The Korean Journal of Ceramics, 4 [3] 193 - 198 (1998)

Fabrication and Inertia Dynamic Friction Properties of Pitch-based Carbon-Carbon Composites

Jinyong Lee, Dong-Soo Suhr, Yun-Soo Lim* Seung-Goo Lee and Jong-Kyoo Park*****

Department of Materials Engineering, Chungnam National University, Taejon 305-764
** Department of Inorganic Materials Engineering, Myong Ji University, Yongin, Kyunggi-do 449-828*
*** Department of Textile Engineering, Chungnam National University, Taejon 305-764*
**** 4-5-3, Agency for Defense Development, P.O. Box 35-4 Yusong, Taejon 305-600*
(Received April 13, 1998)

This paper presents the effects of an initial braking velocity, a braking pressure, and the number of braking stop on the tribological behaviors for the three different C-C composites using an inertia dynamic-friction tester. The C-C composites were prepared through the processes of several cycles of pitch impregnation/carbonization with different friction surface textures such as continuous 8-harness satin fabric (ADD-1), chopped fiber (ADD-2) and chopped fiber (ADD-3) having higher fiber volume fraction on friction surface than ADD-2 by about 10%. ADD-1 exhibited a higher friction coefficient (0.41~0.33) than those of ADD-2 and ADD-3 (0.32~0.26) under the various initial braking velocities and braking pressures. The friction coefficients decreased with increasing the initial velocity and the braking pressure. Wear rate by the thickness change after every 25 stop indicated that ADD-2 and ADD-3 having 1.7~2.7 μm/stop/pair were much lower than that of ADD-1 showing 5.0~6.5 μm/stop/pair. All specimens showed a little bit lower wear rate during the middle stage than the initial and latter stages among 100 braking stops. ADD-1 showed higher friction coefficient and wear rate due to the active pull-out of the fibers, evidenced by thicker wear film and wear debrises.

Key words : Carbon-carbon composites, Inertia dynamic friction coefficient, Wear rate

I. Introduction

Carbon-carbon composites (C-C) have been considering the best choice as an advanced aircraft brake disk materials on account of their low density, excellent thermo-mechanical and high wear resistance due to self-lubricating capability.[1-4] From the start of the application of C-C brake disks on the F-14 in 1973, many advanced fighters, such as the US F-15, F-16 and F-18 and Russian fighter MIG-29 and French Mirage 2000, as well as civilian aircrafts such as the Boeing-747, 757, 767, Airbus, Concorde etc. have been emplying C-C brake disks.[5]

The advanced aircraft brake system is composed of multiple brake disks with rotors sandwiched between stators, which are engaged by hydraulic system. During braking, brake disks should absorb high friction heat converted from stopping energy in order to protect other landing systems and release the heat into the atmosphere effectively.[6] The assembly is usually heated up to 600°C in normal condition and higher than 2000°C under the rejected take-off (RTO) condition.[7]

Although C-C composites have been used as aircraft brake disk materials for years, only few papers are discussing the friction and wear behaviors of C-C brake disk. A reason for this is that much of the research and development have been carried out by industry, where patent protection is necessary.

In order to utilize the full potential of C-C composites as brake materials it is necessary to understand not only the interactions between the tribological behaviors and intrinsic properties of the materials but also the test conditions, such as friction speed and pressure.

In this experiment, three different kinds of C-C composites having different friction surfaces such as continuous 8-harness satin fabric (ADD-1), chopped fiber (V_f= 45%, ADD-2) and chopped fiber with higher volume fraction (V_f=55%, ADD-3) were prepared and inertia dynamic friction tests were carried out in terms of initial braking speed, braking pressure and number of braking stops.

II. Experimental procedure

The C-C composites used in this experiment were prepared by processes of pitch impregnation and carbonization. Table 1 shows the specimen designations, density, heat treatment temperature and friction surface conditions for the three kinds of C-C composites. All samples were fabricated by using a high strength PAN-based carbon fiber (ACELAN TZ-307, 12K, Taekwang Co. Ltd. Korea) as a reinforcement (Table 2) and a coal-tar pitch as a precursor of matrix (Jungwoo Co. Korea). The friction surface and the load-bearing part of the ADD-1 were composed of an 8-harness satin texture whereas

Table 1. Three Different C/C Composites Tested in This Study

Designation	Density (g/cm^3)	Matix precursor	Friction surface	Impregnation & carbonization	Heat treatment (°C) (3 times)
ADD-1	1.77	Coal-tar pitch	Continuous fabric(8HS)	0.001 psi/735 psi	2100
ADD-2	1.78	Coal-tar pitch	Chopped fiber(0.5-2 mm)	0.001 psi/735 psi	2100
ADD-3	1.79	Coal-tar pitch	Chopped fiber(0.5-2 mm)	0.001 psi/735 psi	2100

Table 2. Properties of ACELAN TZ-307 Carbon Fiber Used in this Study

Tensile strength (MPa)	Tensile modulus (GPa)	Elogation (%)	Density (g/cm^3)	Filament diameter (μm)	Thermal expansion (10-6/°C, ∥)
3700	245	1.3	1.8	6.8	-0.1

the friction surfaces and load-bearing parts of the ADD-2 and ADD-3 were consisted of chopped fibers ranging the length of 0.5~2.0 mm and an 8-harness satin weave, respectively. The fiber volume fraction of the friction surfaces were about 65% in ADD-1 and about 55% in ADD-3 which is higher by about 10% than that of the ADD-2. Five times of pitch impregnation and carbonization under the conditions of vacuum of 0.001 psi and 735 psi pressure were repeated to obtain desired density. The carbonizations were conducted at 1000°C between every impregnation with a holding time of 1 hour in the inert atmosphere. Three times of graphitization after the carbonization steps of the 1st, 3rd and 5th were performed at 2100°C. C-C composites with the desired density were machined according to the disk drawings.

The microstructure and crystallization of the each C-C composites were examined using an optical microscope (Nikon Optiphot 150) and X-ray diffractometer (JDX-8030, Cukα, 40 Kv).[8] A scanning electron microscope (Hitachi S-2350) was used to examine the worn friction surfaces after friction test. In order to draw out the correlation between a wear behavior and a hardness, the hardness of friction surfaces was measured using a hardness tester (Wilson, Rockwell series 500) under the test condition of 15-T scale giving major load 15 kgf and minor load 3 kgf with 1/16" steel ball indentor.

The specimens pairing with a rotor and a stator used for the inertia-dynamic friction test were 75 mm in OD, 53 mm in ID and 14 mm in thickness, respectively and the tests were performed using a small-scale inertia dynamo-friction tester in air. The test aimed to evaluate the effect of the initial rotating speed on the friction and wear properties was conducted at 4500 RPM, 5000 RPM and 5500 RPM, respectively, at 8.0 kg/cm^2 pressure. The effects of the braking pressure were investigated at 6.0 kg/cm^2, 7.0 kg/cm^2, and 8.0 kg/cm^2, respectively, under the fixed 5500 RPM. In order to evaluate the change of wear property and the reliability along with the number of stop, 100 stop tests were performed with evaluating wear properties at every 25 stops under the conditions of 8.0 kg/cm^2 and 5500 RPM. All friction coefficients were averages of 25 test runs and calculated from average braking time and the number of a rotor revolution during a test after appling braking pressure. Wear rates were obtained by measuring the thickness change using a micrometer after every 25 stop for the each specimen.

III. Results and discussion

1. Microstructure

The optical microstructure of friction surfaces for the C-C composites are shown in Fig. 1. As shown, ADD-1 contains large pores and matrix rich areas between the warf and fill bundles and many cracks in the interbundle and intrabundles of carbon fibers likely be introduced during pitch pyrolysis. In contrast, ADD-2 and ADD-3 show medium-sized pores ranging about 100~250 μm without large cracks.

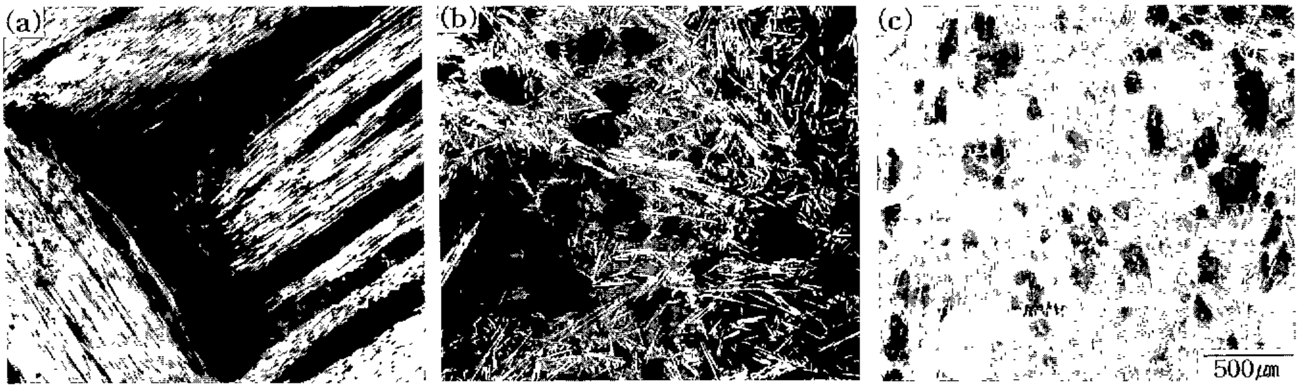

Fig. 1. Optical micrographs of polished friction surfaces of C-C composites (a) ADD-1 (b) ADD-2 and (c) ADD-3.

ADD-1 shows the higher fiber content than the others. Comparing with ADD-2, ADD-3 shows higher fiber content and more homogeneous distribution of pores.

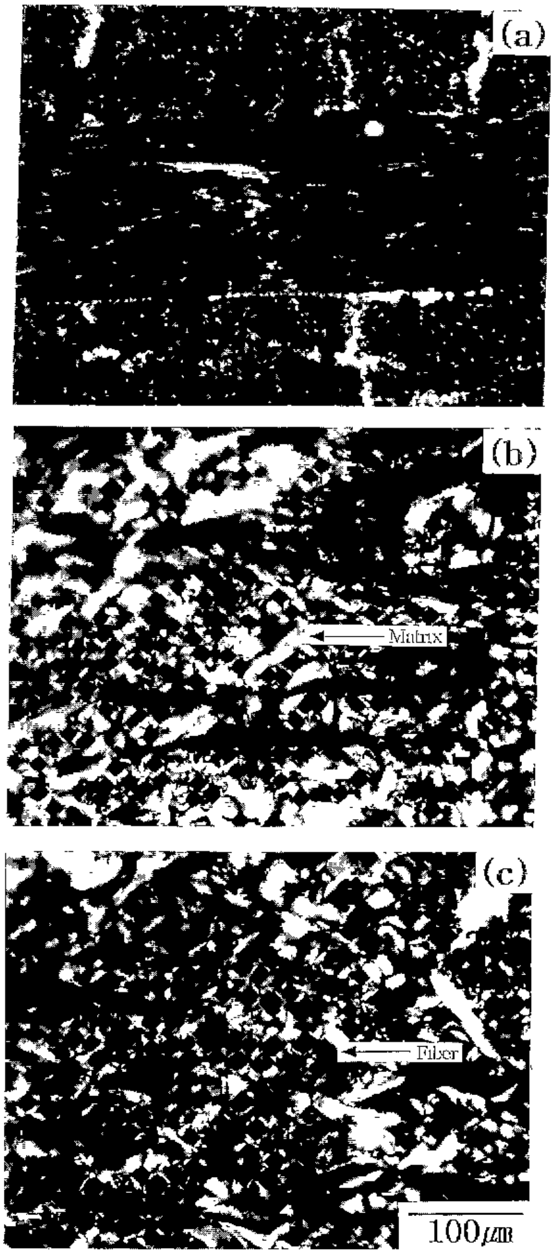

Fig. 2. Polarized light optical micrographs of C-C composites (a) ADD-1 (b) ADD-2 and (c) ADD-3.

Table 3. Structural Parameters of the Three Different C-C Composites Measured by X-ray Diffraction

Parameters / Samples	d_{002}(Å)	Lc(Å)	La(Å)
ADD-1	3.404	96	310
ADD-2	3.373	155	464
ADD-3	3.378	135	406

Fig. 2 shows an anisotropy of the carbon matrix taken at right angles to friction surface with a polarized light optical microscope. Compared with ADD-3, ADD-2 shows more bright color indicating higher anisotropic by containing higher volume fraction of the pitch-based carbon matrix which is known easier graphitizable owing to the liquid state carbonization than PAN-based carbon fiber used at present experiment. On the other hand, ADD-1 revealed more dark except the matrix rich area than the other composites.

Table 3 shows the interlayer spacing (d_{002}), crystallite stack height (Lc) and crystallite stack width (La) calculated by the Scherror equation.[8] Although there was no considerable difference in d_{002} between ADD-2 and ADD-3, ADD-2 revealed more developed Lc and La which seem to be caused by higher matrix content as shown in Fig. 2. ADD-1 showed the least developed anisotropy which may lead high friction coefficient and high wear rate.

2. *Friction coefficient*

Typical friction torque vs. elasped time under the initial rotating velocity of 5500 RPM and 8.0 kg/cm^2 braking pressure for the C-C composites are shown in Fig. 3. All of the samples showed similar friction torque curves having higher friction coefficient at initial and latter braking than middle stage.

Friction coefficient variations at various initial velocities at a braking pressure of 8.0 kg/cm^2 are shown in Fig. 4. As shown in the figure, all specimens exhibiting high friction coefficients at 4500 RPM decreased slightly with increasing initial velocity and dropped considerably at 5500 RPM. This might be explained by the friction

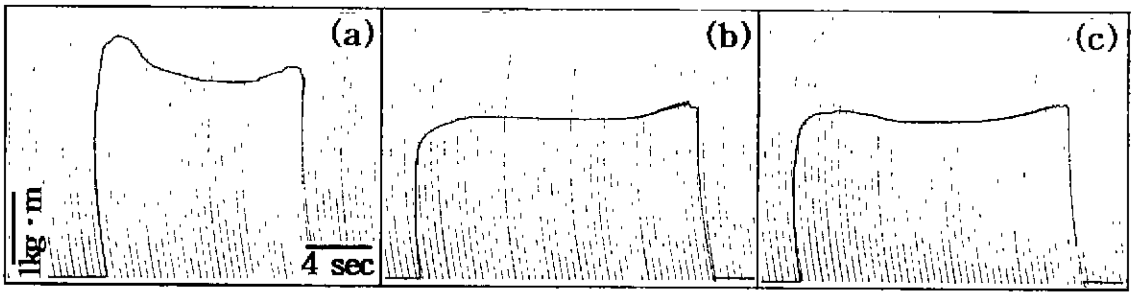

Fig. 3. Friction curves of the three kinds of C-C composites (a) ADD-1 (b) ADD-2 and (c) ADD-3 (X-axis: Elapsed time, Y-axis: Torque).

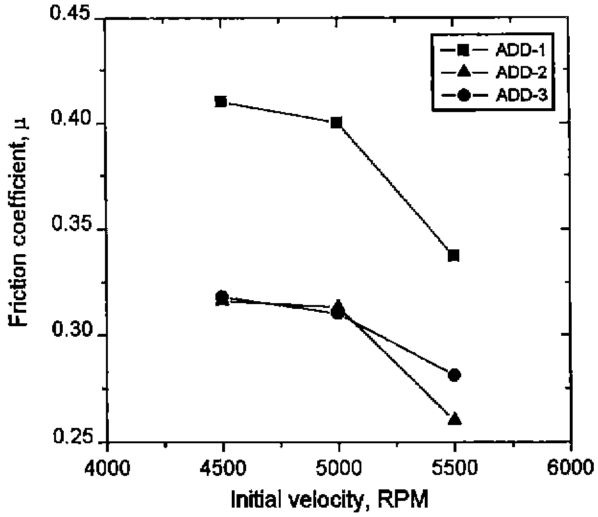

Fig. 4. Change of friction coefficient under the various initial velocity at braking pressure of 8 kg/cm^2.

surface change from particulated wear debrises to film-like owing to the increase of the velocity. With the increase of friction velocity, the kinetic energy to be absorbed by the samples during the test increases the thermo-mechanical work to the certain level which can turn rough friction surfaces into more smooth and flatter leading lower friction coefficient.

Fig. 5 shows the variation of a friction coefficient as a function of braking pressure. Almost no considerable variation of the friction coefficients were observed along with the increase of a braking pressure up to 7.0 kg/cm^2, but friction coefficients showed a tendency to decrease at 8.0 kg/cm^2. ADD-1 showed more decrease of a friction coefficient than the others. These friction coefficient behaviors are coincident in some degree with the previous result insisting on the lower friction coefficient in the higher PV (P : pressure, V : velocity) value in C-C composites.[9]

The higher friction coefficient of ADD-1 can be ascribed to the crimp of fiber warp and weft in the fabric texture placed on a friction surface with some angles.[10] It is known that these crimp angles can give rise to such as a grabbing between the friction surfaces which is known to increase a friction coefficient and a wear rate during real aircraft braking. In comparison with the other samples, ADD-2 showed the lowest friction coefficient under the all test conditions. These behaviors are likely to be from higher content of carbon matrix as depicted earlier which is more graphitizable by a high temperature heat treatment than PAN-based carbon fibers used in this experiment.[11]

3. Wear behavior

Wear rates by the thickness difference under the test conditions of 5500 RPM and 8.0 kg/cm^2 are shown in Fig. 6. While high wear rates of ADD-1 and ADD-2 at initial braking stops decreased at less than about 50 stops, ADD-3 showed a slight increase. From these wear behaviors of an initial stage, about less than 50 stops, ADD-1 and ADD-2 seem to develop wear films on the friction surfaces much easier than ADD-3 owing to low hardness as shown in Table 4. As it were, C-C having relatively low hardness is ground easily and then develops lubricating wear film, thus the decrease of wear rate takes place easier.

In view of the fiber content, ADD-1 should show higher wear resistance and hardness than the others for being higher fiber content, however the wear rate and the hardness of friction surface were the lowest because of, supposely at this time, insufficient content of carbon ma-

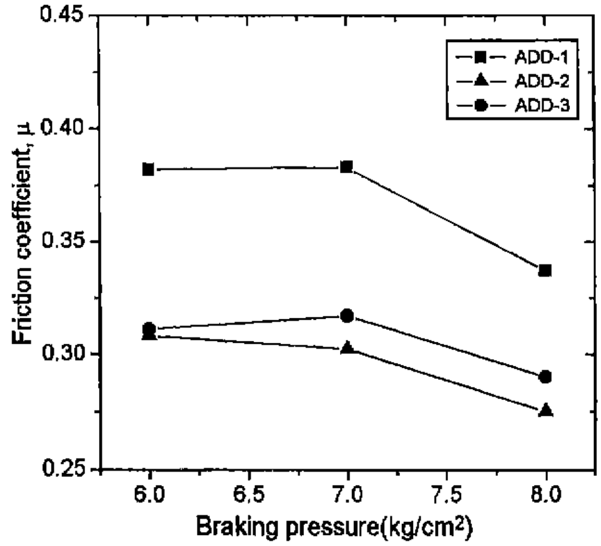

Fig. 5. Change of friction coefficient under the various braking pressure at initial velocity of 5500 RPM.

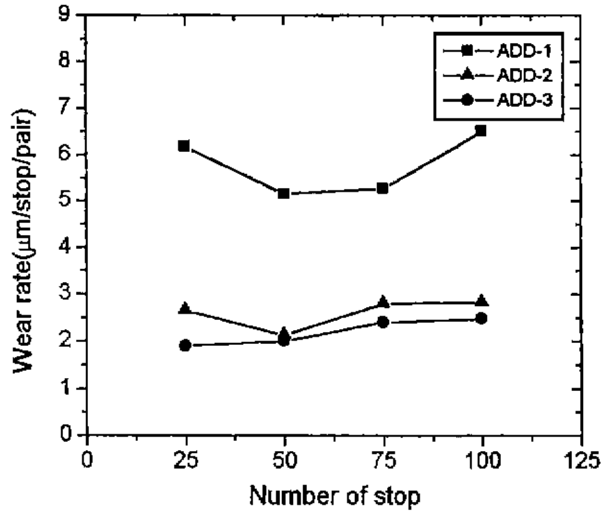

Fig. 6. Variation of wear rate by thickness change for the three different C-C after every 25 stop under 5500 RPM and 8 kg/cm^2.

Table 4. Rockwell Hardness of the Three Different C-C Composites

Hardness / Sample	$HR_{15\text{-}T}$
ADD-1	47.4
ADD-2	60.3
ADD-3	72.3

trix originating from the difficulty of matrix impregnation in the densification among the fibers for fully utilizing the fiber role.[12]

Considering ADD-2 and ADD-3, a friction surface was composed of chopped carbon fibers and owing to the low content of carbon fibers, a pitch matrix impregnation is much easier and thus bonding strength between carbon fibers and matrix seems to be better and results in lower wear rate by reducing such as fiber pull-out. In case of ADD-3, high wear resistance may be ascribed to high content of carbon fiber which retains higher wear resistance than carbon matrix and also enhanced interfacial bonding by the better matrix alignment around the carbon fiber surface than those farther away from the fibers derived from such as stress-induced graphitization.[13]

Photographs of the friction surfaces taken by a SEM after tested at 5500 RPM and 8.0 kg/cm^2 are shown in Fig. 7. As supposed, matrix insufficiency in the intrabundles and matrix rich area between warfs and wefts were on the surface of ADD-1. Also, powdery wear debries and the fiber pull-out appeared. Compared to that of ADD-1, friction surfaces of ADD-2 and ADD-3 exhibited well developed wear films containing slight discontinuity of the films due to pores on the surface. Since in addition to the cause of the breakage of wear

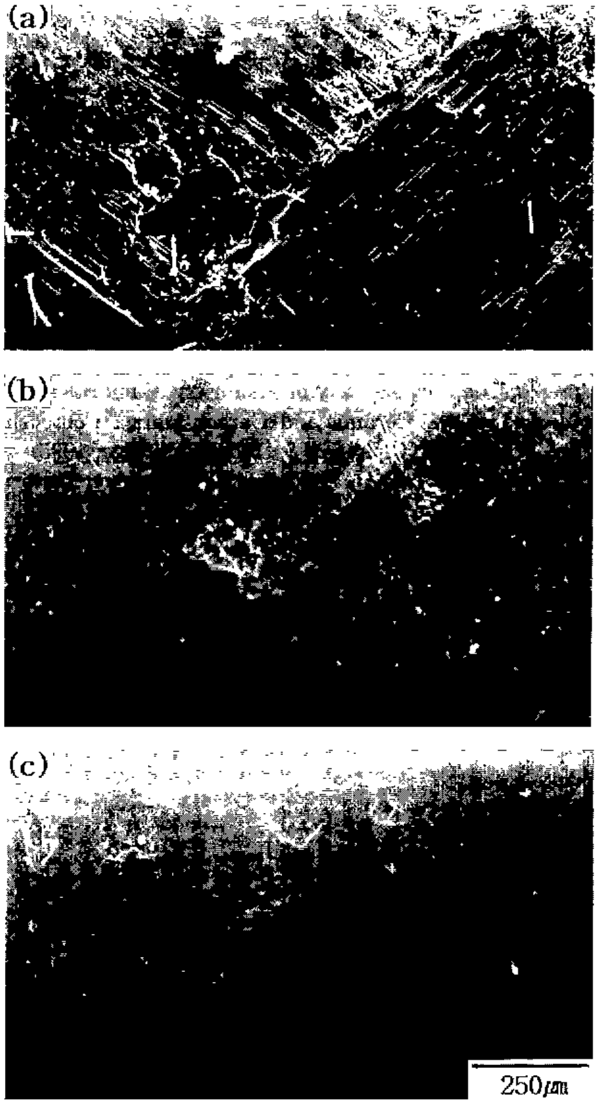

Fig. 7. SEM micrographs showing the worn friction surfaces tested at 5500 RPM and 8 kg/cm^2 (a) ADD-1 (b) ADD-2 and (c) ADD-3.

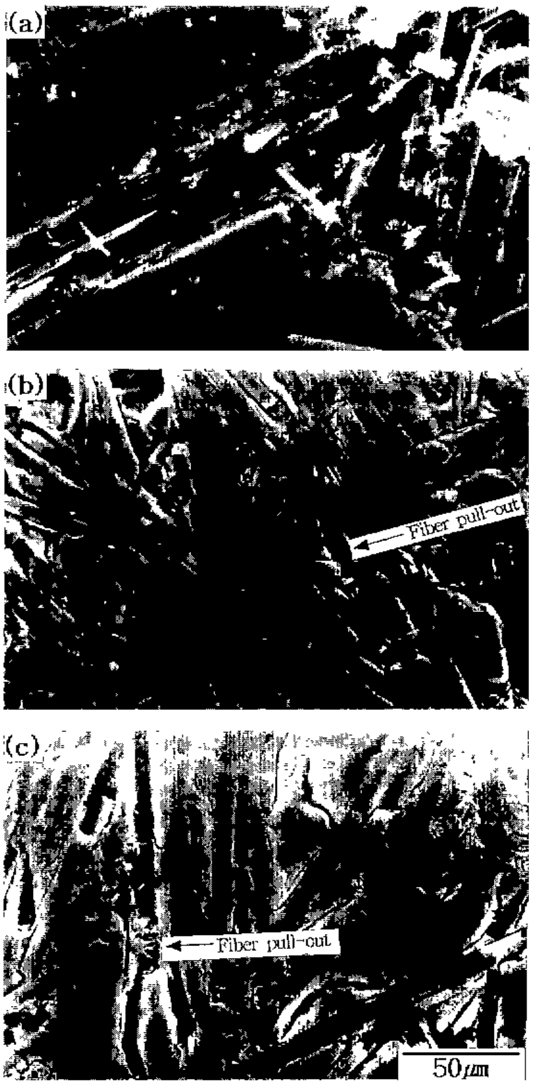

Fig. 8. SEM micrographs showing the fiber pull-out on the friction surfaces tested at 5500 RPM and 8 kg/cm^2 (a) ADD-1 (b) ADD-2 and (c) ADD-3.

films, the pores acting as the diffusion path of oxygen which result in increasing a wear rate by a direct C-C oxidation and materials weakening, should be considered to reduce a wear rate. In Fig. 8, the fiber pull-out traces and the interface debonding were recognizable after tested at 5500 RPM and 8.0 kg/cm^2. Thus, to decrease a wear rate associated with carbon fiber pull-out, the interface characteristics such as the content and microstructure of the primary carbon matrix contacting with carbon fibers directly and likely to be governing the bonding strength should be considered.

IV. Conclusions

Three kinds of C-C composites composed of different friction surfaces were prepared by several cycles of coal-tar pitch impregnation and carbonization. Friction and wear behaviors of the C-C were conducted under the various test conditions such as initial velocity and braking pressure using an inertia friction tester and evaluated from the viewpoint of the microstructure of the friction surface.

Large cracks and pores were observed on the continuous fabric friction surface between the warf and weft and within the fiber bundles due to the fabric geometry and the insufficient pitch impregnation. Friction surfaces consisted of chopped carbon fibers showed smaller and more homogeneous distribution of pores and higher anisotropy, owing to the lower carbon fiber content.

Continuous fabric friction surface showed higher friction coefficient and about 2 times higher wear rate than those of the chopped fiber composites. All specimens exhibited a decrease of friction coefficients with increasing the initial velocity and the braking pressure. The wear rate tending to decrease about within the 50th stop increased along with the test in the 100 stop test.

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