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Possibility of nosing of common Japanese bamboo

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Bamboos, which are abundant in the Asian region and mature in approximately half a year, can be harvested within 3 to 4 years as they are fast growing plants. Since the bundle sheaths of bamboo are graded from the epidermis to the pith cavity [1], bamboo possesses good mechanical characteristics as a light-weight composite material [2]. There are two ways of using bamboos as engineering materials. In the first, the bamboo fiber is used, and applications include paper manufacturing employing bamboo fiber as the raw material, and the use as reinforcement fibers in fiber-reinforced composite materials [3, 4]. The second way, which includes forming, bamboos are used as bulk materials. To use bamboos as bulk engineering materials in the fields of architecture, furniture manufacturing and machines, the development of a forming technology which enables the provision of dimension and shape is important. The forming of bamboos has a long history; in Japan, flattening of bamboos was initiated in the 1910s [5]. Recently, flattening technologies of bamboos which use microwave heating have been developed [6]. In these technologies, flattening of bamboos which are cut lengthwise into half is involved. Forming technologies which make use of the original tubular shape of bamboos have rarely been examined, except for those which involve the bending of bamboos. If the application of tube-forming technologies that are currently employed for metals, such as nosing, to bamboos is possible, then bamboos can have the potential for the realization of unique engineering materials having light weight and high strength. In this study, we experimentally examined the possibility of nosing bamboos.

We used common Japanese bamboos (Madake: *Phyllostachys bambusoides*) with outer diameters between 54 mm and 59 mm (thicknesses between 4 mm and 6 mm). Bamboo specimens of 65 mm length were cut from internodes, and used for the experiments after soaking in water until saturation. Hereafter, the average outer diameter D_m is defined as the arithmetic mean of the maximum and minimum outer diameters of the same bamboo specimen, and the thickness to outer diameter ratio is calculated as t_m/D_m where t_m is defined as the arithmetic mean of the maximum and minimum thicknesses of the bamboo specimen.

First, a bamboo specimen was covered with cling-wrap and heated with 1.17 kW microwave irradiation until the specimen was thermally softened. After removing the cling-wrap, the specimen was introduced into the die shown in Fig. 1a for nosing. The die used was a stainless-steel conical die (half-apex angle $\alpha = 15^\circ$, 30°, or 45°) having a side-restriction guide with a 60 mm internal diameter. The dies were pre-heated in a constant-temperature oven at 105 °C for 1 h, and used for the nosing experiments immediately after removal from the oven. The surface temperature of the bamboo specimen after the removal of the cling-wrap was approximately 110 °C, and that at the start of nosing after introduction into the pre-heated die was approximately 105 °C. The nosing rate was 1.5 mm/s. Nosing was performed without lubricant; however, since hot water was extracted from the bamboo specimen in contact with the die, strictly speaking, the condition cannot be regarded as a complete lubricant-free condition. To set the deformation, the die containing the bamboo specimen was heated and dried in the constant-temperature oven at 105 °C for 2 h, taken out from the oven and air-cooled. After this process, the nosed product was removed from the die, its deformed shape was observed and the outer diameter

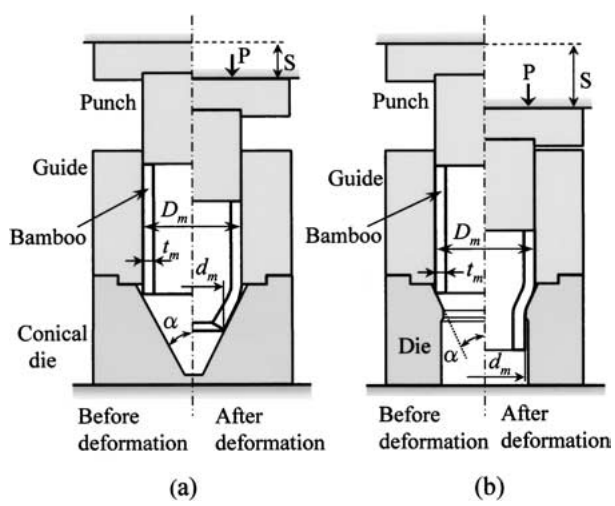


Figure 1 Schematic illustration of conical nosing and reducing of internodes of bamboo culms. (a) Conical nosing and (b) reducing.

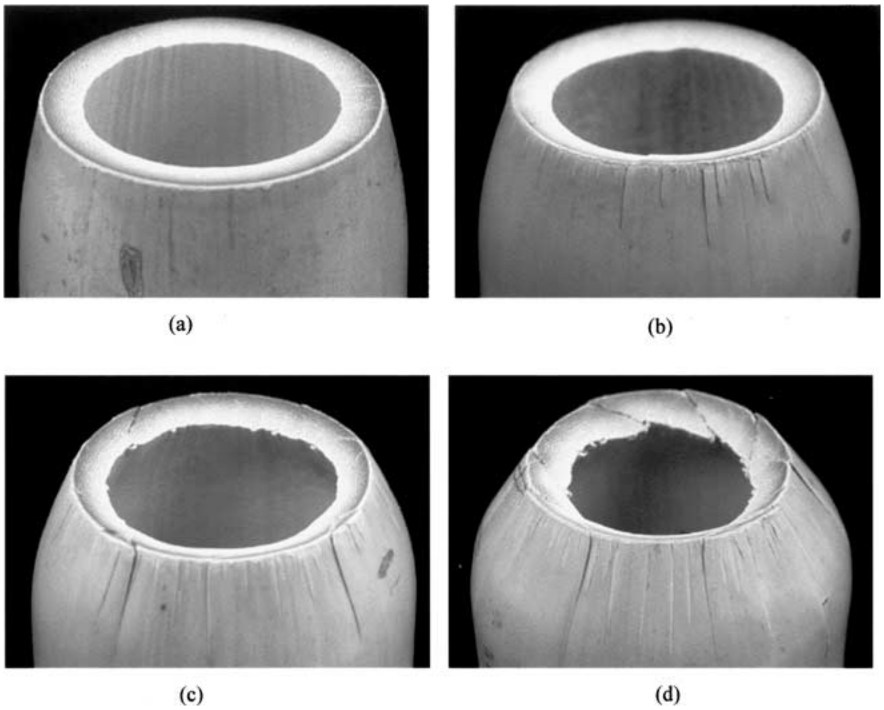


Figure 2 Photograph showing the nosing sequence ($\alpha = 45\,^\circ$, Nosing ratio: $\kappa = (D_\mathrm{m} - d_\mathrm{m})/D_\mathrm{m}$). (a) $\kappa = 0.13$; Success, (b) $\kappa = 0.24$; Splits occurred in the epidermis, (c) $\kappa = 0.28$; Crack growth, and (d) $\kappa = 0.38$; Rupture.

at the tip of the nosed section was measured using a digital vernier caliper. The arithmetic mean of the maximum and minimum measured values of outer diameter was calculated to obtain the average outer diameter d_m. In this experiment, the nosing ratio defined as $\kappa = (D_\mathrm{m} - d_\mathrm{m})/D_\mathrm{m}$ was used as an index of forming [8].

Fig. 1b shows the reducing of bamboo. Here, two dies ($\alpha = 30\,^\circ$) with a post reduction diameter of 45 mm or 52 mm were used. The forming conditions are the same as those of the nosing experiments. The maximum and minimum diameters of a bamboo specimen before and after reducing were measured using a digital vernier caliper, to obtain the departures from roundness of the specimen before and after reducing.

Fig. 2 shows the external appearance of bamboo specimens after nosing. As shown in Fig. 2a, a good nosing condition without the occurrence of splits was obtained at $\kappa = 0.13$. However, when $\kappa = 0.24$ as shown in Fig. 2b, many splits developed in the epidermis from the edge of the nosing in the meridian direction. As the forming process progresses and $\kappa = 0.28$ as shown in Fig. 2c, cracks originating from the numerous splits in the epidermis advanced diagonally inside. When $\kappa = 0.38$ as shown in Fig. 2d, these cracks reached the pith cavity to the state of rupture, and the edge of the bamboo specimen was nosed while the edge of the epidermis was rolled inward. Thus, the nosing of the bamboo specimen is possible, but the nosing limit is determined by the occurrence of splits in the epidermis. Here, up to the stage shown in Fig. 2c, only the edge is in contact with the die, and the taper angle of the conical section of the bamboo is smaller than α of the die (this corresponds to the bending deformation process [8] in the early period of conical nosing

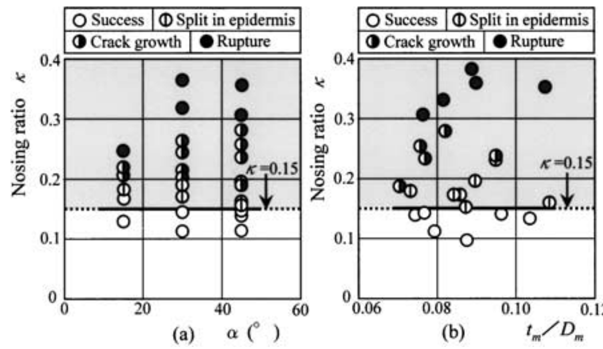


Figure 3 The occurrence condition of a split in the epidermis. (a) Half apex angle of conical die α ($0.07 \leqq t_\mathrm{m}/D_\mathrm{m} \leqq 0.11$) and (b) thickness to diameter ratio $t_\mathrm{m}/D_\mathrm{m}$ ($\alpha = 45°$).

of metal tubes). Although nosing is possible, it is difficult to achieve forming with a desired half-apex angle under the condition in which no splits occur in the epidermis.

Fig. 3a shows the effects of the α on the occurrence of splits. The κ at the occurrence of splits in the epidermis when $\alpha = 15°$ is slightly higher than when $30\,^\circ$ or $45\,^\circ$. However, $\kappa \cong 0.15$ can be an index of occurrence of splits. Fig. 3b shows the effects of the $t_\mathrm{m}/D_\mathrm{m}$ on the occurrence of splits. Splits occurred at $\kappa \cong 0.15$, regardless of the $t_\mathrm{m}/D_\mathrm{m}$.

When hard metal tubes are nosed, sometimes many grooves develop in the meridian direction [7]. For this deformation mode, a mechanism in which grooves develop in the meridian direction originating from the shear band has been proposed for nosing of metal tubes [7]. Since this deformation mode has not been observed in soft tubes, this mode is considered to be a deformation mode specific to hard tubes [8]. Similar to other

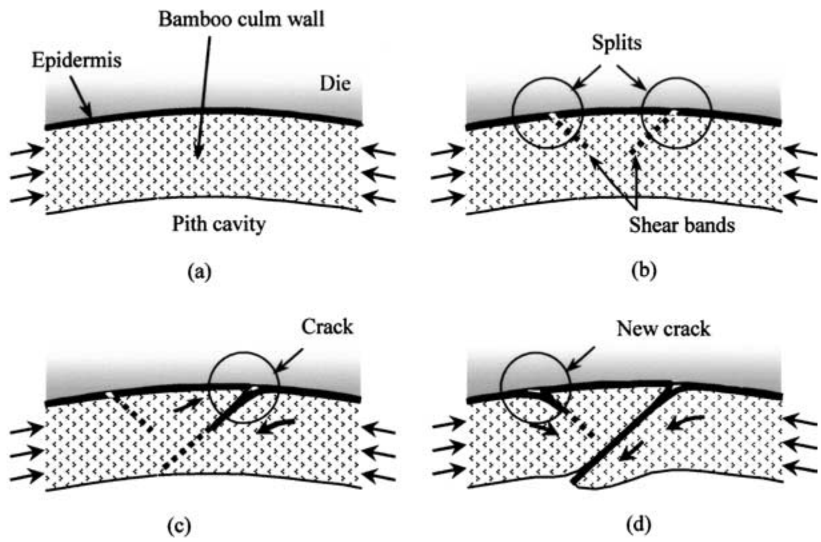


Figure 4 Circumferential deformation sequence showing the split and crack growth associated with the shear band formation. (a) Uniform deformation, (b) split initiation, (c) crack growth, and (d) rupture.

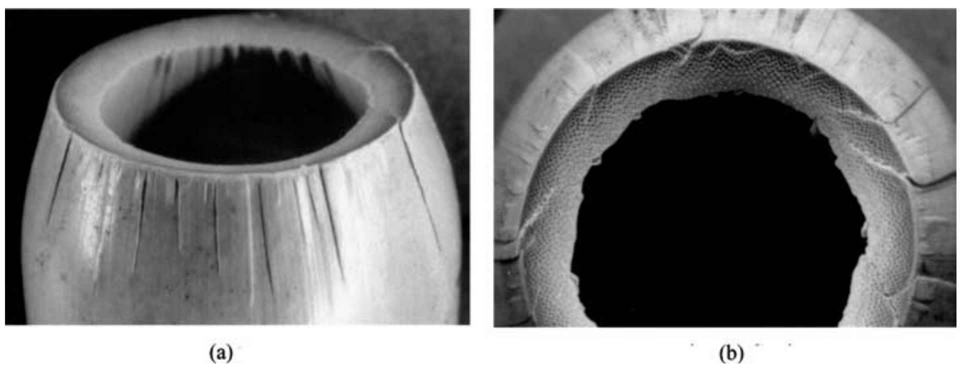
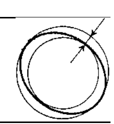


Figure 5 Photograph showing cracks associated with splits. (a) Splits in epidermis, and (b) cracks progressing to the pith cavity.

bamboos, a larger number of bundle sheaths are present and soft tissues (Parenchymatous ground tissue) become scarce near the epidermis in common Japanese bamboos. In contrast, compressive deformation occurs mainly in soft tissues during the flattening of bamboo [9]. Accordingly, it is considered that a graded structure, in which compressive deformation hardly occurs near the epidermis, is present in common Japanese bamboos. If a shear band develops during nosing of common Japanese bamboos, its process of development is considered to be as follows: as shown in Fig. 4, splits develop along the shear band from the hard epidermis which is hardly subjected to compressive deformation, and then the cracks propagate along the shear band diagonally toward the pith cavity. As described above, according to the experimental results, first splits developed in the epidermis, and then cracks originating from these splits propagated toward the pith cavity. As shown in Fig. 5, cracks propagate from the epidermis to the pith-cavity side. Thus, the split-development mechanism predicted from the shear-band mode agrees with the experimental results. Therefore, splits in the epidermis are considered to develop due to the transition of the deformation mode from the "uniform compressive deformation mode" in the circumferential direction in the epidermis where compressive deformation hardly occurs, to the "shear-band mode". Based on this consideration, the reason that splits in the epidermis occurs under the constant condition of a κ value of approximately 0.15, regardless of the nosing half-apex angle or thickness to outer diameter ratio, is speculated to be that the epidermis reaches the limit of uniform compressive deformation under the experimental temperature condition of 105 °C.

On the basis of the above results, reducing common Japanese bamboos without the occurrence of splits in the epidermis should become possible when $\kappa < 0.15$. Although splits occurred in the epidermis while reducing when $\kappa = 0.19$, no splits occurred when $\kappa = 0.122$. Under the condition when no splits occur, the departures from roundness of bamboos can be decreased by reducing, as shown in Table I. In other words, reducing under the condition which prevents the occurrence of

TABLE I Departures from roundness (deviation from circular form in reduced bamboo specimens)

κ	t_m/D_m	ΔR_B (mm)	ΔR_A (mm)	ΔR
0.096	0.083	0.86	0.07	
0.115	0.102	0.58	0.09	
0.122	0.071	0.87	0.06	

ΔR_B: Departures from roundness before reducing (original bamboo).
ΔR_A: Departures from roundness after reducing, κ: Nosing ratio.

splits enables the fabrication of tubular materials with a circular cross section of identical outer diameter, from bamboos having an oval-shaped cross section.

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