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Abrasive wear behaviour of bamboo

Jin Tong, Luquan Ren, Jianqiao Li and Bingcong Chen

Abrasive wear of bamboo (*Phyllostachys pubescens*) against a free abrasive consisting of quartz sand (96.5%-wt) and bentonite (3.5%-wt) was studied on a rotary-disk type abrasive wear tester (a free abrasive wear tester) and the micromorphology of the abraded surfaces were examined by scanning electron microscopy. It was observed that the bamboo fibre (vascular bundle) orientation with respect to the abrading surface had an important influence on the abrasive wear performance. The normally oriented specimens gave much higher abrasion resistance than the parallel-oriented ones, the surface layer than the inner layer, and the vascular bundle than the matrix tissue.

Keywords: *abrasive wear, bamboo, fibre-reinforced composite*

Introduction

Bamboo is a natural fibre-reinforced composite. Though various cells can be observed in bamboo, these cells can, in mechanics, be classified into two types: matrix tissue cells and sclerenchyma cells. Matrix tissue cells are leptodermous and act as the matrix of general composites. Sclerenchyma cells mainly consist of vascular bundles enveloped in the matrix tissue. The vascular bundles are reinforcers of bamboo. A vascular bundle is made of many phloem fibres, which may be considered as fibres in general composites. A phloem fibre is composed of several layers of pillar fibres and micro-fibres in each layer of the pillar fibres are spirally arranged at a certain spiral angle which is varied as different layers of pillar fibres. Also, a vascular bundle is composed of many right-handed spiral phloem fibres at a certain spiral angle.

Lakkard and Patel[1] demonstrated that bamboo has excellent mechanical properties with specific strength and modulus compared to that of unidirectional glass fibre-reinforced plastics. Li *et al.*[2] gave a double-folded spiral composite model based on the arrangement of bamboo fibres at fine scale. Three thousand carbon fibres were twisted up in a bundle in Z lay at the spiral angle of 60–70° and then two such bundles were twisted up in S lay at the same spiral angle to prepare carbon fibre/Sn composites. It was verified that the tensile strength of the composites was 40% higher than that of non-twisted fibre composite with the same fibre number. Yakou and Sakamoto[3] used carborundum emery paper as the opposite material to study the abrasive properties of *Phyllostachys pubescens*.

Lhymn *et al.*[4], Voss and Friedrich[5] and Tewari *et al.*[6] demonstrated that the abrasion resistance of carbon fibre- and glass fibre-reinforced plastics (PA66, PPS, PEEK, polycarbonate, PES, polyethermide, bulk liquid crystal polymer and PTFE) was a function of abrasive particle size and the fibre orientation with respect to the sliding direction. The object of the present work is to study the influence of fibre orientation with respect to the abrading surface and the abrasive particle size on the abrasive wear of bamboo stem in free abrasive conditions.

Experimental details

Specimens of dimensions 60 mm × 8 mm × 3 mm were cut from the same bamboo stem of *Phyllostachys pubescens* and mounted in steel plates of dimensions 60 mm × 35 mm × 6 mm, one bamboo specimen in each steel plate. Four types of bamboo specimens were prepared. In the N-type, the vascular bundle orientation was normal to the abrading surface (Figure 1(a)). In the P_s- and P_I-type the bundle orientation

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School of Agricultural Machinery Engineering, Jilin University of Technology, Changchun 130025, PR China
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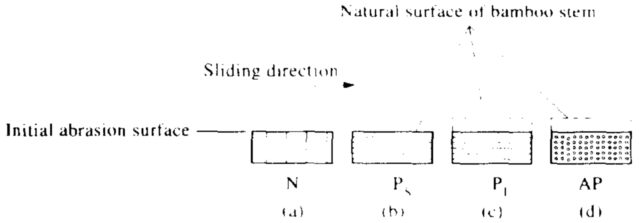

Fig 1 Schematic diagram showing fibre orientation with respect to the sliding direction for the N, P_s, P_l and AP specimens

was parallel both to the abrading surface and the sliding direction and the initial abrasion surface was the natural surface of bamboo stem for the P_s-type specimen (Fig 1(b)) and was 2 mm under the natural surface for the P_l-type specimen (Fig 1(c)). In the AP-type the bundle orientation was parallel to the abrading surface but normal to the sliding direction and the initial abrasion surface was also 2 mm beneath the natural surface (Fig 1(d)).

Two different sizes of quartz sand (0.45–0.90 mm and 0.25–0.45 mm, respectively) and bentonite (76 μm) were used as abrasive, which contained quartz sand of 96.5%-wt and bentonite of 3.5%-wt. The water content of the abrasive was 3%-wt.

The abrasion tests were run on a rotary-disk type abrasive wear tester (a free abrasive wear tester). Four specimens can be installed on the specimen holder at positions perpendicular to each other as shown in Fig 2. Their positions can be changed successively to abrade one by one every 5.5 minutes, i.e. 801.9 m of sliding distance. The abrading specimen was embedded 40 mm in abrasive. The impact angle between abrasive and the abrading surface was 35°. During abrasion the rotary disk rotated to drive the abrasive to be slid against the abrading specimen. The total sliding distance for each specimen was 9622.8 m, the relative sliding velocity 2.43 m/s, and the temperature of the surrounding air 19°C. The abrasion of specimens was expressed by their abrasion depth. The micromorphologies of abraded surfaces were examined by scanning electron microscopy.

Experimental results and discussion

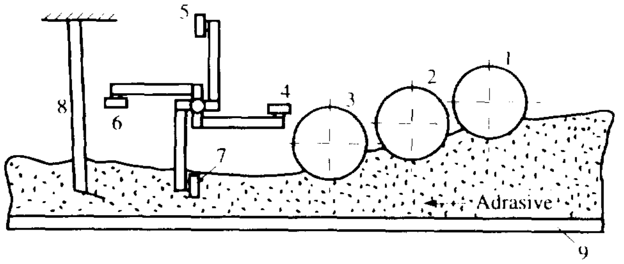

Fig 2 Schematic diagram of the operation of a rotary-disk type abrasive wear tester. 1–3 Compacting wheels, 4–7 test specimens, 8 subsoiler, 9 rotary disk

Table 1 Test results of abrasive wear of bamboo stem

Quartz sand diameter (mm)	Abrasion depth (mm)			
	N	P_s	P_l	AP
0.45–0.90	0.455	1.401	1.975	1.985
0.25–0.45	0.112	0.621	0.818	0.875

Results of abrasion tests given in Table 1 show that the fibre (vascular bundle) orientation with respect to the abrading surface has a significant influence on abrasive wear of a bamboo stem. Normally oriented specimens give best abrasion resistance under the same test conditions and their abrasion depths are lower by a factor of 4–8 than parallel-oriented specimens. The surface layer of a bamboo stem is of higher abrasion resistance than the inner layer. Abrasion depths of all specimens increase as abrasive particle size increases.

Figures 3–6 illustrate the surface morphologies of various specimens abraded against the abrasive containing quartz sand of 0.45–0.90 mm diameter. As seen in Figs 3 and 4, for the P_l- and AP-type specimen, wear debris generation occurs due to microcutting and microcracking mechanisms induced by hard abrasive particle asperities because there are grooves and microcracks on their abraded surface. In Fig 5 the magnitude of microcutting and microcracking damages of the P_s-type specimen is obviously depressed as compared to the P_l- and AP-type specimens. In Fig 6 the abraded surface morphology of the N-type specimen is somewhat complex. A certain depth of the matrix tissue was removed to make the vascular bundle fibres protrude on the matrix (Fig 6(a)), which suggested that the vascular bundle fibres is of higher abrasive wear resistance than the matrix tissue, that is, the normally oriented fibres can protect the matrix from further wear. As the asperities of abrasive particles were easily pushed into the ducts of vascular bundles and there was tensile stress in the surface layer behind the contact zones of abrasive particle asperities with the abrading surface, it was observed that there existed pits and microcracks (Fig 6(b), (c)) at the centre of every vascular bundle. These microcracks propagated during the continual loading of abrasive particles. Microcracks were observed on the abraded surface of the bundle fibres, but no microcutting feature, as shown in Fig 6(d). Their abrasive wear seems due to ductile delamination, that is, the microcracks propagated slowly and then some small pits were formed. The microcutting and microcracking damage of abraded surface of the matrix tissue between the bundles was less than that of the P_l- and AP-type specimen but greater than that of the P_s-type specimen, as shown in Fig 6(e).

The morphologies of surfaces of various specimens abraded by the abrasive containing quartz sand of 0.25–0.45 mm diameter were also examined by scanning electron microscopy. Their features were similar to those by the abrasive containing quartz sand of 0.45–0.90 mm diameter but represented less abrasion damage.

Fig 3 SEM micrographs of the surface of the P_f-type specimen abraded by an abrasive containing quartz sand of 0.45–0.90 mm diameter

Fig 4 SEM micrographs of the surface of the AP-type specimen abraded by an abrasive containing quartz sand of 0.45–0.90 mm diameter

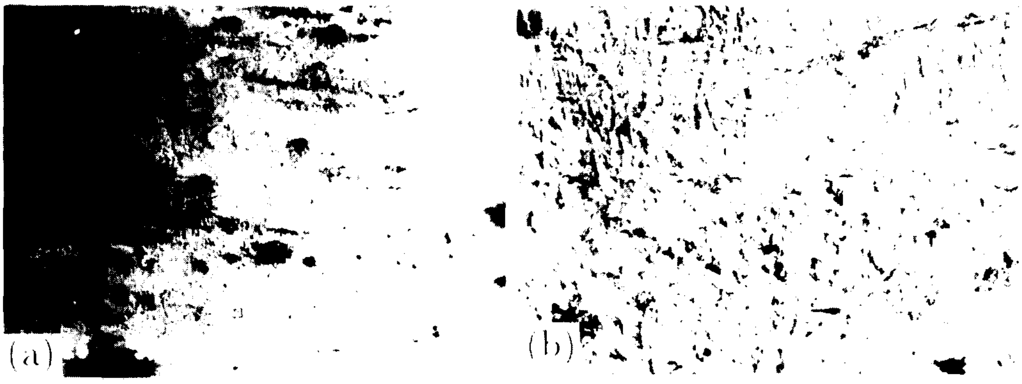

Fig 5 SEM micrographs of the surface of the P_s-type specimen abraded by an abrasive containing quartz sand of 0.45–0.90 mm diameter

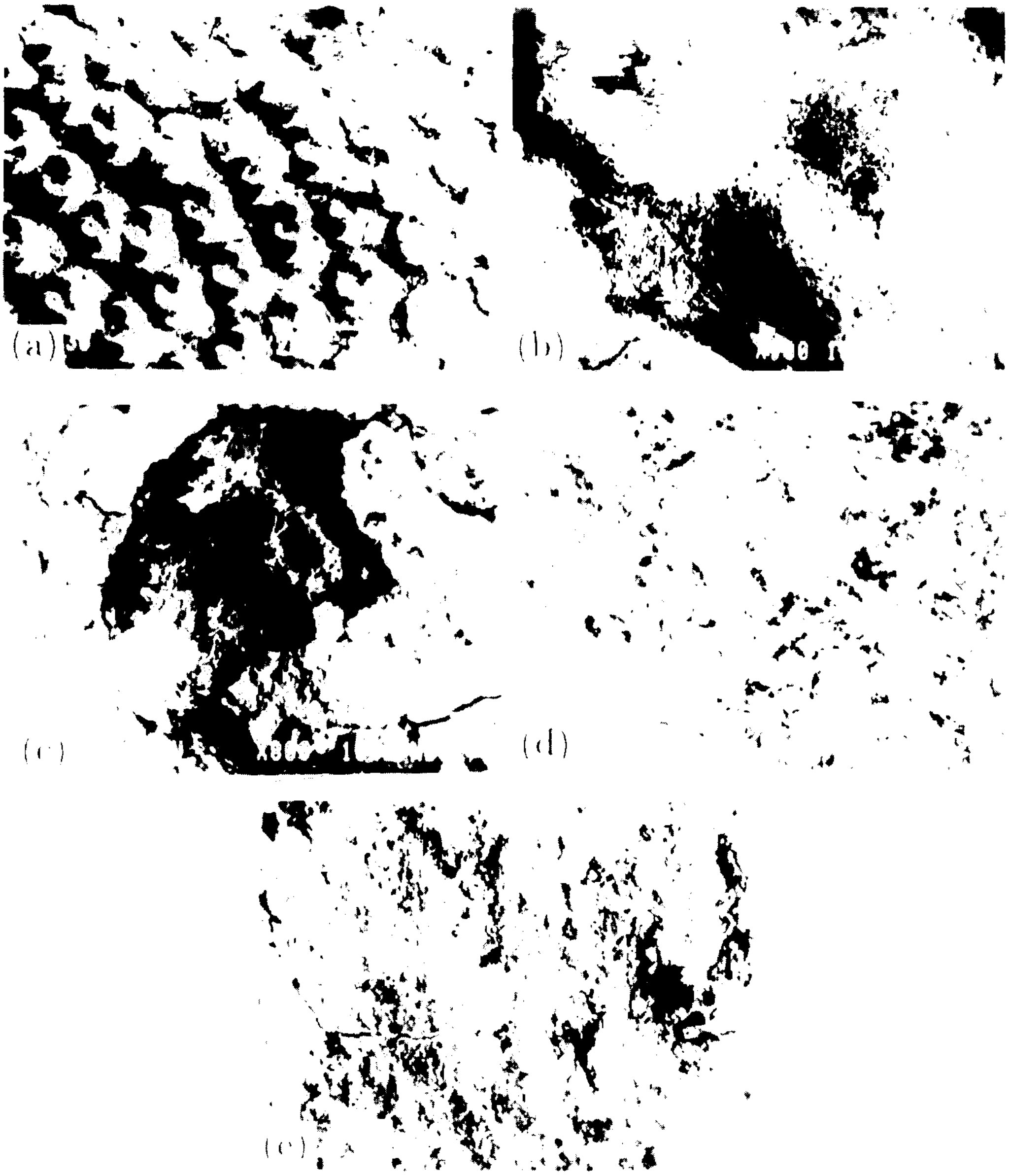

Fig 6 SEM micrographs of the surface of the N-type specimen abraded by an abrasive containing quartz sand of 0.45–0.90 diameter

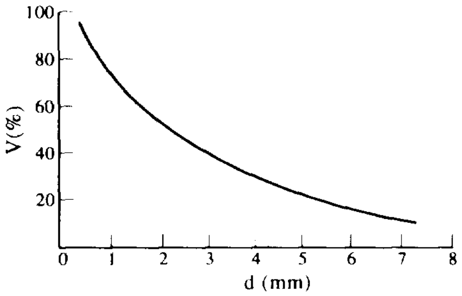

*Fig 7 The relationship between the vascular fibre volume fraction (*V*) and the distance from the outside surface (*d*)*

The cleavage strength and the transverse tensile strength of a bamboo stem are several MPa, while its longitudinal tensile strength reaches 100–400 MPa[7]. The bundle fibre volume fraction (*V*) of a bamboo stem of *Phyllostachys pubescens* decreases with the distance (*d*) from its natural surface and there exists a similar relationship between the longitudinal tensile strength and the bundle fibre volume fraction. Figure 7 illustrates[7] the relationship between *V* and *d*. An increase in the bundle fibre content can improve the elastic modulus and longitudinal tensile strength of bamboo stem. Yakou and Sakamoto[3] measured the hardness of *Phyllostachys pubescens* and demonstrated that the average hardness of the fibre and matrix tissue decreased continuously from the outside surface toward the inside surface. Therefore, it is considered that the abrasion resistance of the surface layer of a bamboo stem (P_s-type specimen) is higher than that of its inner layer (P_I- and AP-type specimen) due to higher vascular fibre content and greater hardness. Because of the lower cleavage strength and transverse tensile strength of a bamboo stem, abrasive particles easily cut the surface layer of P_I- and AP-type specimens to generate grooves, microcracks and brittle rupture. Since the vascular bundle consists of sclerenchyma phloem fibres, its ductility and strength are higher than those of the matrix tissue which consists of leptodermous cells and, therefore, the vascular bundle gives better abrasion resistance than the matrix tissue. During a wear test of the N-type specimen, a certain depth of matrix tissue was first removed by microcutting and microcracking mechanisms to bare the end of the bundle fibres on the matrix. Rolling of abrasive particles may occur on such an abrading surface and further removal of matrix tissue is hindered by the bared ends of the bundle fibres. This phenomenon may be considered as an unsmoothed effect in free abrasive wear of fibre-reinforced composites, similar to the unsmoothed surfaces in studies on soil adhesion and sliding resistance[8,9]. This would become important for bionics design of polymer- and metal-matrix composites and the microstructure of steel for soil-engaging components in agriculture.

Conclusions

The free abrasive resistance of a bamboo stem is affected by the vascular bundle fibre orientation with respect to the abrading surface and abrasive particle sizes. Abrasion depth of bamboo decreases as abrasive particle size decreases. Normally oriented specimens give much higher abrasion resistance than parallel-oriented ones, the surface layer than the inner layer, and the vascular bundle than the matrix tissue.

Acknowledgements

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