DAMAGE EVALUATION IN PAPER-BASED FRICTION MATERIALS SUBJECTED TO COMPRESSIONAL LOADING

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1 Introduction
A clutch in a vehicle is a mechanical device which provides for power transmission from an engine to wheels, when engaged. Recently, the paper-based friction material which is composed of some kinds of fiber, such as aramid and cellulose, and phenolic resin is used for clutch discs of automatic transmission. The mechanical performance of friction material has been improved so as to achieve high-efficiency power transmission. It is demanded that friction materials have a variety of superior characteristics. For example, high friction properties and high wear resistance are desired to improve the ability of power transmission. High anti-judder performance, heat resistance and strength are also needed to guarantee their reliability in operation. The friction materials should be developed to optimize these performances.

To produce paper-based friction materials with high performances, many investigations have been performed. The friction properties[1-3], contact characteristics between friction materials and other materials[4-7] and dynamic compressive behavior[8-11] were investigated. For the strength evaluation, the effect of porosity on fracture strength[12-15], and fatigue property under compressive loading[16] were examined. The authors carried out the in-plane tensile tests by using smooth and notched specimens[17] and out-of-plane fracture toughness tests by using double cantilever beam specimen[18] to evaluate mechanical properties of the paper-based friction materials. Moreover, the shear-compressive fatigue tests were also carried out to investigate the fatigue strength of paper-based friction material and the influence of constituents on fatigue strength[19, 20]. This shear-compressive loading condition was regarded as a real loading condition in automotive automatic transmissions. It was found that the fatigue strength was very high when the compressive stress was dominant under shear-compressive loading. On the other hand, in automobile industries, a conventional compression test[16] has been conducted in order to evaluate the fatigue strength of paper-based friction materials. The authors also conducted the conventional compressive tests at room temperature in air and investigated the fatigue behavior of the friction materials composed of aramid fiber and phenolic resin, and cellulose fiber and phenolic resin. Figure 1 shows the thickness reduction as a function of the number of load cycles. The reduction of thickness is normalized by the original thickness. The thickness of both materials decreases with increasing the number of cycles. The aramid- and cellulose-based materials are broken at about $10^6$ and $10^5$ cycles, respectively. In the fatigue tests and conventional tests which we conducted, the fatigue mechanism of the friction materials was not clarified because it was difficult to evaluate damage evolution due to their complicated microstructure.

This paper deals with the investigation of damage behavior in paper-based friction materials under out-of-plane compressive loading. The influence of...
compressive stress on damage behavior was examined by measurement of the number of damage sites and length of damage by cross-section observation of friction materials. The influence of constituents on damage evolution was also investigated.

2 Experimental Procedure
2.1 Material and Specimen
The materials used are aramid- and cellulose-based materials. The aramid- and cellulose-based material are composed of aramid fibers and phenolic resin, and cellulose fibers and phenolic resin, respectively. Table 1 shows the constituents and porosity of both materials. The materials include the fibers of 70wt% and phenolic resin of 30wt%. The porosity was measured by a mercury intrusion technique.

Figure 2 shows the specimen geometry for out-of-plane compressive loading test. The thickness of both materials is 1.1±0.1mm. The materials were cut into square shape with 10mm on a side. Preliminarily, a flat cross-section was formed by a cross-section polishing machine (CP) to observe the cross-section by a scanning election microscope (SEM). Figures 3(a) and (b) show the cross-section of the aramid- and cellulose-based materials, respectively. The aramid-based material is composed of thick and thin fibers. On the other hand, the cellulose-based material is composed of thick fibers.

2.2 Cyclic Compressive Loading Test
The out-of-plane compressive loading tests were carried out in order to investigate the mechanical properties under the compressive loading and the influence of compressive stress on damage behavior in the paper-based friction materials. The tests were carried out under the cyclic compressive stress with stress ratio of 0.1 and applied load rate of 1MPa/sec. The compressive loading was repeated five cycles, and then the maximum stress increased stepwise up to 100MPa. During the tests, the hysteresis loops of the fifth cycle in load-displacement relation were obtained. After the fifth cycle at stress level of 5, 10, 20, 50, 100MPa, the cross-section made by CP was observed with SEM. Figure 4 shows the observation sites in the cross-section of both materials. Twelve and eleven areas on the cross-section of aramid- and cellulose-based materials were observed, respectively.

Table 1. Constituents and porosity of the paper-based friction materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aramid-based material</th>
<th>Cellulose-based material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramid fiber (wt%)</td>
<td>70.0</td>
<td>0</td>
</tr>
<tr>
<td>Cellulose fiber (wt%)</td>
<td>0</td>
<td>70.0</td>
</tr>
<tr>
<td>Phenol resin (wt%)</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Total (wt%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>57.6</td>
<td>57.4</td>
</tr>
</tbody>
</table>

Fig.3 Cross-section of the paper-based friction materials.
2.3 Definition of damage type

The damage initiated in the paper-based friction materials is categorized as damage in fiber, damage in resin, interfacial debonding between fiber and resin, and unidentified damage. Figure 5 shows an example of the damage initiated in the cellulose-based material. According to Fig. 5(a), the cellulose fibers are glued each other with resin before the compressive test. When the compressive stress reaches 100MPa, the interfacial debonding between cellulose fiber and resin, damage in cellulose fiber, and unidentified damage are observed.

2.4 Evaluation of damage

In order to investigate damage behavior in the paper-based friction materials quantitatively, the number of damage sites and the length of damage are measured. The number of damage sites $D_N$ is defined by a ratio of the total number of observed damage sites to total observation area, as in eq. (1).

$$D_N = \frac{\text{The number of damage sites}}{\text{Total observation area}}$$

(1)

The total damage length $D_L$ is also defined by a ratio of total length of damage to total observation area, as in eq. (2).

$$D_L = \frac{\text{Total length of damage}}{\text{Total observation area}}$$

(2)

where the damage length is defined by distance between both edges of damage, as shown in Fig. 6. The number of damage sites $D_N$ and total damage length $D_L$ were measured for each damage type, defined in section 2.3.

Fig. 4 Observation sites in cross-section of the paper-based friction materials.

Fig. 5 Example of damage in the cellulose-based material.
3 Results and Discussion

3.1 Compressive deformation behavior

The hysteresis loops of aramid- and cellulose-based materials of the fifth cycle for each stress level are shown in Fig. 7. In both materials, the hysteresis loop shifts to the high strain direction and its gradient becomes steep with increasing stress level. In order to evaluate mechanical properties of each material under compressive loading, the maximum strain $\varepsilon_0$, strain range $\Delta \varepsilon$ and unloading elastic modulus $E$ are defined as in Fig. 7[19]. The unloading elastic modulus is defined as a slope of the unloading relation from the maximum stress of hysteresis loop.

Figure 8 shows the maximum strain, strain range, unloading elastic modulus as functions of the maximum compressive stress in both materials. In both materials, the maximum strain and unloading elastic modulus increase with increasing maximum compressive stress, while the strain range remains as constant low value. These results are explained as
follows: the paper-based friction material is a porous material with porosity of about 60%. The porosity decreases with increasing compressive stress, and then the paper-based friction materials become dense and the unloading elastic modulus becomes high. Therefore, the gradient of the hysteresis loops becomes steep and the strain range does not increase as compared with an increase in the stress range. Figure 9 shows the thickness reduction normalized by the original thickness as a function of maximum applied stress. The thickness of both materials decreased with increasing compressive stress. The reduction of thickness in the cellulose-based material was larger than that in the aramid-based material. The change of thickness is affected by plastic deformation of fibers and resin and damage evolution. Here, the macroscopic mechanical properties under the compressive loading have been clarified. However, the reason why the fatigue fracture occurs under the compressive loading is not clarified. In the next section, the damage behavior under the compressive loading is investigated microscopically.

3.2 Damage behavior
Figure 10 shows the example of damage observed in the aramid-based material. Before the compressive test, the thick and thin aramid fibers are observed, although the resin is not observed clearly, as shown in Fig. 10(a). When the compressive stress is increased to 50MPa, some cracks initiate and propagate into fibers. When the compressive stress is increased to 100MPa, two cracks initiates in other fibers. Figure 11 shows the example of damage in the cellulose-based material. From Fig. 11(a), the cellulose fibers are bonded each other with resin before the compressive test. When the compressive stress is increased to 20MPa, the interfacial debonding between cellulose fiber and resin is observed, as shown in Fig.12 (b). When the compressive stress is increased to 50MPa, the interfacial debonding and damage in resin occur in other sites.
3.3 Evaluation of damage evolution

Figure 12(a) shows the number of damage sites in the aramid-based material as a function of compressive stress. The interfacial debonding, damage in fiber and unidentified damage occur under compressive stress of 20MPa, and then with increasing compressive stress, the interfacial debonding does not increase, while the number of damage sites in fiber increases. Figure 12(b) shows the total damage length in the aramid-based material as a function of compressive stress. The total damage length increases with increasing compressive stress. The interfacial debonding is dominant in the aramid-based material because the length of interfacial debonding is longer than that of the other damage. According to Figs. 12 and 13, the damage occurs below compressive stress of 5MPa in the cellulose-based material, although any damage in the aramid-based material does not occur under 10MPa. When compressive stress is increased to 100MPa, the total damage in the cellulose-based material is much longer than that in the aramid-based material. Therefore, the damage in cellulose-based material seems to be easier to occur than in aramid-based material.

There is little difference between the mechanical properties of each material under compressive loading macroscopically, as mentioned in Sec.3.1. However, from the microscopic viewpoint, the damage behavior, such as damage type and damage length, under compressive loading depend on the material constituents. It seems that the damage behavior affects the change of thickness reduction of the friction materials. That is, the thickness of cellulose-based material become thinner than that of aramid-based material because the compressive property of the cellulose-based material may be affected by the damage evolution.

As mentioned above, the fatigue life of cellulose-based material is shorter than that of aramid-based material from the result of the conventional tests. During the conventional test, the damage behavior in aramid- and cellulose-based materials may affect the fatigue life. That is, the fatigue life of cellulose-based material is shorter than that of aramid-based
material because the damage in cellulose-based material is easier to occur than in aramid-based material. To explain the fatigue life in more detail, the influence of cyclic loading on damage behavior needs to be considered. This is remained as future investigation.

4. Conclusion
The out-of-plane compressive loading tests were carried out in order to investigate the damage behavior of aramid- and cellulose-based materials under compressive loading. The number of damage sites and length of damage were measured to characterize the damage evolution with compressive stress. The conclusions are summarized as follows.

1. The paper-based friction materials become dense and the unloading elastic modulus becomes high under the high compressive stress.
2. For aramid-based material, the interfacial debonding, damage in fiber and unidentified damage occur under compressive stress of 20MPa. The total damage length increases with increasing compressive stress. The damage in fiber is dominant under compressive loading.
3. For cellulose-based material, damage in fiber occurs under the compressive stress of 5MPa, the interfacial debonding and damage in resin occur under the compressive stress of 10MPa. The damage length increases with increasing compressive stress, and the interfacial debonding is dominant under compressive loading.
4. The damage in cellulose-based material is much longer than that in aramid-based material. The damage in cellulose-based material is easier to occur than in aramid-based material.

References
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