Effect of Surface Texturing on Friction Transition of C/C Composite Material

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Carbon-carbon (C/C) composites are widely used as sliding materials owing to their excellent mechanical properties. However, it is well known that the C/C composites exhibit an unstable frictional behavior called the friction transition, the main mechanism of which remains unclear. In this study we focused on the mechanism of the friction transition by examining the morphology of wear debris obtained using a thrust-cylinder-type tribotester. Moreover, to improve the tribological properties of C/C composites, we discussed the effect of surface texturing. The sliding results suggested that agglomeration of wear debris caused the friction transition. Furthermore, the friction transition was prevented by the effects of surface texturing.

Keywords: C/C composites, tribology, wear debris, surface texturing

1. Introduction

Carbon-carbon (C/C) composites are composite materials in which the carbon matrix is reinforced by carbon fiber. The features of C/C composites include low density, high strength, high toughness, and excellent performance at high temperature. Owing to these excellent mechanical properties, C/C composites are used as brake materials in airplanes and racing cars [1,2]. However, the friction coefficient of C/C composites abruptly increases when two C/C composites are in contact under dry conditions. This phenomenon is generally called the friction transition [1-10]. The friction transition leads to severe wear [1,2], which strongly affects the life of materials. Therefore, the friction transition of C/C composites is a serious problem for sliding materials. Previous works discussed the cause of the friction transition in terms of the effect of wear debris [1,3,5,8-10] or temperature [4,6,7]. The friction transition is similar to the phenomenon of seizure in metal materials, which is generally caused by wear debris. However, the critical reason that the friction transition occurs remains unclear. Therefore, it is important to identify the main cause of the friction transition. In addition, to improve the life of C/C composites when they are used as sliding materials, tribological solutions that prevent the friction transition are required.

It is well known that surface texturing enhances the tribological properties of sliding materials [11-19]. In particular, under dry conditions, surface texturing contributes to stable friction behavior by trapping wear debris on the sliding surface [11,15]. Although many reports have been published on the effects of surface texturing on the tribological properties of sliding materials [17-19], there have been few reports about the C/C composites. We expected that the friction transition of C/C composite material would be suppressed by the surface texturing.

In this study, we investigated the mechanism of the friction transition in detail in terms of the morphology of wear debris by using a thrust-cylinder-type tribotester. Moreover, to improve the tribological properties of C/C composites, we evaluated the effect of surface texturing on the prevention of the friction transition.

2. Experimental details

2.1. Materials

The specimens were made of C/C composites consisting of poly-acrylo-nitrile-type carbon fiber and phenol resin, which were treated at over 2000°C after the carbonization process. The C/C composites had an average surface roughness of 7.95 μm and a density of 1.5-1.55 g/cm³.
2.2. Tribotester and specimens

Figure 1 shows a schematic overview of a thrust-cylinder-type tribotester. A load was applied from under the stator specimen. The rotor specimens were rotated by a motor. The friction coefficient was measured using a torque meter. Figure 2 shows the specimens in the sliding test, which were the stator specimen ($\phi 44 \text{ mm} \times t 10 \text{ mm}$) and the rotor specimens ($\phi 43 \text{ mm} \times t 10 \text{ mm}$). Two types of rotor specimens, flat specimens and those with radial slits were prepared to evaluate the effect of surface texturing. The radial slit specimen has 32 slits placed radially on the sliding surface (width, 1 mm; depth, 2 mm). The apparent contact areas of the flat and radial slit specimens were 533.3 and 392.8 mm$^2$, respectively. In this study, two sliding tests, a constant speed test and step speed test, were conducted under dry contact and atmospheric conditions.

2.3. Test conditions

2.3.1 Constant speed test

Constant speed tests were performed using the flat and radial slit rotor specimens to confirm the effect of surface texturing and to observe the time variation in the morphology of wear debris. The test conditions were a load of 300 N, sliding speed of 500 rpm and sliding time of 10 min after a running-in period (a load of 300 N, sliding speed of 30 rpm, and sliding time of 30 s). The temperature was measured by a thermocouple located 2 mm below the sliding surface of the stator specimen. The wear debris was collected by carbon tape on the sliding surface of the stator specimen before the test, at sliding times of 1 and 5 min, and after the test. The collected wear debris was observed using field-emission scanning electron microscopy (FE-SEM) (ZEISS, GeminiSEM, DE). In addition, the wear volume was calculated from the thickness of the rotor specimens before and after the sliding test.

2.3.2 Step speed test

The step speed tests were performed using three flat specimens, A, B, and C, to clarify the influence of sliding speeds on the friction transition. Those tests were performed under a load of 300 N. The sliding speed was varied after a running-in period (under the same conditions as in the constant speed test) to cause the friction transition easily [2,10]. Figure 3 shows the sliding speed versus the sliding time in the step speed test. The sliding speed was varied in 100 rpm steps and did not exceed 500 rpm for specimen A, 1000 rpm for specimen B, and 1600 rpm for specimen C. The wear debris was collected by carbon tape on the sliding surface of a stator specimen after the sliding test for each specimen. The collected wear debris was observed using FE-SEM. The surface roughness of the sliding surface of each specimen after the test was observed using laser microscopy.

3. Results and discussion

3.1. Constant speed test with flat and radial slit specimens

Figure 4(a) shows the frictional behavior of the flat
and radial slit specimens. In the flat specimen, the friction transition occurred at a sliding time of 460 s, at which the friction coefficient increased dramatically from 0.1 to 0.6. The sliding test was then stopped because of the high friction coefficient. There was no indication of the friction transition in the frictional behavior before the friction transition. In contrast, the friction coefficient of the radial slit specimen was stable at approximately 0.1 during the entire sliding time, and the friction transition did not occur. Figure 4(b) shows the temperature behavior of the flat and radial slit specimens. The temperature of the flat specimen increased dramatically after the friction transition. However, the temperature of the radial slit specimen at the end of the test was higher than the temperature of the flat specimen at the moment when the friction transition occurred. This result indicates that the temperature is not the main reason for the friction transition.

Figure 5 shows SEM images of the wear debris. The wear debris of the flat specimen [Figs. 5(a-d)] was agglomerated during sliding. In particular, the wear debris after 1 min [Fig. 5(b)] was granular and consisted of separate particles. Subsequently, some of the wear debris after 5 min [Fig. 5(c)] was agglomerated. At this time, the friction transition had not occurred. After further sliding, the wear debris after the test [Fig. 5(d)] was completely agglomerated. This wear debris was flat and lustrous, unlike that before the friction transition. In contrast, the wear debris of the radial slit specimen was always granular and consisted of separate particles. The morphology of the wear debris of the radial slit specimen was the same throughout the sliding test.

Table 1 summarizes the wear volume of the flat and radial slit specimens. The results indicate that the wear volume of the flat specimen was much larger than that of the radial slit specimen.

### 3.2. Step speed test with flat specimen

Figure 6 shows the frictional behavior of specimens A, B, and C. The friction transition did not occur in

<table>
<thead>
<tr>
<th>specimen</th>
<th>Flat</th>
<th>Radial slits</th>
</tr>
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<tbody>
<tr>
<td>Change thickness [mm]</td>
<td>0.023</td>
<td>0.001</td>
</tr>
<tr>
<td>Wear volume [mm³]</td>
<td>12.2659</td>
<td>0.3928</td>
</tr>
</tbody>
</table>
specimens A and B. The friction coefficients of specimens A and B were approximately 0.1 after a running-in period [Figs. 6(a,b)]. In contrast, the friction transition occurred in specimen C. The friction coefficient of specimen C was approximately 0.1 until the speed reached 1500 rpm but increased dramatically from 0.1 to 0.6 at 1600 rpm. The experimental results indicate that the sliding speed influenced on agglomeration of wear debris. Figure 7 shows SEM images of the wear debris. The wear debris of specimen A were not agglomerated, and the wear debris of specimen B were partially agglomerated. In contrast, the wear debris of specimen C were completely agglomerated. Furthermore, the reason that the friction transition did not occur under 1500 rpm conditions might be the wear debris did not agglomerate completely. The wear debris were agglomerated completely at 1600 rpm condition. Therefore, the friction transition occurred at 1600 rpm condition. These results indicate that the sliding speed influenced agglomeration of the wear debris. Figure 8 shows the surface roughness ($S_a$), which was measured by laser microscopy of the sliding surface of each specimen. The results indicate that specimen B was slightly smoother than specimen A. In contrast, the surface roughness ($S_a$) of specimen C was much lower than that of specimen B. These results indicate that the surface roughness was much lower after the friction transition before the friction transition.

3.3. Mechanism of the friction transition

A comparison of the wear debris of the flat and radial slit specimens in the constant speed test shows that the friction transition occurred when the wear debris was agglomerated during sliding. Before the friction transition, the wear debris existed as small particles [Figs. 5(b,f-h)]. During this time, the small particles of wear debris acted as a solid lubricant. The existence of this wear debris on the sliding surface contributed to stable frictional behavior. Li et al. mentioned this phenomenon; the rolling ability of nanoparticles could restrict the increase in the frictional force [20]. In contrast, when the wear debris was agglomerated during sliding, the small particles of wear debris were gradually lost, and the sliding surface gradually became smooth [Fig. 8]. The density of wear debris on the sliding surface increased when the amount of wear debris increased. At this time, the wear debris would adhere to other wear debris and squeezed by the frictional shear stress. As a result, these wear debris might be agglomerates each other. When agglomeration of wear debris covered the entire sliding area, the small particles of wear debris were completely lost, and the sliding surface became quite smooth. The smooth sliding surface might cause the increase in adhesion force due to the increasing of real contact area. Accordingly, the friction coefficient increased suddenly owing to the increased adhesion force, and the friction transition occurred. Figure 9 shows a schematic of this phenomenon. Consequently, it was confirmed that the main cause of the friction transition is agglomeration of wear debris.

3.4. Effect of surface texturing

The friction transition did not occur in the radial slit specimen. Considering the mechanism of the friction transition, the friction coefficient was stable at
approximately 0.1 because the wear debris of the radial slit specimen always existed as small particles. The wear debris was not agglomerated because it was ejected from the sliding surface through the slits by centrifugal force. The density of the wear debris decreased, suppressing its agglomeration. Consequently, the friction transition was prevented by the effect of surface texturing. Although the radial slit specimen has many slits, its friction coefficient was the same as that of the flat specimen. Furthermore, the wear volume of the radial slit specimen was smaller, which is consistent with previous work [1,2]. These results indicate that surface texturing prevented the friction transition and reduced the wear volume, maintaining the brake performance. This demonstrates that the tribological properties of the C/C composite are improved by surface texturing.

4. Conclusions

The main reason for the friction transition in a C/C composite and the effect of surface texturing on prevention of the friction transition were investigated. The main conclusions are as follows:

• A constant speed test shows that the friction transition occurred when the wear debris was agglomerated during sliding. In contrast, when the wear debris was not agglomerated during sliding, the friction transition did not occur. The main cause of the friction transition is agglomeration of wear debris.

• It is confirmed that the wear debris before the friction transition existed as the small particles. On the other hand, the wear debris after the friction transition completely agglomerated. It considered that such morphological change of wear debris is the key factor for the friction transition.

• The friction transition did not occur in radial slit specimens, which confirmed that surface texturing can prevent the friction transition. This is because agglomeration of wear debris was suppressed by the effect of surface texturing. As a result, the tribological properties of the C/C composite were improved by the effect of surface texturing.

Reference


