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Effects of coal tar pitch addition on the wear behavior of carbon/carbon composites

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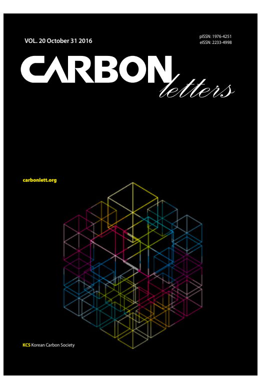

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Carbon/carbon (C/C) composites are acknowledged as high performance materials because of their good mechanical properties such as wear resistance, even at the higher temperature, due to their low thermal expansion [1-5]. Their hardness and light weight in addition to their superior mechanical properties at high temperature make C/C composites the best material to make brakes for aircrafts and other high weight vehicles. Accordingly, a number of studies have been conducted on the performance of C/C composites brake [6-9]. Generally, C/C composites are produced by the carbonization of the matrix precursors of carbon composites. However, some defects, such as porosity and micro-cracks, are also induced during carbonization, and these defects degrde the mechanical properties. Therefore, various methods have been adopted to reduce the development of defects during the manufacture of C/C composites [10-14]. On the other hand, coal tar pitch extracted from the recycling of petroleum-based fuel is relatively inexpensive to manufacture; therefore, it is extensively used as a source of carbon precursors [15-16].

The current study investigated C/C composites reinforced with coal tar pitch. C/C composites were prepared by blending coal tar pitch into phenol resin to densify and reduce the porosity during carbonization. The effect of the coal tar pitch weight percentage on the wear properties of the C/C composites was also investigated.

Carbon fibers were purchased from Taekwang Industrial Co. (Seoul, Korea), phenol resin was purchased from Kangnam Chemical Co. (Seoul, Korea), and coal tar pitch was obtained from GS Caltex (Seoul, Korea).

The phenol resin and the coal tar pitch were blended in a deep bath at 60°C for impregnation during the carbon fiber filament winding process. Unidirectional prepregs of carbon-fiber-reinforced composites were made from the filament winding. The contents of coal tar pitch for the samples were 0 (reference), 5, 10, 20, and 30 wt%, respectively. The produced mixtures were dried for 72 h at room temperature to vaporize the remaining content of methane and moisture. After drying, the prepregs were laminated unidirectionally on a hot press at the rate of 2°C/min up to 180°C over 2 h to make a green body. This green body was then carbonized by the injection of nitrogen gas at the rate of 200 mL/min, and the temperature was raised to 1100°C by 1°C/min over 2 h to make the C/C composites. The resulting composites were machined to 30 mm × 30 mm × 2 mm for the wear test specimens.

The wear properties of the specimens were analyzed by a wear testing machine using the ball-on disk method. A zirconia ball-type tip was used for the test, and the friction coefficient and wear loss data for each specimen were obtained by sliding the zirconia ball on a track of 11.5 mm radius with the speed of 0.04 m/s for 7200 s, and the applied load was 5 kgf. To confirm the reproducibility of the data, tests were conducted five times.

The friction coefficient patterns of the specimens are compared in Fig. 1. It can be clearly seen that the friction coefficients of all the specimens stabilized after 3600 s, and the average friction coefficient along with the error deviation values are summarized in Table 1. As displayed in Table 1, the friction coefficient for the specimen without coal tar pitch is the lowest (0.231). Additionally, for the specimens with 5, 10, 20, and 30 wt%

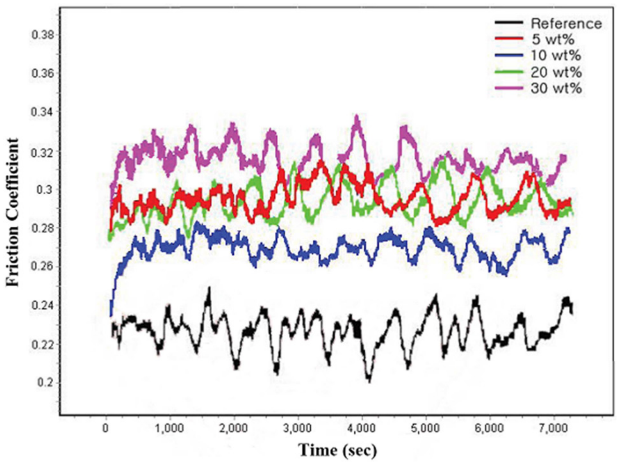

Fig. 1. Change of friction coefficient as a function of sliding distance for each specimen.

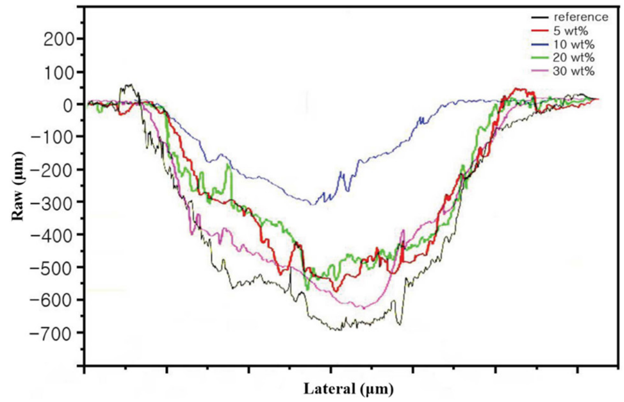

Fig. 2. Wear depth profile measured by surface profilometer for each specimen.

the friction coefficient values are 0.292, 0.274, 0.299, and 0.312, respectively. In comparison to the specimen without coal tar pitch, the specimen with 5 wt% coal tar pitch shows a 26% increase in the friction coefficient, the 10 wt% specimen shows a 17% increase, the 20 wt% specimen shows a 29% increase, and the 30 wt% specimen shows 34% increase. Hence, it can be concluded that friction coefficient increases with a higher coal tar pitch weight percentage, which suggests that the surface of the specimen becomes rougher with the addition of coal tar pitch.

A surface profilometer was used to calculate the wear volume loss of each type of specimen, which was determined by:

$$V = 2\pi rA, \quad (1)$$

where V is the wear volume, r is the wear track radius, and A is the cross section area of the worn surface.

Generally, a material with a low friction coefficient shows less wear volume loss. However, the wear volume loss calculated using the surface profiler on the worn surface (Fig. 2) indicates otherwise. Table 2 presents the wear volume loss related to each C/C composite in relation to the coal tar pitch content. The calculated wear volume loss for the specimen without coal tar pitch was 3.056×10^{-1}, that for the specimen with 5 wt% coal tar pitch was 2.326×10^{-1}, that for the specimen with 10 wt% coal tar pitch was 1.420×10^{-1}, that for the specimen with 20 wt% coal tar pitch was 2.099×10^{-1}, and that for the specimen with 30 wt% coal tar pitch was 2.708×10^{-1}. It can be observed from the table that, in comparison to the specimen without coal tar pitch, the specimens with coal tar pitch showed lower wear volume loss; in particular, the specimen with 10 wt% showed around a 53% reduction in wear volume loss. This may be attributed to the structural weakness of the matrix material without coal tar pitch. Consequently, when the zirconia ball slides on the surface, the matrix is etched out and form debris because of weak bonding, resulting in more wear volume loss. On the contrary, the specimens reinforced with coal tar pitch exhibit better interfacial bonding within the matrix and less wear volume loss.

Similar outcomes showing low friction with high wear rate have been observed in materials such as graphite and polytetrafluoroethylene (PTFE), for which intramolecular bonding is weaker and the shear strength is lower than the applied shear force due to their basic structures [17-20]. Furthermore, among the specimens with coal tar pitch, the specimen with the lowest friction coefficient showed the least wear volume loss. It was found that after reinforcement with coal tar pitch, the surfaces of the specimens became rough. Therefore, as the coal tar pitch content increased, the surfaces of the specimens became rougher, which contributed to the increased friction coefficient and wear volume loss.

To compare the fracture morphology of the worn surfaces of the specimens, scanning electron microscopy (SEM) analysis was carried out. Fig. 3 shows SEM images of the worn surfaces of the specimen without coal tar pitch and the specimen reinforced with 10 wt% coal tar pitch. The SEM image

Table 1. Average and deviation of the friction coefficients

	Reference	5 wt%	10 wt%	20 wt%	30 wt%
Average friction coefficient (μ)	0.231	0.292	0.274	0.299	0.312
Deviation of friction coefficient (μ)	0.22–0.24	0.28–0.30	0.26–0.28	0.28–0.31	0.3–0.32

Table 2. Wear volume loss of each specimen

	Ref.	5 wt%	10 wt%	20 wt%	30 wt%
Wear volume loss (cm^3)	3.056×10^{-1}	2.326×10^{-1}	1.420×10^{-1}	2.099×10^{-1}	2.708×10^{-1}

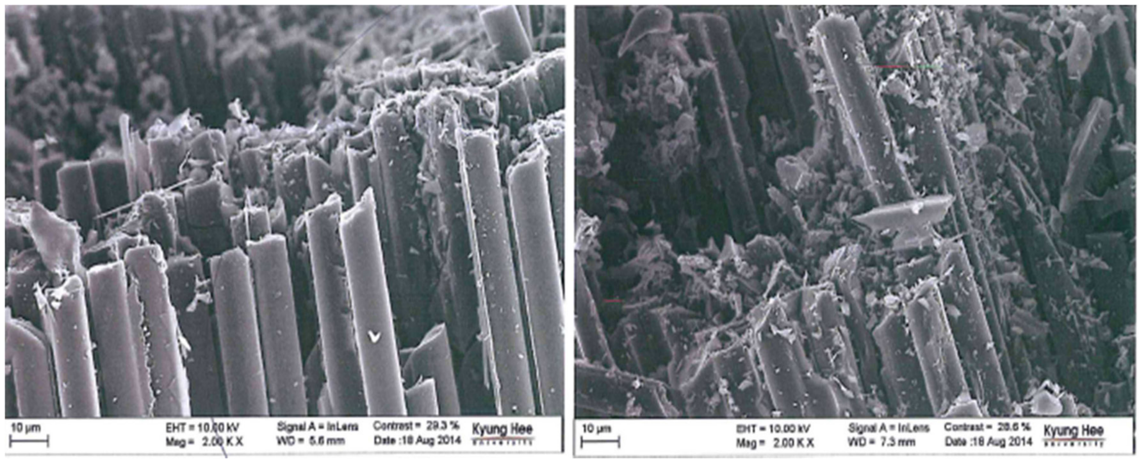

Fig. 3. Scanning electron microscope images of the worn surfaces of (a) reference composites and (b) 10 wt% coal tar pitch composites.

of the specimen without coal tar pitch (Fig. 3a) displayed poor interactions between the carbon fibers and the matrix, which led to the breakage of the carbon fibers and ultimately, the matrix.

On the other hand, the specimen with 10 wt% coal tar pitch (Fig. 3b) showed improved interactions and adhesion between the matrix and the carbon fibers and less breakage of carbon fibers in comparison to the specimen without coal tar pitch. However, debris formed by the matrix cracking was also observed, which may explain the rougher surface that leads to an increased friction coefficient. Altogether, the SEM observations validate the conclusion that reinforcement with coal tar pitch in the matrix leads to a higher friction coefficient but lower wear volume loss. However, the wear volume loss starts increasing for specimens containing more than 10 wt% of coal tar pitch.

The effects of the coal tar pitch reinforcement on the wear characteristics of C/C composites were investigated with variation of the coal tar pitch weight percentage to 5, 10, 20, and 30 wt%. This study obtained the following results. The friction coefficient of the C/C composites increased after reinforcement with coal tar pitch. On the contrary, the wear volume loss decreased after the coal tar pitch reinforcement. The specimen reinforced with 10 wt% of coal tar pitch displayed the lowest wear volume loss of 53% in comparison to the specimen without coal tar pitch. This occurred because the matrix debris enhanced the friction coefficient, while less carbon fiber breakage in the coal tar pitch reinforced matrix led to a lower wear volume loss. Moreover, when the coal tar pitch content was increased to more than 10 wt%, the wear volume loss started increasing. Based on these results, we conclude that the optimum weight percentage of coal tar pitch in a C/C composite is 10 wt%.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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