Tensile Properties and Mechanism of Laser-cut Bamboo Slivers

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This study aimed to evaluate the tensile properties and the failure mechanisms of bamboo slivers that were subjected to different methods of laser-cutting with changing parameters. The failure of the sample was observed through *in situ* tensile testing combined with scanning electron microscopy. The results indicated that laser-cutting could achieve high efficiency and minimal size variation in machining; however, the calculated sample size needed modification. When the laser power, cutting rate, and sample size were equal to 40 W, 5 mm × s^{-1}, and 2 mm, respectively, the achieved tensile strength was 328.8 MPa, and the tensile modulus was 25.2 GPa. During testing, the surface of the laser-cut sample exhibited brittle fractures (with its interior typically damaged between the basic tissue and the fiber interface), fiber breakage, and fiber extraction.

Keywords: Bamboo sliver; Laser-cut; Tensile properties; In situ tensile

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INTRODUCTION

Bamboo is an important forest resource due to its green environmental protection, broad application, and excellent mechanical properties (*e.g.*, high strength and satisfactory toughness). It is widely used in architecture, furniture, and transportation, among other industries (Vogtländer *et al.* 2010; Zhang *et al.* 2011; Deng *et al.* 2016). As a functional gradient material, bamboo exhibits a mechanical performance mainly determined by its vascular bundle or the performance of the fibrous sheath (Shang 2011; An 2013). Numerous studies have shown that the tensile strength of bamboo slices, vascular bundles, sheaths, and fibers gradually increased successively. In addition, the tensile strength of the bamboo wall layer gradually decreases from the outside to the inside (Cao 2010; Liu 2010; An 2013; Chen *et al.* 2015).

With the development of bamboo industrialization, different processing units of bamboo are industrialized and marketed. The fine planning bamboo slivers and bamboo bundles are the processing units that comprise a large proportion of the current market for the utilization of bamboo. Fine bamboo sticks retain the strength of bamboo while bamboo bundles retain the toughness of bamboo (Meng *et al.* 2011; Yu 2012; Zhang 2012; Yu 2014; Chen *et al.* 2017). Additionally, bamboo slivers comprise the third-largest processing unit of bamboo material in large-scale applications. Bamboo slivers both retain the high strength of the bamboo material and fully exhibit the toughness of bamboo, providing a high value-added utilization of the bamboo material. Bamboo slivers, one of the most important units for bamboo application, is a form of bamboo processing and utilization. It is used in laminated bamboo, woven handicrafts from bamboo slivers, bamboo sliver winding pipes, and other products. Therefore, the performance of bamboo slivers directly determines the performance of the products made from bamboo slivers. To use bamboo slivers more effectively and to optimize their performance, their basic properties need to be more accurately determined. The tensile property is one of the important basic mechanical properties of bamboo sliver products. Traditional testing of the tensile property of bamboo sliver includes direct measurement, patch strengthening, and dumbbell-milling.

With the development of science and technology, laser engraving and laser cutting have become common techniques. Bamboo materials can be easily cut, particularly into a dumbbell shape, with a laser. The tensile performance of bamboo strips can be easily tested. Laser-cutting exhibits a strong controllability, good processing quality, high precision, and high efficiency; thus, it has been widely used to process metal, plastics, wood, and other materials (Fang *et al.* 2003; Choudhury and Shirley 2010; Li *et al.* 2016). Laser-cutting uses laser energy directly on the surface of the material, producing an amount of heat that can be sufficient to cause the material to melt, burn, or gasify to separate the material (Tong *et al.* 2010; Stepanov *et al.* 2015). Studies have been conducted to evaluate the influencing factors of laser cuts on wood and to evaluate application of this approach in the bamboo and wood industries (Sun and Yan 2000; Eltawahni *et al.* 2013; Xu *et al.* 2016; Zhao *et al.* 2016). However, no research has been reported regarding the effects of laser cuts on the properties of bamboo.

To improve the efficiency and the speed of evaluating the tensile properties of bamboo sticks, this study evaluated the influence of the method on the tensile properties of bamboo slivers through comparing laser-cutting with traditional techniques (direct measurement, patch strengthening, and dumbbell milling). Additionally, the effects of the parameters of laser cuts on the tensile properties of bamboo slivers and the failure mechanism were investigated. The aim of this study is to explore the feasibility and reliability of using laser cutting in processing samples for the tensile testing of bamboo slivers and to provide reference for testing method.

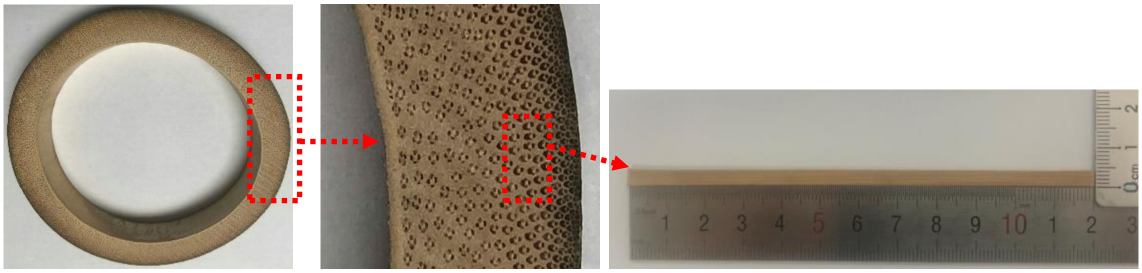
EXPERIMENTAL

Materials

Four-year-old Moso bamboo (*Phyllostachys pubescens*) was obtained from Anji, Zhejiang Province, China. The initial moisture content of the bamboo ranged from 8% to 12%. The experimental equipment included a mechanical testing machine (Instron 5582; Instron, Norwood, MA, USA), field emission environment scanning electron microscope (FEG-ESEM, XL30; FEI Company, Hillsboro, OR, USA), stereo microscope with INFINITY analysis software (Camera Model-Li165; Lumenera, Ottawa, Ontario, Canada), a scanning electron microscope (Quanta 2000; FEI Company, Hillsboro, OR, USA), a microtester (2 kN; Deben UK Ltd., London, UK), laser cutter machine (CMA-6040; Guangdong Dazu Yueming Laser Company, Dongguan, China), and an electronic digital caliper.

Sample preparation

The bamboo strip was obtained from a component close to the outer layer of the bamboo (Fig. 1), as typically used in factories.



(a) (b) (c)

Fig. 1. Images of bamboo sliver (c) prepared from bamboo culm (a) and bamboo cross-section (b)

The strip was mechanically isolated by a bamboo strips machine (Anji Demai Bamboo & Wood Machinery Co., Ltd., Huzhou, China). The bamboo culm was cut into slivers of fixed dimensions (1200 mm in length and 4 mm in width) and then processed into rectangular shapes. Four methods including untreated, reinforced rectangle, mechanical processing into a dumbbell shape, and laser-cut processing into a dumbbell shape were used to process tensile samples. Finally, the untreated bamboo slivers, or sample A, as shown in Fig. 2 (a), that measured 120 mm × 4 mm × 1 mm (length × width × thickness) were processed. The reinforced rectangle bamboo slivers, or sample B, as shown in Fig. 2 (b), rectangular bamboo slivers were attached with poplar veneer using epoxy resin as the reinforcing sheet to prevent the holding end from cracking due to stress concentration. The mechanical processing into a dumbbell shape bamboo slivers, or sample C, as shown in Fig. 2 (c), rectangular bamboo slivers were obtained *via* mechanical processing of dumbbell bamboo slivers, and the dumbbell-type bamboo slivers were processed with a Bosch Dremel 4000 engraving machine (Dremel, Racine, WI, USA). The center design width was 2 mm.

The side of samples near the outer layer of the bamboo were up, and processed using a CMA-6040 laser cutter (Guangdong Dazu Yueming Lase Company, Dongguan, China), and the experimental equipment provides the CO_2 laser with the wavelength of 10.64 μm and maximum power output of 80 W (Li *et al.* 2016). The processing parameters of the sample are listed in Table 1, and the morphology is shown in Fig. 2 (c) and (d).

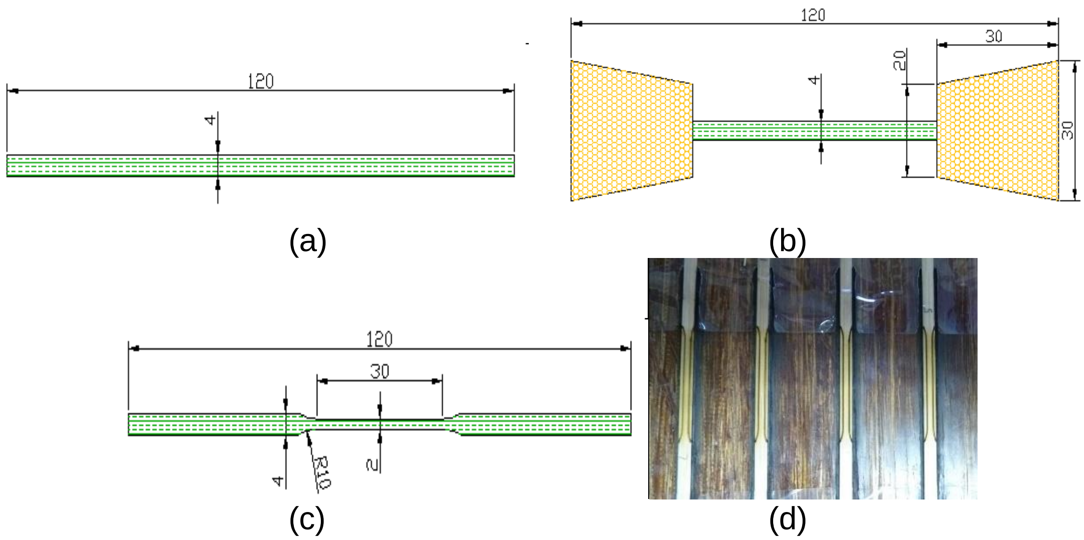


Fig. 2. Schematic of sample size obtained using different methods: (a) untreated bamboo slivers (sample A), (b) reinforced with plates and bamboo slivers (sample B), (c) dumbbell-shaped bamboo slivers (samples C and D with mechanical processing and laser cuts), and (d) laser-cut samples

Table 1. Parameters of Laser-cut Bamboo Slivers

Sample	D	E	F	G	H	I	J
LP (W)	40	36	44	40	40	40	40
CR (mm $\times$ s^{-1})	5	5	5	2	8	5	5
DW (mm)	2	2	2	2	2	1	1.5

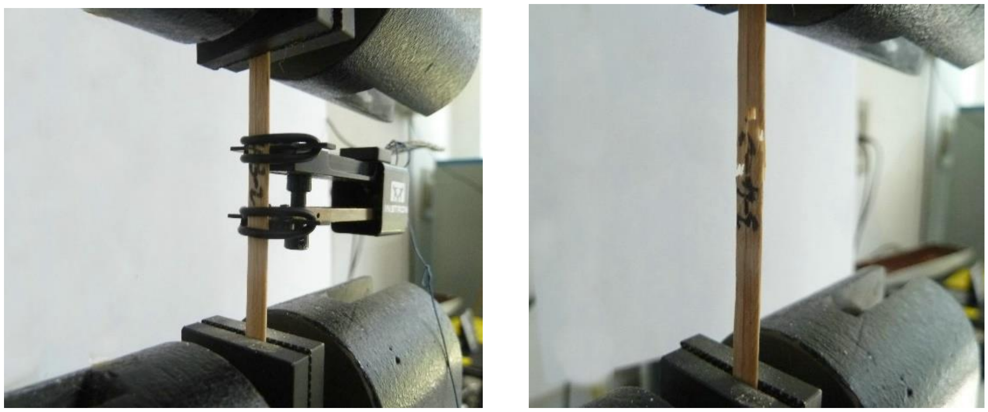
LP- laser power; CR- cutting rate; DW- design width (as shown in Fig. 2 (c))

Methods

Properties test

The cross-sections of the bamboo slivers were observed using a stereo microscope (Camera Model-Li165; Lumenera, Ottawa, Ontario, Canada), and the morphology of the cross-sections of the bamboo slivers was recorded with an INFINITY1 microscope camera (Lumenera, Ottawa, Ontario, Canada).

The tensile properties of the bamboo slivers were evaluated using a high-resolution commercial mechanical tester (Microtester 5582; Instron, Norwood, MA, USA) with a strain rate of 3.0 mm/min at an ambient environment of 25 °C and 65% relative humidity. A contact extensometer (scale designation: 12.5 mm) was used to measure the tensile strain and calculate the tensile modulus (Fig. 3). A total of 12 samples of each type were tested. All strain measurements in this study were obtained through determining the crosshead displacement.



(a) (b)

Fig. 3. Tensile property testing results of bamboo slivers: (a) tensile modulus with extensometer and (b) bamboo sliver with brittle failure

The destructive electron microscopy morphology of bamboo slivers was observed using field-emission environmental scanning electron microscopy (FEG XL-30).

The tensile failure of the bamboo slivers was measured through *in situ* electron microscopy tensile testing, including the use of Quanta 2000 electron microscopy and a Microtest 2000 micromechanical experimental machine. The load of the sensor was 2 kN and the loading rate was 0.1 mm/min.

RESULTS AND DISCUSSION

Laser-cutting Effects on Bamboo Sliver Morphology

The sizes of the bamboo slivers that were processed using four methods are listed in Table 2. The widths of the center of the bamboo slivers were affected by the applied method. With respect to the width and the variation coefficient under the four methods, the sequence in decreasing order was C, D, and B, which was similar to A. Among these samples, the width of sample C largely varied with the design width, and the variation coefficient of the central width of the sample was the largest. This indicated a low dimensional accuracy of the machined sample and a low success rate of machining. The width of the bamboo sliver processed *via* laser-cutting was smaller than the design width, and the error ranged from 0.25 mm to 0.15 mm. The cross-sections of samples D, I, and J were presented as under the narrow width of the isosceles trapezoid (Fig. 4). The angle between both sides and the bottom was approximately 80°, as determined using the INFINITY software. Corrugated lines appeared on the cutting surface, which led to the erroneous measurement of the sample width. The thickness of the laser-cut sample was assumed to be the trapezoid height (LG), which was equal to 1 mm. The width of the sample was the bottom length of the trapezoid (LX). The length of the trapezoid (LS) was $LX - (2 \times LG \times \cot(80°))$. The theoretical variation between the upper surface width and the lower surface width of the sample was 0.35 mm.

Table 2. Dimensions of Bamboo Slivers Processed Using Different Methods

Sample	A	B	C	D
DW (mm)	4.00	4.00	2.00	2.00
W (mm) (CV)	4.06 (1.21)	4.04 (1.23)	1.56 (10.37)	1.85 (3.25)
T (mm) (CV)	1.09 (5.86)	1.08 (5.87)	1.04 (4.8)	1.05 (4.71)

DW- design width; *W*- width; *T*- thickness; CV- coefficient of variance

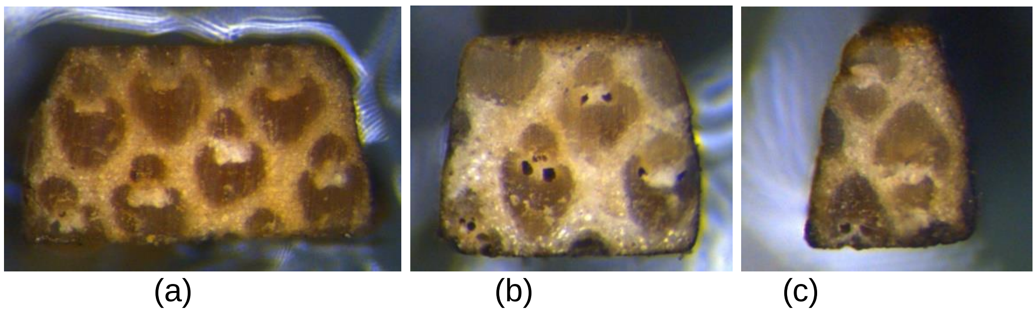


Fig. 4. Cross-section of bamboo slivers with different design dimensions: (a) design width = 2 mm, (b) design width = 1.5 mm, and (c) design width = 1 mm

Figure 5 shows the surface microtopography of both the untreated bamboo sliver and the laser-cut bamboo sliver. Figure 5(b) shows that the laser-cut bamboo sliver exhibited a smooth surface, surface burning, and carbide densification without burr. In addition, the surface of the vascular bundle fiber cap, vascular bundle sheath, xylem, and phloem were carbonized and formed a smooth surface. The part of vascular bundles and parenceymal cells became grooves and pits, respectively, and the boundaries of vascular bundles and parenceymal cells disappeared, as shown in Fig. 5(b) (Jiang *et al.* 2004; Zhang *et al.* 2006; Shao *et al.* 2009; Tian *et al.* 2012).

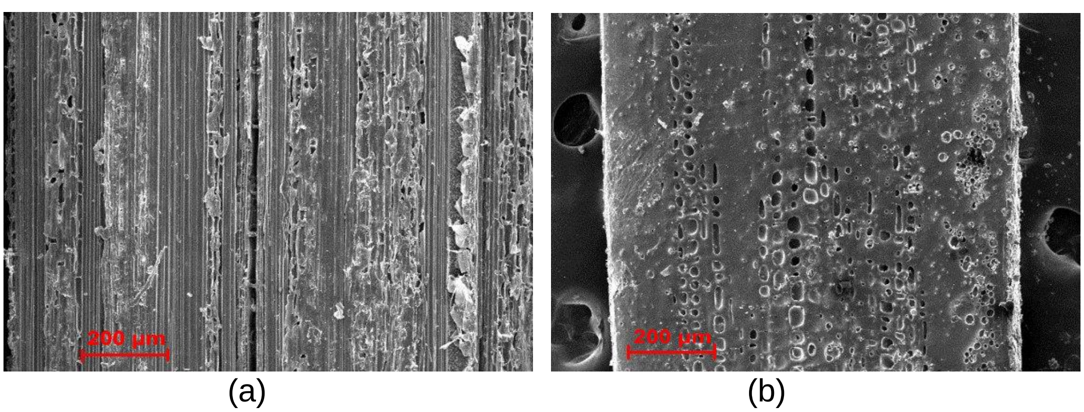


Fig. 5. Surface microtopography of bamboo slivers: (a) untreated bamboo sliver and (b) laser-cut bamboo sliver

Effects of Different Methods on the Tensile Properties of Bamboo Slivers

Table 3 shows the tensile strength and the tensile modulus of the bamboo slivers under the four different processing methods. The tensile strength of the samples came in the following descending order: C > B > D > A. The tensile modulus of the samples was in the order: A ≈ C > D ≈ B. Figure 6 shows the load-displacement diagram of the samples under their different processing methods. The results indicated that the slope of the load-displacement curve of sample A was higher than that of sample B even though the samples were similar in size. The reason was because reinforcing plates were used for the clamping compression, resulting in a lower modulus than the actual value. The slope of the load-displacement curve of sample D was higher than that of sample C, which was not consistent with the calculated modulus. This difference was attributed to the dimensional measurement error for D, causing the calculated result to be lower than the real value. Comparison of the four curves showed that the curves A, B, and C had one load reduction caused by the removal of the extensometer during testing. The bamboo slivers eventually exhibited brittle failure. The first load reduction of sample D was similar to those of other samples but was followed by multiple failures. The reason was because the surface of sample D was carbonized and brittle after being laser-cut, thus damaging the bamboo slivers and reducing their tensile properties.

Table 3. Tensile Properties of Bamboo Sliver Processed Using Different Methods

Sample	A	B	C	D
Load (N) (CV)	1325.58 (11.1)	1354.71 (11.61)	605.53 (15.88)	581.92 (11.87)
TS (MPa) (CV)	286.95 (11.94)	311.58 (14.65)	368.88 (8.52)	297.49 (12.28)
TM (GPa) (CV)	24.91 (12.56)	22.87 (9.06)	24.51 (10.18)	22.79 (8.09)

TS- tensile strength; TM- tensile modulus

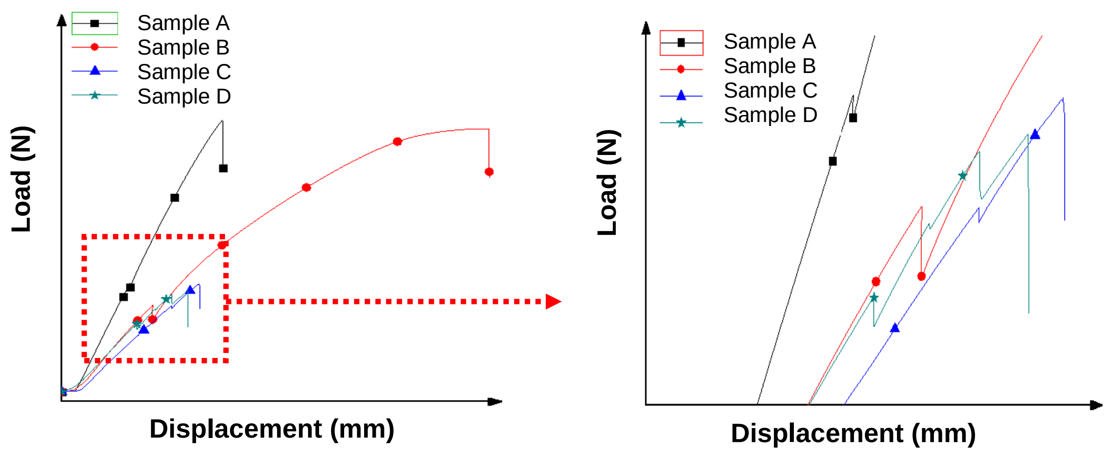


Fig. 6. Load-displacement curves depicting different processing methods

The tensile properties of the bamboo slivers were affected by the different processing techniques. The untreated bamboo slivers of sample A achieved low failure rates, most of which occurred in the clamped position. The tensile strength of sample A was the lowest, only approximately 286.95 MPa. In addition, the load-displacement curve of the tensile modulus of the calculated and selected linear areas achieved the highest results (approximately 24.9 GPa), which could be considered as the real value of the bamboo sliver. At both ends of the bamboo slivers of sample B, reinforcing plates were added to improve the success rate of the test. However, slippage of the reinforcing plates occurred in some samples. The tensile strength of the tested sample B increased to 311.6 MPa, but the tensile modulus decreased to 22.9 GPa. The processing efficiency of sample B was the lowest.

The bamboo sliver that was mechanically processed into a dumbbell-shape (sample C) resolved the side damage of the sample, and improved the testing success rate. However, the processing efficiency of sample C was low, and machining traces easily appeared on the surface of the samples. The sample C needed to be sanded twice to improve the surface machining precision and to reduce size variation. The mechanical processing retained the original properties of the bamboo slivers, and the tensile modulus of sample C was 24.5 GPa, which was consistent with sample A. The tensile strength of sample C was 368.9 MPa, which was the highest among the values measured using the four different processing methods. The bamboo sliver that was laser-cut into a dumbbell-shape (sample D) exhibited a high processing efficiency, and the variation coefficient of the sample size was relatively small because the surfaces of the bamboo sticks were burned and carbonized by the laser. In addition, the sample D was an irregular trapezoid, and the measured dimension of the sample D was greater than the actual value. The tensile strength and tensile modulus of sample D were 297.5 MPa and 22.8 GPa, respectively, which were smaller than those of sample C.

To modify sample D, the upper bottom width and the median line width of the trapezoid were used in the calculation of the sample size: LX - 0.35 mm and LX - 0.175 mm, respectively. The tensile strength and the tensile modulus were calculated using the INSTRON software. When calculated with the top width, the tensile strength and tensile modulus were 368.6 MPa and 28.2 GPa, respectively. The calculated tensile strength was consistent with that of sample C; however, the calculated tensile modulus was considerably higher than that of sample C. When calculated with the median width, the tensile strength and tensile modulus were 328.8 MPa and 25.2 GPa, respectively. The calculated tensile modulus was closer to that of sample C. Thus, when the laser power was 40 W and the cutting rate was 5 mm $\times$ s^{-1}, the upper bottom width and the middle width could be used to calculate the tensile strength and tensile modulus of the laser-cut sample, respectively.

Effects of Different Laser Parameters on the Properties of Bamboo Slivers

The laser power and the cutting speed largely influenced the laser efficiency and the surface quality of the material. A higher laser power and a lower laser-cutting speed resulted in a greater energy per unit area or per unit time. In addition, the slit width and the thermal influence area were observed, which might have increased the severity of burns on the material surface. In contrast, a lower laser power and a higher laser-cutting speed resulted in the material being difficult to cut off. Therefore, to ensure a good quality cutting of the sample, an appropriate cutting speed should be selected. Additionally, the work efficiency and the cutting time should be shortened as much as possible, and an appropriate laser power and cutting speed should be selected.

Table 4 shows the tensile properties of bamboo slivers cut by laser with different laser power, and with a cutting speed of 5 mm $\times$ s^{-1}. The tensile modulus of the bamboo strips decreased when the laser power was increased. The highest tensile strength was achieved at a laser power equal to 40 W. When the laser power was 36 W, the cutting depth of part of the sample was lower than the thickness of the sample, and the sample could not be completely cut off, requiring artificial separation. By increasing the laser power, the difference in the laser absorption capacity between the upper surface and the lower surface of the bamboo sticks increased, and the difference in the size of the width increased. The measured size was higher than the real value, and the lowest calculated tensile strength was achieved. When the laser power was 44 W, the bamboo surface exhibited a large coverage of burns, hence the lowest tensile modulus.

Table 4. Tensile Properties of Bamboo Sliver with Different Levels of Laser Power

Sample	LP (W)	*W* (mm) (CV)	Load (N) (CV)	TS (MPa) (CV)	TM (GPa) (CV)
D	40	1.85 (3.25)	581.92 (11.87)	297.49 (12.28)	22.79 (8.09)
E	36	1.89 (4.79)	574.28 (13.95)	290.68 (8.61)	22.84 (10.43)
F	44	1.92 (6.00)	523.31 (9.79)	253.87 (8.46)	19.59 (9.32)

LP- laser power; *W*- width; TS- tensile strength; TM- tensile modulus

Table 5 shows the tensile properties of the bamboo slivers with different cutting speeds and with a laser power of 40 W. The variation coefficient of the sample size decreased with an increase in the cutting speed. When the cutting speed was set at 8 mm $\times$ s^{-1}, the highest tensile strength and the largest tensile modulus of the bamboo slivers were achieved, and the laser only slightly influenced the performance of the sample. When the cutting speed was low, the upper surface of the sample was severely burned, and the width of the bamboo sticks exhibited the largest variation from that of the design width.

Table 5. Tensile Properties of Bamboo Sliver with Different Cutting Rates

Sample	CR (mm $\times$ s^{-1})	*W* (mm) (CV)	Load (N) (CV)	TS (MPa) (CV)	TM (GPa) (CV)
D	5.00	1.85 (3.25)	581.92 (11.87)	297.49 (12.28)	22.79 (8.09)
G	2.00	1.51 (3.30)	463.97 (15.04)	303.46 (8.44)	23.78 (9.39)
H	8.00	1.71 (2.20)	591.81 (16.02)	332.74 (11.12)	28.01 (9.68)

CR- cutting rate; *W*- width; TS- tensile strength; TM- tensile modulus

Table 6 shows the tensile properties of the bamboo slivers with different design sizes, a laser strength of 40 W, and a cutting speed of 5 mm $\times$ s^{-1}. The actual sizes of the samples were smaller than their respective design values, which was an error. The smaller design width size of samples, the greater influence on its width size. In addition, the variation coefficient of the width increased, and the carbonized surface layer largely affected the tensile properties of the bamboo sticks, which resulted in a larger design width and a lower tensile strength and tensile modulus. The tensile strength and tensile modulus of samples I and J exhibited lower values than those of sample D.

Table 6. Tensile Properties of Bamboo Sliver with Design Size

Sample	DW (mm)	*W* (mm) (CV)	Load (N) (CV)	TS (MPa) (CV)	TM (GPa) (CV)
D	2.00	1.85 (3.25)	581.92 (11.87)	297.49(12.28)	22.79 (8.09)
I	1.00	0.77 (7.39)	138.19 (25.92)	168.25 (20.57)	17.07 (8.91)
J	1.50	1.22 (3.26)	289.04 (7.67)	224.41 (9.47)	18.65 (12.23)

DW- design width; *W*- width; TS- tensile strength; TM- tensile modulus

Mechanism of Tensile Failure on Laser-cut Bamboo Slivers

Figure 7 shows the morphology of the fiber pulling-breaking interface of the laser-cut bamboo slivers. The bamboo fiber was drawn from the basic tissue, which showed that the basic tissue between the fiber interfaces was the weak point (Fig. 7). Burrs were formed on the surface of the basic tissue.

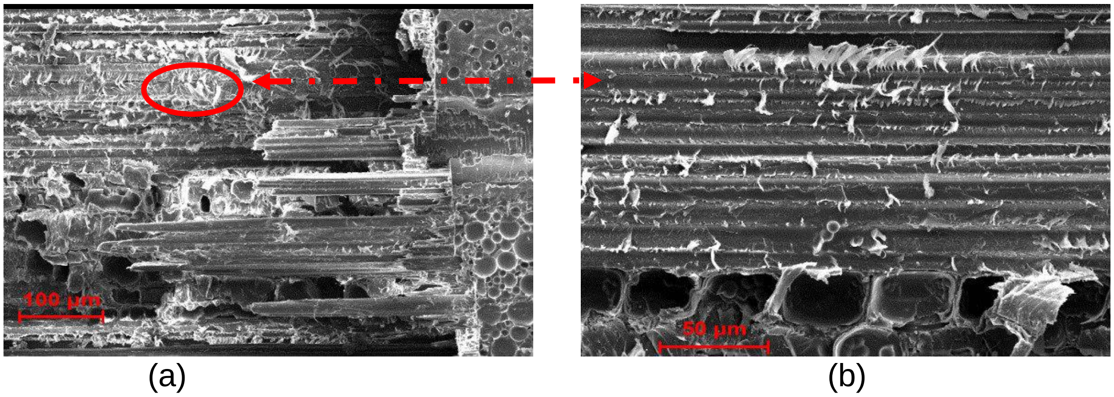


Fig. 7. Tensile fracture of laser-cut bamboo slivers: (a) surface of laser-cut bamboo sliver and (b) inner fracture morphology of bamboo

Figure 8 shows the dynamic failure process of *in situ* tensile testing of the laser-cut bamboo slivers. As shown in Fig. 8, the surface of the bamboo sliver produced carbonized burns and presented a trapezoidal shape with a narrow upper width and a larger lower width during stretching. Microcracks were first formed on both sides of the bamboo strips, and no fiber bundles were pulled out on both sides of the bamboo sliver. When the load was increased, the crack propagate into parenceymal cells or the interface between bamboo fibers and parenceymal cells. The surface of the bamboo parenceymal cells was torn, or the interface between fibers and parenceymal cells engendered slips, which result in the burrs generated on the surface of the parenceymal cells (Fig. 7). Bamboo fibers were finally pulled out or broke from the vascular bundles or parenceymal cells (Amada *et al.* 1997; Shao *et al.* 2009; Liu 2010; Tian *et al.* 2012).

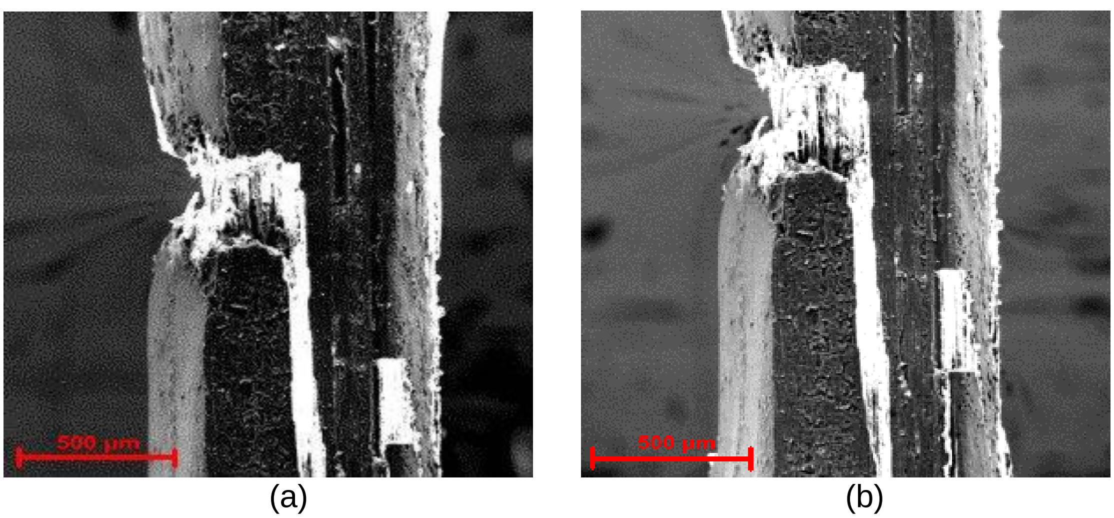


Fig. 8. *In situ* SEM images of tensile property of laser-cut bamboo slivers: (a) initial destruction of bamboo sliver and (b) peak load failure of bamboo sliver

CONCLUSIONS

1. Laser-cutting processing of bamboo silvers could achieve low size variation. When calculated with the median width of bamboo silvers, the tensile strength and tensile

modulus were 328.8 MPa and 25.2 GPa, respectively.

2. The laser-cutting parameters affected the performance of the sample. For the bamboo slivers, the optimal laser power, cutting rate, and sample size found in this study were 40 W, 5 mm × s^{-1}, and 2 mm, respectively.
3. During the testing of the laser-cut bamboo slivers, brittle fracture was observed on the surface of the bamboo slivers. In addition, interface separation between the bamboo fibers and the parenceymal cells, bamboo fibers fracture and fiber pulling mainly occurred in the internal component.

ACKNOWLEDGMENTS

This research was supported by the National Key R&D Program of China, Grant No. 2017YFD0600802, and Public Technology Research Program of Zhejiang province, China, Grant No. LGG18C160001.

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Article submitted: February 12, 2019; Peer review completed: March 29, 2019; Revisions received: April 19, 2019; Revisions accepted: April 23, 2019; Published: April 25, 2019. DOI: 10.15376/biores.14.2.4708-4720