exposed. An analogous effect is the role of pebbles between the stone and ice in a curling match. Simultaneously, the role of the epoxy

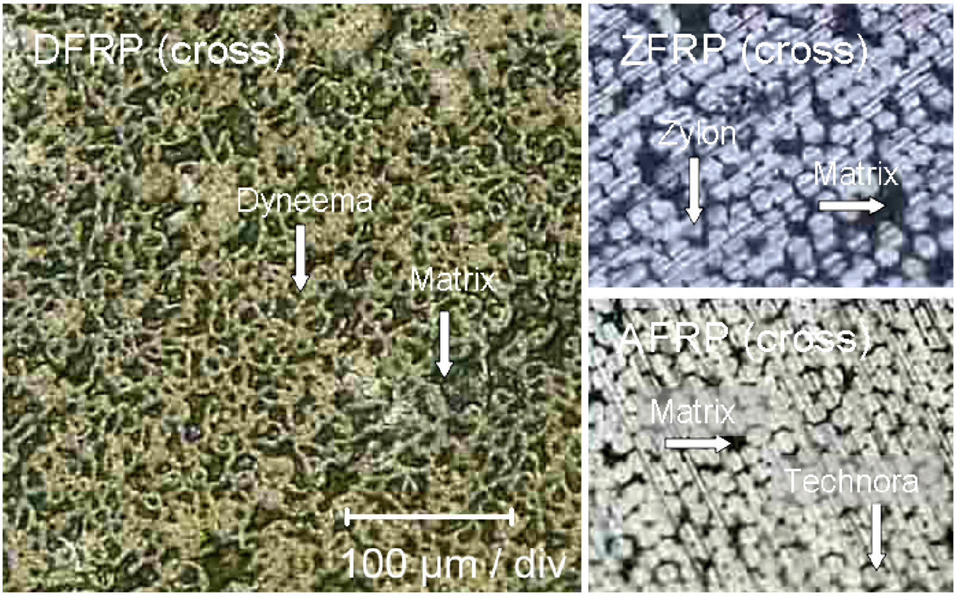

Figure 14. Optical micrographs of cross-sections of DFRP, ZFRP and AFRP. This figure is published in color on http://www.brill.nl/acm

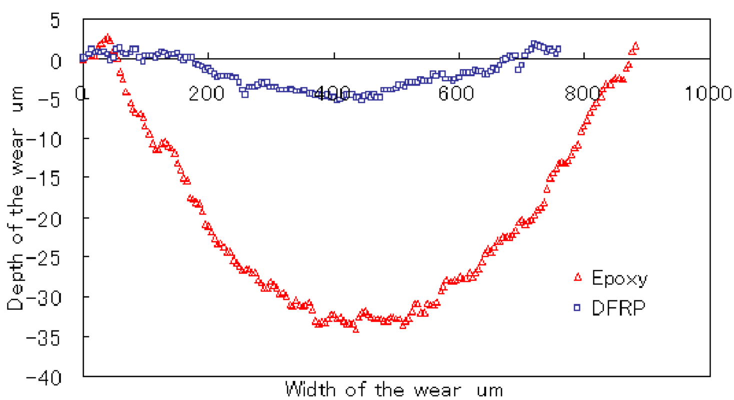

Figure 15. Wear of DFRP and epoxy resin. This figure is published in color on http://www.brill.nl/acm

resin changes to become a support around the fiber (Fig. 16). We call this phenomenon the 'reticular residue effect'.

The friction surface of the reticular section consists of ultra-high molecular weight polyethylene fibers with excellent friction properties. Due to wear losses (mainly epoxy resin) resulting in a reduced friction area, there is a consequent further reduction in friction. This may indicate that the friction force of DFRP is even less than that of the parent ultra-high molecular weight polyethylene fiber for the same size area of friction surface.

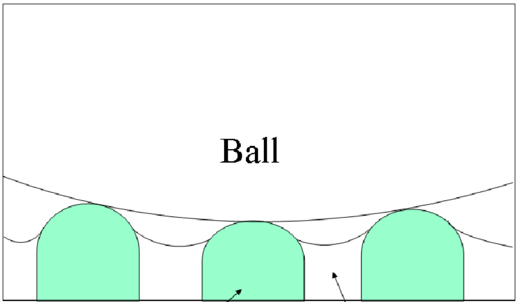

Figure 16. Model of interface between ball and FRP. This figure is published in color on http://www.brill.nl/acm

5. Conclusions

To develop high-performance fiber-reinforced composites with low friction coefficient properties, 'super fibers' (Dyneema, Zylon, Torayca and Technora) and epoxy resin were used to fabricate composite specimens. The developed high-performance fiber-reinforced composites have both excellent friction performance and mechanical properties. It is found that the friction coefficients of composites across the fiber lay-up were generally lower than those of specimens cut along the direction of the fiber lay-up, and a significant fiber direction dependence was observed.

The friction coefficient of DFRP was the lowest among the four composite materials. The fiber mass fraction of the composites contributed a significant amount to the anti-friction properties of the materials: samples with a higher fiber mass fraction had a lower friction coefficient. The novel 'reticular residue effect' phenomenon was observed on the DFRP samples and is a likely important cause for the mechanism of the low friction coefficient of the DFRP.

The work described in this paper indicates that it is possible to extend the application of high-performance fiber-reinforced composites into the field of anti-friction parts with improvements to mechanical efficiency, increased life of industrial components, and energy saving.

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References

1. A. Yamanaka, T. Kashima, S. Nago, K. Hosoyama, T. Takao, S. Sato and M. Takeo, Coil bobbin composed of high strength polyethylene fiber reinforced plastics for a stable high field superconducting magnet, *Physica C* **372–376**, 1447–1450 (2002).

2. S. Uchikawa, Bakelised bearings for rolling mills, *J. Iron Steel* **26**, 526–536 (22nd Symposium of the Iron and Steel Institute of Japan, September 1939) (in Japanese).
3. Mitsuboshi Belting Ltd., MEP® UHMW, Pamphlet N017-C 2002.09 (in Japanese).
4. J. Berzen, H. W. Birnkraut and G. Braun, Ultrahigh molecular weight polyethylene (UHMW-PE): application in artificial joints, *Brit. Polym. J.* **10**, 281–287 (1978).
5. C. L. Choy, Thermal conductivity of polymers, *Polymer* **18**, 984–1004 (1977).
6. C. L. Choy, W. H. Luk and F. C. Chen, Thermal conductivity of highly oriented polyethylene, *Polymer* **19**, 155–162 (1978).
7. Y. Ohta, High strength and high modulus fibers, *Sen'i Gakkaishi* **60**, 270–274 (2004) (in Japanese).
8. Toyobo Co. Ltd., available at: http://www.toyobo.co.jp/e/products/s_sizai.htm
9. T. Hongu, Super fiber with high Young's modulus and high strength, *J. Japan Soc. Mech. Engrs.* **89**, 1427 (1985) (in Japanese).
10. Teijin Co. Ltd., available at: http://www.teijinaramid.com/
11. Toray Co. Ltd., available at: http://http://www.torayca.com/index2.html
12. H. Ishihara and M. Shibaya, The current situation of super fiber in Japan and fiber technology, *J. Textile Engng* **58**, 3–6 (2005) (in Japanese).
13. Information on Toyobo, Dyneema®, Pamphlet (1997) (in Japanese).
14. T. Hayashi, *Engineering Composites*, p. 309. JUSE Press Ltd. (1971) (in Japanese).