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ORIGINAL ARTICLE

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Two-body and three-body abrasive wear properties of katsura wood

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Abstract Two-body and three-body abrasive wear tests of katsura wood were carried out using abrasive paper and moving abrasive grains, respectively. The two-body and three-body abrasive wear properties were investigated and compared. The wear rate of two-body abrasive wear was two orders of magnitude larger than that of three-body abrasive wear. Moreover, two-body abrasive wear of katsura wood increased with higher applied surface pressure, whereas three-body abrasive wear did not always depend on the applied surface pressure. Based on these results and observation of the wear surface profiles, it is suggested that two-body abrasive wear is more affected by yield stress and surface microstructure, and three-body abrasive wear is more affected by the cutting action of moving abrasive grains. Furthermore, during wear tests with different abrasive grain sizes, critical grain size effects of two-body abrasive wear were observed at low applied surface pressures but not at high applied surface pressures. The critical grain size effects of three-body abrasive wear were observed at both low and high applied surface pressures.

Key words Two-body abrasive wear · Three-body abrasive wear · Katsura wood · Yield stress · Grain size effect

Introduction

The abrasive wear test method, which involves cutting the materials mechanically on abrasive paper, has been used for metals, plastics, and composite materials.[1–6] Recently, the wear test method has also been applied to wood,[7–9] and it has become the fundamental test for evaluating wear resistance. The wear that occurs during the test is usually known as two-body abrasive wear (two-body wear): cutting of the material by fixed abrasive grains.[1–4] The wear of materials due to moving abrasive grains is classified as three-body abrasive wear (three-body wear).[5,6] When wood is used under outdoor conditions, three-body wear (rather than two-body wear) can be thought of as representing the actual wear phenomenon.

The studies on abrasive wear of wood have mainly involved two-body wear tests using abrasive paper. Based on the results of two-body wear tests, the following wear properties have been clarified.[1–4] The two-body wear of katsura wood is considered to be phenomenologically the same as that of aluminum when the yield stress of materials is adopted as the comparative variable for abrasive wear.[7] Moreover, the critical grain size effect of abrasive wear, in which the wear rate remains constant in the range exceeding a certain grain size, is observed at low applied surface pressures but not at high applied surface pressures for some woods, including katsura wood.[8,9] In this study, three-body wear of katsura wood was examined using moving abrasive grains. Furthermore, the three-body wear properties were investigated and compared with the two-body wear properties.

Experimental

The specimen used in the experiment was katsura (*Cercidiphyllum japonicum* Sieb. and Zucc.) wood with a density of 0.47 g/cm^3, moisture content of 10.6%, and average annual ring width of 1.6 mm. For the two-body and

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Table 1. Properties of katsura wood (*Cercidiphyllum japonicum* Sieb and Zucc.) used in this experiment

Orientation	Yield stress: σ_y (MPa)
Longitudinal direction	59
Radial direction	16
Tangential direction	12

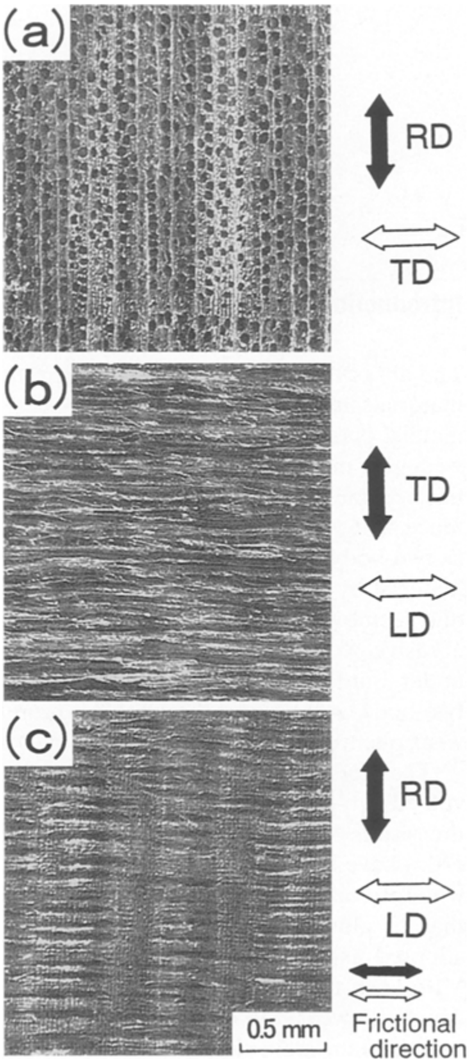

Fig. 1. Optical micrographs of katsura wood. **a** Axial section. **b** Tangential section. **c** Radial section. *RD*, radial direction; *TD*, tangential direction; *LD*, longitudinal direction

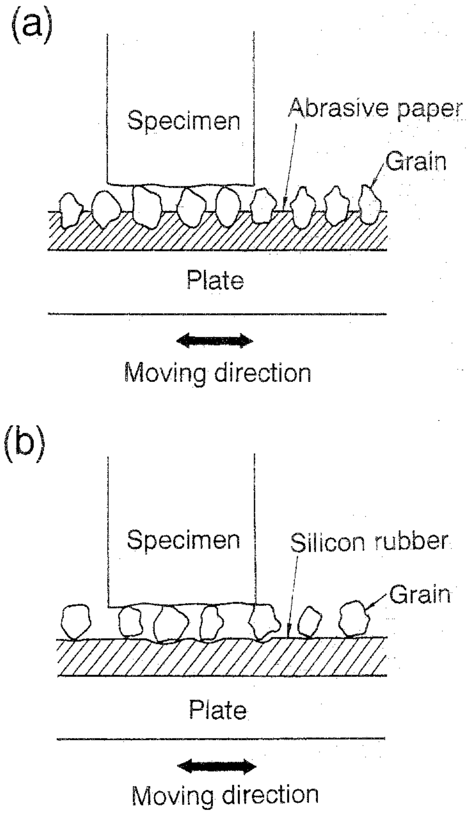

Fig. 2. Abrasive wear tests in this experiment. **a** Two-body wear test. **b** Three-body abrasive test

three-body wear tests on katsura wood, the axial, tangential, and radial sections were used as the frictional surfaces. The frictional surface area of the specimen was 3 × 4mm. Table 1 shows the yield stresses of katsura wood during compression tests. The yield stress in the longitudinal direction on the axial section was the highest among the three directions (59MPa); the yield stresses in the radial and tangential directions on the tangential and radial sections were 16 and 12MPa, respectively. Figure 1 shows micrographs of the axial, tangential, and radial sections. Because the microstructure of each surface has different characteristics, two frictional directions were selected: (1) parallel and perpendicular to the direction of the annual rings; and (2) parallel and perpendicular to the direction of the fibers. The two frictional directions are represented here by the symbols shown in Fig. 1: The directions on the axial section are represented by RD and TD, on tangential section by TD and LD, and on the radial section by RD and LD, where RD, TD, and LD represent the radial, tangential, and longitudinal directions.

The two-body and three-body abrasive wear tests were performed on each frictional surface of the specimen. The wear machine used for the experiment had a plate moving at a constant speed of 20mm/s.[5] The specimen, which was pressed from above, was worn by sliding the plate with abrasive paper or moving abrasive grains. Figure 2a shows the detail of the two-body wear test. Abrasive paper was placed on the surface of the plate. The specimen was typically worn on the virgin surface of the abrasive paper by reciprocating the plate. Figure 2b shows the details of the three-body wear test. The moving abrasive grains were put on the surface of a silicon rubber floor. For the three-body wear test, the specimen was worn on the silicon rubber floor with the moving abrasive grains by reciprocating the plate. The silicon rubber was used to allow the three-body wear to proceed under the frictional condition that the moving abrasive grains fall in the floor materials. Using #100 abrasive paper with applied surface pressure

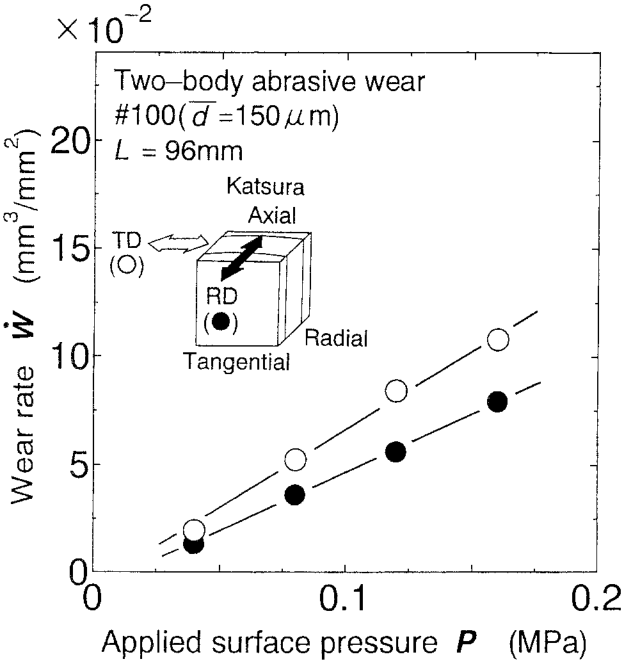

Fig. 3. Relation between wear rate $\dot{W}$ and applied surface pressure P in the two-body abrasive wear test on axial sections of katsura wood

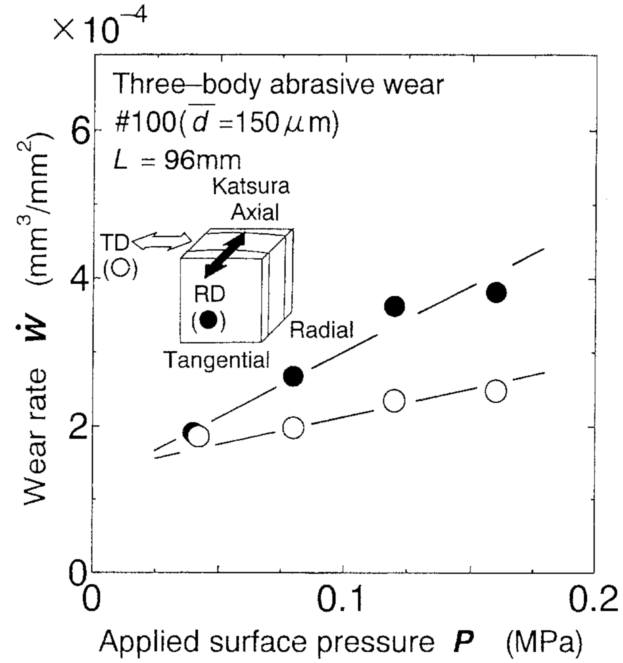

Fig. 4. Relation between wear rate $\dot{W}$ and applied surface pressure P in the three-body abrasive wear test on axial sections of katsura wood

P of 0.16MPa, the wear ratio of the silicon plate against the specimen was 2.8%. The grains on abrasive paper and the moving abrasive grains used in the experiment were #400 alumina (mean abrasive grain size $\bar{d}$ = 40μm), #220 ($\bar{d}$ = 75μm), #150 ($\bar{d}$ = 110μm), #100 ($\bar{d}$ = 150μm), #80 ($\bar{d}$ = 150μm), #60 ($\bar{d}$ = 225μm). The applied surface pressure P of the frictional surface was in the range 0.04–0.16MPa.

Results and discussion

Dependence of applied surface pressure during two-body and three-body abrasive wear

Figure 3 shows the relation between the wear rate $\dot{W}$ (mm^3/mm^2) and the applied surface pressure P for two-body wear on axial sections. The wear rate $\dot{W}$ is the value of the wear volume (mm^3) of the wear distance L = 96mm divided by the frictional surface area (mm^2) of the specimen. The wear rate $\dot{W}$ under the frictions of RD and TD increases linearly; and $\dot{W}$ of the TD friction is higher than that of RD friction. Figure 4 shows the relation between the wear rate $\dot{W}$ and the applied surface pressure P of three-body wear on axial sections. The rate $\dot{W}$ of three-body wear is two orders smaller than that of two-body wear. Moreover, $\dot{W}$ of RD and TD frictions increases linearly, and $\dot{W}$ of RD is higher than that of TD. The results in Figs. 3 and 4 indicate that the wear rates $\dot{W}$ of both two-body and three-body wear increase with increasing applied surface pressure. However, the wear rate of RD friction was higher in the three-body wear tests, whereas the wear rate of TD friction was higher in the two-body wear tests.

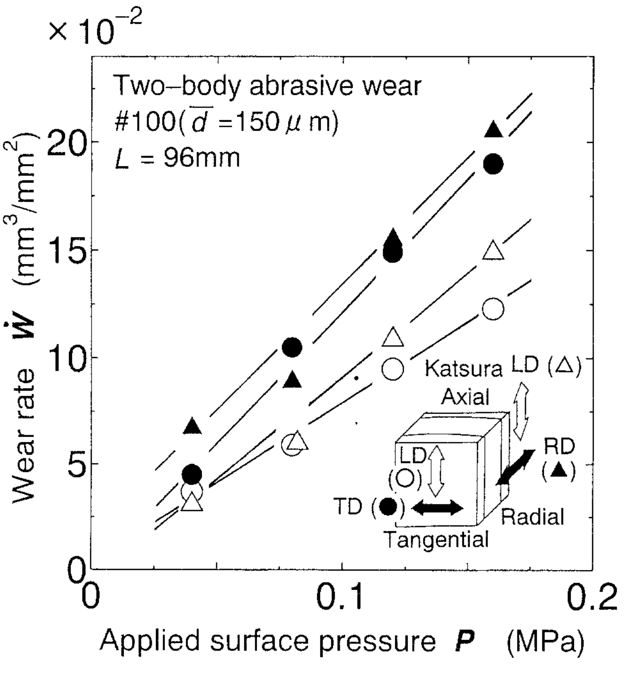

Fig. 5. Relation between wear rate $\dot{W}$ and applied surface pressure P in the two-body abrasive wear test in tangential and radial sections of katsura wood

Figure 5 shows the relation of the wear rate $\dot{W}$ and the applied surface pressure P for two-body wear on tangential and radial sections. $\dot{W}$ on the tangential and radial sections increases linearly with increasing applied surface pressure, and $\dot{W}$ on both sections is larger than that on the axial section. Moreover, $\dot{W}$ of TD and RD frictions on the perpendicular direction of the fibers is higher than that of LD

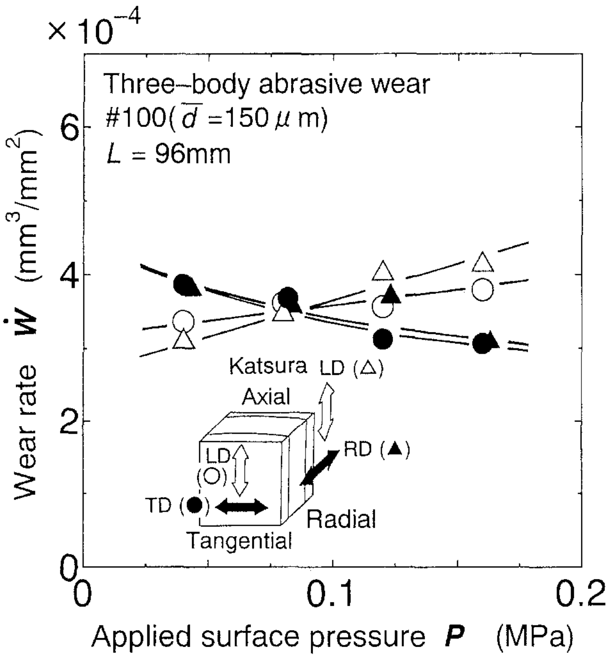

Fig. 6. Relation between wear rate $\dot{W}$ and applied surface pressure P in the three-body abrasive wear test in tangential and radial sections of katsura wood

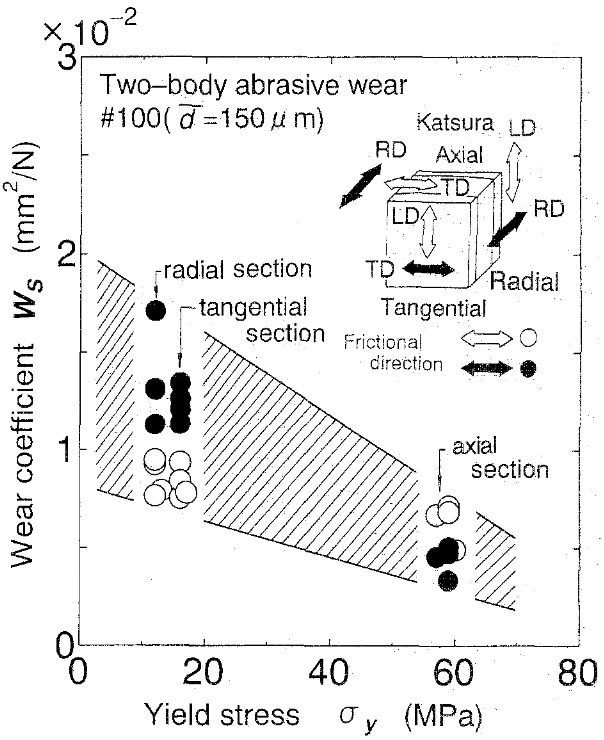

Fig. 7. Relation between wear coefficient W_S and yield stress σ_y in the two-body abrasive wear test on katsura wood

friction in the parallel direction. In contrast to these results, Fig. 6 shows the results of the three-body wear tests. Based on these results, $\dot{W}$ of LD friction on tangential and radial sections tends to increase with P. However $\dot{W}$ of TD and RD frictions decreases with increasing P, and $\dot{W}$ at higher applied surface pressure becomes smaller than that of LD frictions.

From the above results, it is apparent that the two-body wear rate of katsura wood is two orders larger than the three-body wear rate, and that the two-body wear rate increases with increasing applied surface pressure. However, the three-body wear rate of tangential and radial sections is not always dependent on the applied surface pressures.

Factors controlling two-body and three-body abrasive wear

Two-body wear of the axial, tangential, and radial sections in katsura wood was closely related to the yield stress of the material; and the wear rate of these sections was smaller with higher yield stress.[7] Therefore, the factors controlling three-body wear of katsura wood are discussed here based on results obtained from these two-body and three-body wear tests.

Figure 7 shows the relation between the wear coefficient W_S (mm^2/N) and the yield stress σ_y for two-body wear. As in the previous study,[7] the criterion for abrasive wear was used to examine the relation to yield stress. The criterion was the wear coefficient, which is the wear volume (mm^3) divided by the applied load (N) and sliding distance (mm). In Fig. 7, the values of wear coefficient W_S are scattered because they represent the total data of two-body wear on the axial,

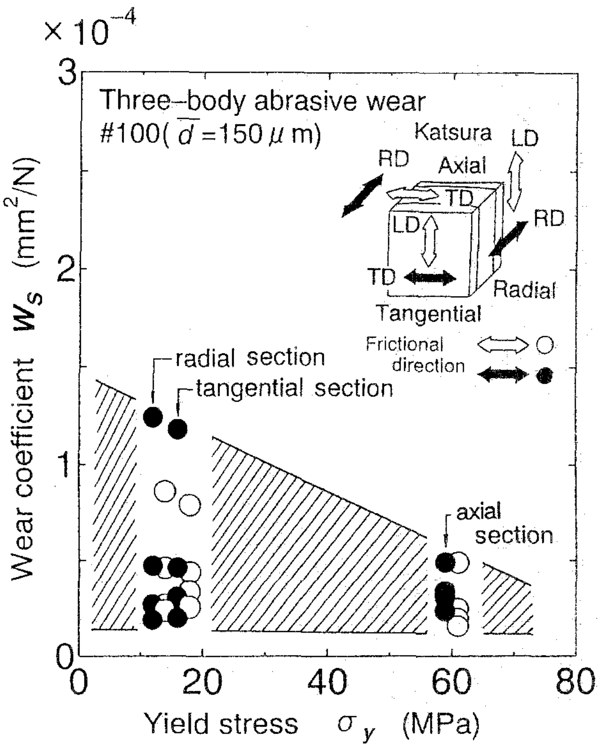

Fig. 8. Relation between wear coefficient W_S and yield stress σ_y in the three-body abrasive wear test on katsura wood

tangential, and radial sections shown in Figs. 3 and 5. The values for W_S tend to be smaller with larger σ_y when judged from the total data including parallel and perpendicular frictional directions for annual rings and fibers. In the previous report on two-body wear tests of katsura wood,[7] the values of W_S on #180 abrasive paper ($\bar{d} = 88\mu$m) were not scattered by frictional direction. However, in this case of using #100 abrasive paper ($\bar{d} = 150\mu$m), the W_S of TD and RD frictions on the tangential and radial sections are larger than that of LD frictions; W_S of TD friction on the axial section is larger than that of RD friction. The difference in W_S caused by frictional direction may be because the wear of katsura wood by large abrasive grains (#100) was affected by the surface microstructure. On the other hand, Figure 8 shows the relation between the wear coefficient W_S and the yield stress σ_y for three-body wear. W_S of TD and RD frictions on tangential and radial sections is not only larger than that of LD frictions, but the W_S is smaller. Moreover, these smaller values of W_S are almost the same as values on the axial section. Therefore, W_S for three-body wear tends not to depend on the yield stress σ_y. Based on these results, it is thought that the three-body wear of katsura wood is affected more by other factors controlling abrasive wear, whereas two-body wear is affected by yield stress and wood surface microstructure.

Therefore, the frictional surface after the three-body wear tests was examined to investigate the influence of other factors. Figure 9 shows micrographs of the frictional surfaces. The frictional direction of each surface is represented on both sides of the micrograph. Compared with the surface conditions before the wear tests (Fig. 1), the vessel structures on the axial section are almost crushed by TD and RD frictions (Fig. 9a,b), and the scratch traces of abrasive grains can be observed along the frictional directions. Scratch traces by LD frictions on the tangential and radial sections (Fig. 9c,e) can be observed along the frictional direction. However, no scratch traces by TD and RD frictions (Fig. 9d,f) can be observed along the frictional direc-

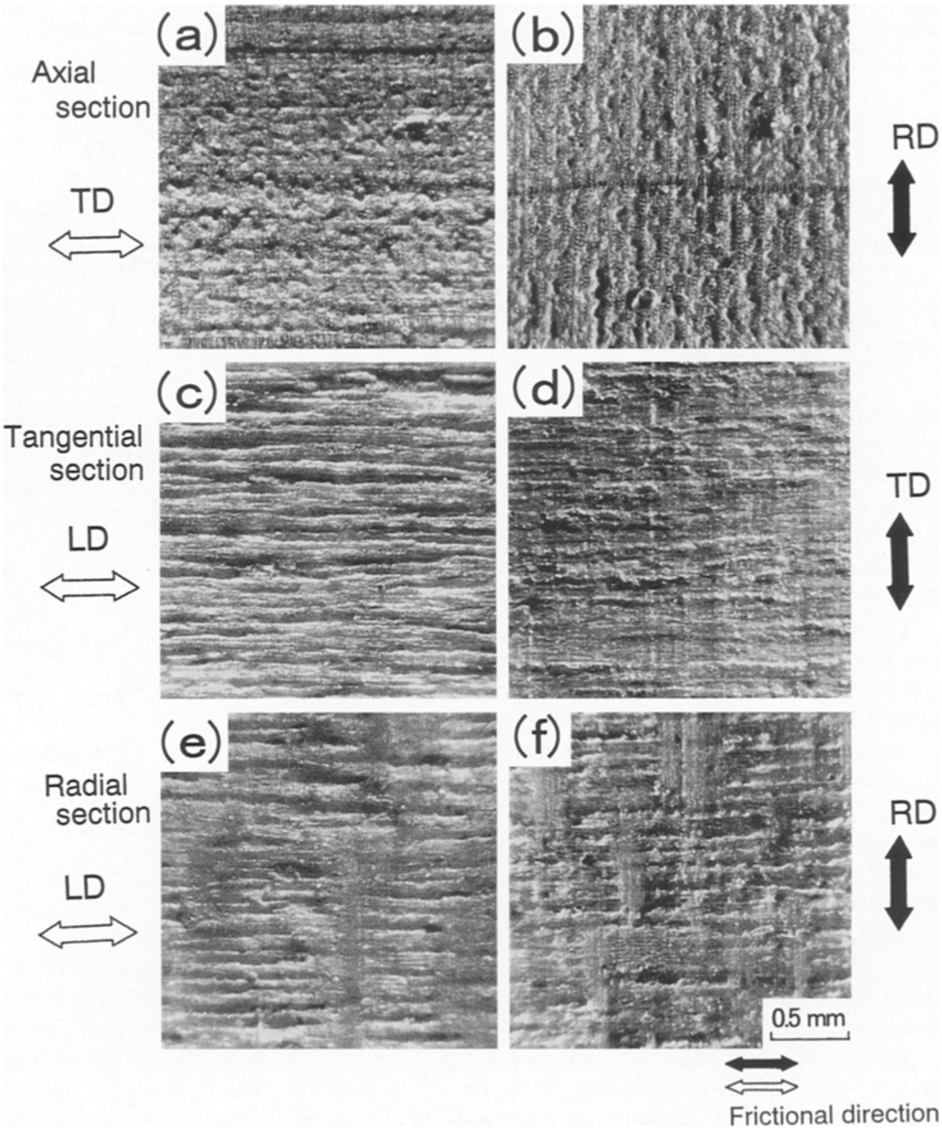

Fig. 9. Optical micrographs of the wear surface of katsura wood. **a,b** Axial sections. **c,d** Tangential sections. **e,f** Radial sections

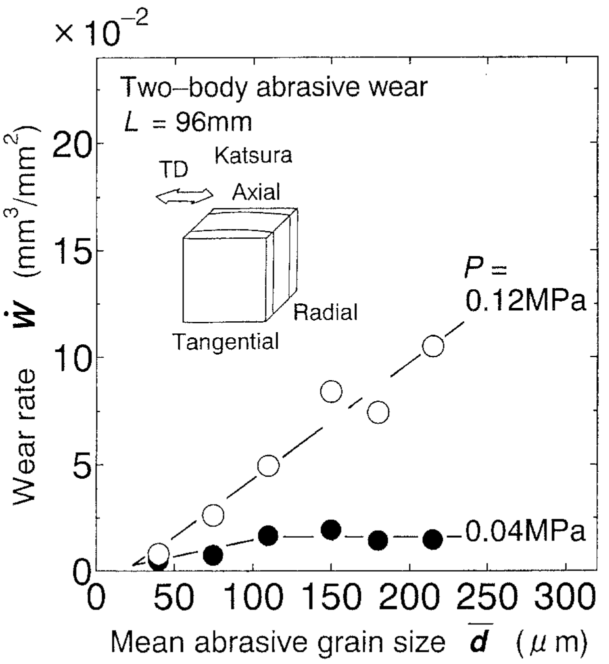

Fig. 10. Relation between wear rate $\dot{W}$ and mean abrasive grain size $\bar{d}$ in the two-body abrasive wear test on axial sections of katsura wood

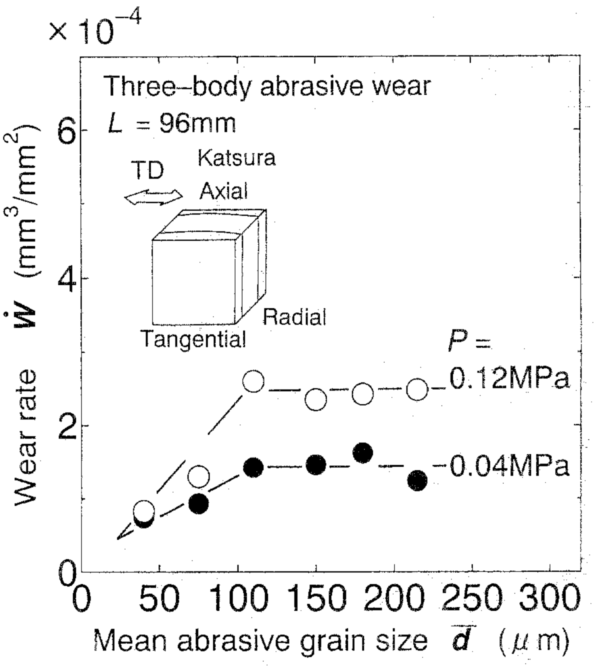

Fig. 11. Relation between wear rate $\dot{W}$ and mean abrasive grain size $\bar{d}$ in the three-body abrasive wear test on axial sections of katsura wood

tion even though the surface roughness was greater than that before the wear tests (Fig. 1b,c). Based on these results, it is suggested that three-body wear of katsura wood is affected more by the cutting action of moving abrasive grains than by yield stress and wood surface microstructure.

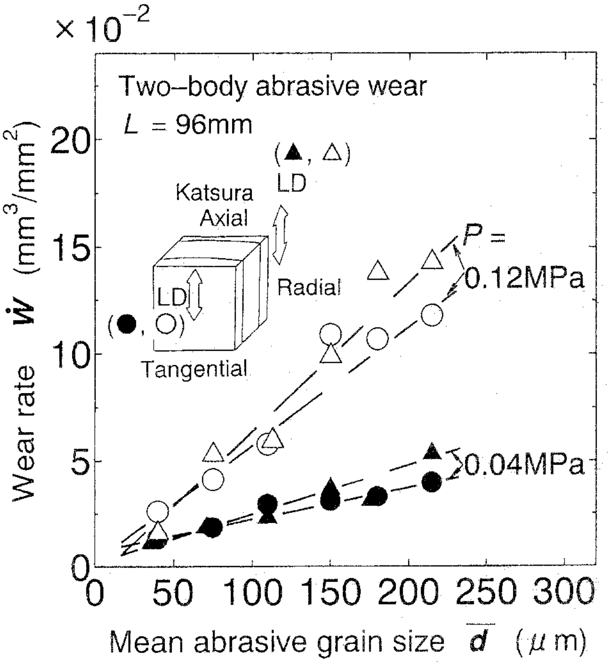

Fig. 12. Relation between wear rate $\dot{W}$ and mean abrasive grain size $\bar{d}$ in the two-body abrasive wear test in tangential and radial sections of katsura wood

Effect of abrasive grain size during two-body and three-body abrasive wear

Based on the results of the two-body and three-body wear tests of katsura wood, the wear rate of TD and RD friction on the axial section and of LD friction on tangential and radial sections tended to increase with the applied surface pressures. Therefore, in the following tests the effect of abrasive grain size was examined under the common dependence of applied surface pressure.

Figure 10 shows the relation between the wear rate $\dot{W}$ and the mean abrasive grain size $\bar{d}$ during two-body wear of TD friction on axial sections. As reported in previous papers,[8,9] $\dot{W}$ under $P = 0.04$MPa increases with $\bar{d}$ until the mean abrasive grain size is almost 100μm; $\dot{W}$ remains constant when the abrasive grain size exceeds 100μm. In other words, a critical grain size effect is observed in the range of low applied surface pressure. However, $\dot{W}$ increases linearly with $\bar{d}$ at a high applied surface pressure of $P = 0.12$MPa, and then the critical grain size effect is not observed. Figure 11 shows the relation between the wear rate $\dot{W}$ and the mean abrasive grain size $\bar{d}$ during three-body wear. Under these conditions, the critical grain size effects are observed at applied surface pressures of $P = 0.04$ and 0.12MPa.

Figure 12 shows the relation between the wear rate $\dot{W}$ and the mean abrasive grain size $\bar{d}$ for two-body wear of LD frictions on tangential and radial sections. $\dot{W}$ of tangential and radial sections increases linearly with $\bar{d}$ at applied surface pressures of $P = 0.04$ and 0.12MPa. In these cases, the critical grain size effects are not observed at either low or high applied surface pressures. Here, it is obvious that the boundary values of the applied surface pressure P_C, which indicates the condition regardless of whether the

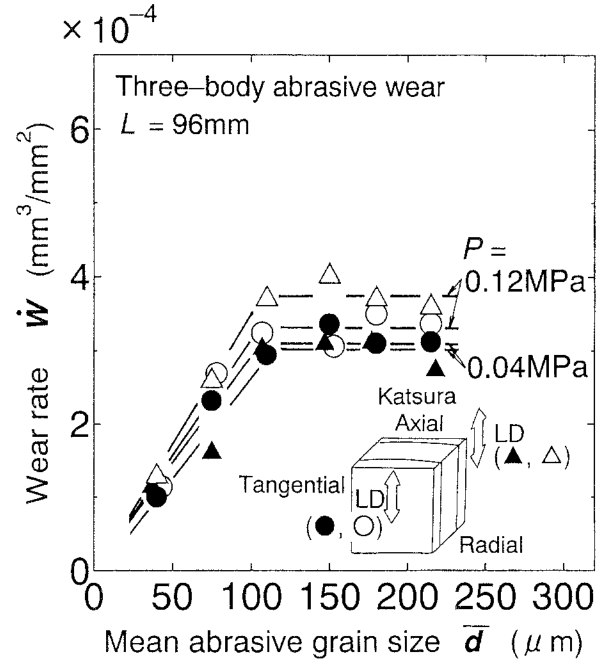

Fig. 13. Relation between wear rate $\dot{W}$ and mean abrasive grain size $\bar{d}$ in the three-body abrasive wear test in the tangential and radial sections of katsura wood

critical grain size effects are observed, become higher with increasing yield stress σ_y.[8,9] Moreover, if the value of P/σ_y is beyond $P_C/\delta_y = 0.0017$, the critical grain size effects are not observed.[9] Therefore, P/σ_y was calculated within the range of the applied surface pressures in this experiment. Then P/σ_y varied in the range 0.0007–0.0020 for the axial section, 0.0025–0.0075 for the tangential section, and 0.0033–0.0100 for the radial section. Based on these results, it can be concluded that the critical grain size effects are not observed in Fig. 12 because P/σ_y of the tangential and radial sections is much higher than the boundary value of $P_C/\sigma_y = 0.0017$.

Figure 13 shows the results of wear of the tangential and radial sections by moving abrasive grains. In the three-body wear tests, the critical grain size effects are observed with applied surface pressures of $P = 0.04$ and 0.12 MPa. Consequently, it has been clarified that the critical grain size effects of two-body wear are not observed at high applied surface pressures and that the boundary value, which indicates whether the effects are observed, are controlled by the yield stress of the material. In contrast, the critical grain size effects of three-body wear are usually observed at both low and high applied surface pressures.

Conclusions

Two-body and three-body abrasive wear properties of katsura wood were examined using abrasive paper and moving abrasive grains. These wear properties were investigated and compared. The results obtained are as follows.

1. The two-body wear rate of katsura wood was two orders larger than the three-body wear rate.
2. The two-body wear rate increased with higher applied surface pressure, whereas the three-body wear rate did not always depend on applied surface pressure.
3. Two-body wear of katsura wood was affected by yield stress and surface microstructure. Three-body wear was affected more by the cutting action of moving abrasive grains.
4. During wear tests using abrasive grains of different sizes, critical grain size effects of two-body wear were observed at low applied surface pressure but not at high applied surface pressure. In contrast, critical grain size effects of three-body wear were observed at both low and high applied surface pressures.

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