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Vibrational Properties of Smoke-Heated Sugi (*Cryptomeria japonica* D. Don) Wood[*1]

燻煙熱処理スギ材の振動的性質[*1]

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Summary

Sugi (*Cryptomeria japonica* D. Don) wood was smoke-heated for about 35 hours at a temperature of 80℃ inside the log. After smoke-heating, changes in vibrational properties, such as dynamic Young's modulus (E), specific Young's modulus (E/ρ), dynamic shear modulus (G), specific shear modulus (G/ρ), and loss tangent ($\tan\delta$), were examined. Based on the results, the effects of smoke-heating on the acoustic properties of the wood were discussed. With smoke-heating, the relative degree of crystallinity (RDC) was greatly increased in heartwood but not in sapwood. In agreement with the increase of RDC, E greatly increased in heartwood. E/ρ increased in both heartwood and sapwood, the increase ratios being about 9%. In contrast, G/ρ decreased slightly in both heartwood and sapwood. On the other hand, $\tan\delta$ increased slightly in heartwood by smoke-heating, while almost no change was observed in sapwood. Some acoustic properties, such as E/ρ, E/G, and $E\rho$, increased by smoke-heating, whereas G/ρ decreased. The results obtained here suggest that the acoustic properties of wood used in the manufacture of musical instruments could be improved by smoke-heating.

Keywords: *Cryptomeria japonica,* Smoke-heating, Vibrational properties, Dynamic Young's modulus, Dynamic shear modulus, Loss tangent

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要 旨

スギ丸太を80℃，35時間燻煙熱処理した．熱処理後，動的ヤング率（E），比動的ヤング率（E/ρ），動的せん断弾性率（G），比動的せん断弾性率（G/ρ），損失正接（tanδ）などの振動的性質及びこれらの性質と関係のある相対結晶化度（RDC）について調査した．RDCは，燻煙熱処理によって心材で増加する傾向を示したが，辺材では大きな変化は認められなかった．Eは，RDCの増加と対応して，心材で増加する傾向を示した．また，E/ρは心材，辺材ともに約9%の増加を示した．対照的に，G/ρは心材，辺材ともに減少する傾向を示した．一方，tanδは，辺材ではほとんど変化が認められなかったが，心材において増加する傾向が認められた．しかしながら，燻煙熱処理によって音響的性質を表わす物理量であるE/ρ，E/G及びEρは増加する傾向を示し，反対にG/ρについては減少する傾向が認められた．これらの結果から，燻煙熱処理は，これまで楽器用材に適さないと言われている木材の材質改良に効果的であることが示唆された．

キーワード：スギ，燻煙熱処理，振動的性質，動的ヤング率，動的せん断弾性率，損失正接

Introduction

Sugi, the Japanese cedar (*Cryptomeria japonica* D. Don) tree, is one of the main species planted in Japan. Sugi wood has been mainly used for building traditional wooden houses. However, it is extremely difficult to process this wood due to its very high moisture content in addition to the uneven distribution of sapwood and heartwood, which makes the process of timber drying complicated.

In Japan, several researchers have attempted smoke-heating of sugi logs to improve the quality of the wood (Okuyama *et al.* 1988, 1990; Nomura 1995; Andoh *et al.* 1996; Tejada *et al.* 1997; Ishiguri *et al.* 1998, 2000; Yoshizawa *et al.* 1999). Smoke-heating has resulted in the improvement of several wood qualities, the reduction of growth stress, the increase of the sawing yield, and the decrease of the moisture content. However, excessive treatment frequently causes surface checks, carbonization, and discoloration. Therefore, the establishment of a more suitable schedule for smoke-heating is required by the Japanese wood industry. In a previous paper, we examined how smoke-heating changed the quality of wood (Ishiguri *et al.* 1998). With smoke-heating, the modulus of elasticity (MOE) in the bending of sapwood showed a significant increase, whereas almost no differences in bending strength between control and smoke-heated woods were found in heartwood. We also found that the increase in the relative degree of crystallinity (RDC) in sapwood almost corresponded to the increase ratio of MOE.

On the other hand, it is well known that the vibrational properties of wood, such as the dynamic Young's modulus (E), the dynamic shear modulus (G), and the loss tangent (tan δ), which are closely related to the acoustic properties of music instruments made of wood, are altered by heating (Kadita *et al.* 1961; Hirai *et al.* 1972; Nakao *et al.* 1983; Kubojima *et al.* 1998, 2000; Obataya *et al.* 2000). It has been reported that E was increased in the initial stage of heating at low temperature below 160℃ (Kadita *et al.* 1961; Hirai *et al.* 1972; Nakao *et al.* 1983; Kubojima *et al.* 1998). This is considered to be due to the increase in the degree of crystallinity accompanied with the crystallization of cellulose by heating (Hirai *et al.* 1972; Kubojima *et al.* 1998). In contrast, Obataya *et al.* (2000) reported that the specific dynamic Young's modulus (E/ρ) decreased due to the thermal degradation of cell wall constituents and varied depending on the moisture content when compared at the same moisture content. On the other hand, changes in tan δ as a result of heating are also complicated. Nakao *et al.* (1983) reported that the tan δ of karin wood decreased with an increase in the degree of crystallinity by heating for 20 hours at 160℃. However, when spruce wood was heated at low temperature in the longitudinal direction, tan δ increased at the early stage of treatment and then became constant (Kubojima *et al.* 1998). In addition, it was reported that the G/ρ value decreased with an increase of the heating time at 160℃ (Kubojima *et al.* 1998). Thus, changes of the vibrational properties by heating are now a controversial

Table 1. Chracteristics of sugi sample trees used in this experiment

Age (years)	20
Length (cm)	300
Diameter (cm)	16
Average annual ring width (mm)	1.9
Moisture content at green condition (%)	80.4
Density at green condition (g/cm^3)	0.96

issue.

In the present study, the effects of smoke-heat treatment on vibrational properties, such as E, G, and tan δ, were investigated using sugi wood. Based on the results obtained, acoustic properties were discussed in relation to RDC.

Materials and Methods

Materials

Twenty-year-old Sugi (*Cryptomeria japonica* D. Don) trees growing in the Nasu district, Tochigi, Japan, were used in this experiment. The characteristics of the sample trees used in this experiment are shown in Table 1. Green logs were cut into half for end-matching. The first cut log was used for smoke-heating and the second one as control.

Smoke-heating of logs

Smoke-heating of logs was conducted using a special kiln, a smoke-heating system with increased far-infrared radiation (Andoh *et al.* 1996; Ishiguri *et al.* 1998; Yoshizawa *et al.* 1999) (Fig. 1). The temperature inside the log was controlled at 80 - 100℃ for 35 hours (Fig. 2). The changes of temperature inside the log during treatment were recorded with a thermocouple inserted 8 cm deep from the log surface and a date recorder (Hakusan, LS-3000TC). The moisture contents of logs were 24 to 45% after smoke-heating.

Vibration tests

For the vibration test, 48 clear specimens of 200(L)×20(R)×5(T) mm were prepared from the heartwood and sapwood of the control and smoke-heated logs. Specimens were conditioned at 20℃ and 65% RH before the test, the moisture content being 12%.

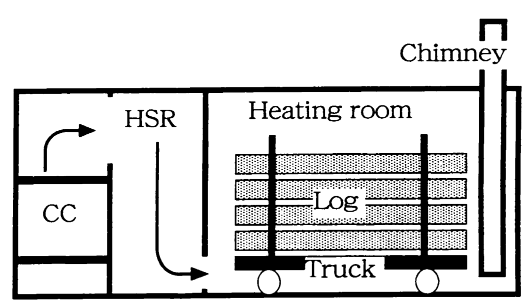

Fig. 1. Illustration of a smoke-heating system.
Note: CC; Combustion chamber, HSR; Heat storage room.

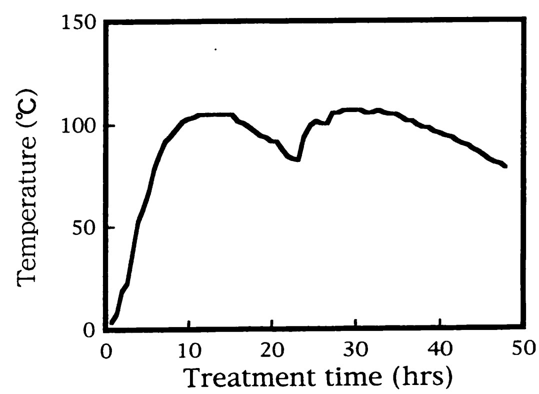

Fig. 2. Temperature changes inside a log during smoke-heating measured at 8 cm in depth from the surface.

The vibrational properties, E, G, and tan δ, were obtained by the free-free flexural vibration method. The specimen was suspended by threads and then tapped with a small wooden hammer. Resonance frequency was determined using an FFT analyzer. The values of E and G were calculated by Goens-Hearmon regression (Goens 1931; Hearmon 1958) using the resonance frequency obtained.

Using the amplitude of vibration corresponding to the 1st cycle (A1) and that of the vibration corresponding to the 10th cycle (A10) on a free vibration curve of the first mode, the logarithmic decrement (λ) was calculated from the following equation: $\lambda = (1/10)\ \ln (A1/A10)$. Then, the tan δ was determined by dividing λ by π.

Relative degree of crystallinity (RDC)

After the vibration test, wood meal (60 - 120 mesh) was prepared from vibration-test specimens. Wood meal was conditioned at 20℃ and 65% RH for two weeks.

An X-ray diffraction intensity curve was obtained using an X-ray diffraction apparatus (JEOL, JDX-12VA). RDC

Table 2. Condition for X-ray diffraction analysis

Characteristic X-ray	CuK α
Slit div. angle (deg.)	1/2
scatter. slit (deg.)	1/2
receive. slit (mm)	0.2
Tube voltage (kV)	40
Tube current (mA)	100
Time const. (sec)	1
Scanning speed (deg./min)	2

was determined from the X-ray diffraction intensity curve according to Segal's method (Segal *et al.* 1959). The measurement of RDC was conducted under 65% RH at 20℃. Table 2 shows the condition of the X-ray diffraction analysis.

Results and Discussion

Relative degree of crystallinity (RDC)

Table 3 shows the changes of RDC in sugi wood by smoke-heating. With smoke-heating, RDC was greatly increased in heartwood but not in sapwood.

It is well known that the degree of crystallinity (DC) increases in the initial stage of heating at lower temperatures (Hirai *et al.* 1972; Inoue and Norimoto 1991; Kubojima *et al.* 1998). Hirai *et al.* (1972) reported that DC increased until about 100 hours by heating at 100 and 150℃. However, when wood was heated at a high temperature of 200℃, DC increased at first but then decreased rapidly after 1 hour of treatment. This tendency became more remarkable at 250℃. These initial increases of DC are considered to be due to the crystallization of the cellulose amorphous region (Hirai *et al.* 1972) and to the formation of intermolecular cross-linking or the aggregation of cellulose molecule with decomposition of matrix substances by heating (Inoue and Norimoto 1991).

On the other hand, it has also been recognized that an increase of DC in wood occurred during smoke-heating of a log at a low temperature (Tejada *et al.* 1997; Ishiguri *et al.* 1998). Ishiguri *et al.* (1998) reported that when a sugi log was smoke-heated for about 35 hours at a temperature of 80℃ inside the log, RDC increased in both heartwood and sapwood. In the present study, the increase of RDC in heartwood is noteworthy, although it still remains to be clarified why no significant increase was found in sapwood.

Table 3. Relative degree of crystallinity (%) of smoke-heated wood

	Heartwood	Sapwood
Control	41.9	45.2
Smoke-heated	47.8	45.3
Increase ratio (%)	+14.8	+0.2

Dynamic Young's modulus (E) and specific dynamic Young's modulus (E/ρ)

Tables 4 and 5 show changes of E and E/ρ in sugi wood by smoke-heating. They tended to increase in both heartwood and sapwood by smoke-heating. However, the increase ratio of E was greater in heartwood than in sapwood. On the other hand, the increase ratio of E/ρ values was about 9% in both heartwood and sapwood.

In general, although the Young's modulus increases at the initial stage of heating at lower temperatures, it decreases with the increase of heating time and temperature (Kadita *et al.* 1961; Hirai *et al.* 1972; Inoue and Norimoto 1991; Kubojima *et al.* 1998, 2000). Hirai *et al.* (1972) reported that the E of Japanese cypress (Hinoki; *Chmaecyparis obtusa* Sieb. et Zucc.) significantly increased by heating for 100 hours at 100℃ but decreased by heating for only 1 hour at 250℃. Kubojima *et al.* (1998) also examined changes in E/ρ by heating sitka spruce (*Picea sitchensis* Carr.) and found that, in the longitudinal direction, E/ρ increased at the initial stage at 120 and 160℃ and then became constant. However, at 200℃, it increased at the initial stage but then decreased with the increase in heating time. The increase in E and E/ρ found in the present study might be due to the crystallization and the decrease in moisture content, this fact being in agreement with the earlier report by Kubojima *et al.* (1998).

Dynamic shear modulus (G) and specific dynamic shear modulus (G/ρ)

As shown in Tables 4 and 5, G and G/ρ decreased slightly in both heartwood and sapwood by smoke-heating.

Table 4. Vibrational properties of smoke-heated wood

Specimen		ρ (g/cm^3)	E (GPa)	G (GPa)	tan δ ($\times 10^{-3}$)
Heartwood	Control	0.47	13.6	0.80	5.48
	Smoke heated	0.47	14.9	0.78	5.71
	IR (%)		+9.6	-2.5	+4.2
Sapwood	Control	0.45	13.0	0.83	5.26
	Smoke heated	0.43	13.5	0.76	5.29
	IR (%)		+3.8	-8.4	+0.6

Note: ρ ; density at testing, E; dynamic Young's modulus, G; dynamic shear modulus, tan δ ; loss tangent, IR; increase ratio.

Table 5. Acoustic properties of smoke-heated wood

Specimen		E / ρ ($GPa/g \cdot cm^{-3}$)	G / ρ ($GPa/g \cdot cm^{-3}$)	E/G (GPa/GPa)	E ρ ($GPa \cdot g/cm^3$)
Heartwood	Control	28.7	1.70	17.0	6.4
	Smoke heated	31.4	1.66	19.1	7.0
	IR (%)	+9.4	-2.4	+12.4	+9.4
Sapwood	Control	28.8	1.84	15.7	5.8
	Smoke heated	31.3	1.77	17.7	5.9
	IR (%)	+8.7	-3.8	+12.7	+1.7

Note: ρ ; density at testing, E; dynamic Young's modulus, G; dynamic shear modulus, IR; increase ratio.

When sitka spruce wood was heated at low temperatures, the value of G/ρ decreased by longer treatments at 120 and 160℃ (Kubojima *et al.* 1998). The results obtained by the present study were similar to those of Kubojima *et al.* (1998). However, the reason for the changes in G or G/ρ by heating has not been elucidated yet. Further research is needed concerning the relationship between the values of G and G/ρ and the thermal changes of cell wall components by smoke-heating.

Loss tangent (tan δ)

Table 4 shows the tan δ of control and smoke-heated woods. The tan δ increased in heartwood by smoke-heating, the increase ratio being about 4%. However, the change of tan δ value in sapwood was not significant.

In general, logarithmic decrement (λ) and tan δ , which is determined by dividing λ by π , are influenced by structure changes of cell wall components. For example, in the case of spruce, the value of λ in the longitudinal direction decreased to half when wood was treated with formaldehyde (Yano *et al.* 1986). This decrease was considered to be due to the formation of cross-linking between molecules in non-crystalline regions of the cell wall. As well as chemical treatment, heating treatments of wood have been recognized as causing a decrease in tan δ (Nakao *et al.* 1983; Kubojima *et al.* 2000). Nakao *et al.* (1983) reported that the tan δ of karin *(Pterocarpus sp.)* wood decreased by heating for 20 hours at 160℃, corresponding to the increase of DC, which is considered to be due to the aggregation of the molecular structure in the non-crystalline region (Yano *et al.* 1986). In contrast, Kubojima *et al.* (1998) reported that, in sitka spruce, tan δ increased in the longitudinal direction with an increase of DC at the initial stage of heating for 20 hours at 160℃. In the present study, tan δ also increased in heartwood by smoke-heating, corresponding to the increase in RDC. However, the reasons for this tan δ fluctuation by smoke-heating have not been clarified yet.

Evaluation of acoustic properties

Spruce *(Picea spp.)* wood has been widely used in the manufacture of various musical instruments because of its good acoustic properties (for example, as the soundboard of violins, guitars, and pianos). The wood of these species has low values of ρ and tan δ and a high value of E, which results in good-quality soundboards (Fukada 1951). However, the supply of high-quality woods for the manufacture of musical instruments has decreased because of the destruction of forests. Therefore, the use of less popular woods which have so far been unused because of their lower quality should be considered for this purpose.

On the other hand, the improvement of acoustic properties by heating and chemical treatment of wood has been attempted in various species (Okano 1991). Nakao et al. (1983) reported that, when spruce and karin woods were heated at 160℃, tan δ decreased with the increase in DC. Furthermore, Yano (1994) revealed that the chemical treatment of sugi wood with formaldehyde and saligenin was effective in improving the acoustic properties, and that the resulting properties of this wood were superior to those of *Picea spp.* It remains critical to find a method to improve the acoustic properties of wood.

In the present study, the acoustic properties of wood were evaluated from the point of view of several factors, such as tan δ, E/ρ, E/G, and Eρ (Okano 1991). As shown in Table 5, E/ρ, E/G, and Eρ values increased in both heartwood and sapwood by smoke-heating. The results of the present study suggest that smoke-heating is effective for the improvement of the acoustic properties of wood which has been considered unsuitable for use in the manufacture of musical instruments.

Conclusion

In the present study, to investigate the changes of vibrational properties in sugi wood by smoke-heating, a sugi log was smoke-heated for about 35 hours at a temperature inside the log of 80℃. After smoke-heating, E, E/ρ, G, G/ρ, tan δ, and RDC were determined. The results obtained were as follows:

(1) RDC increased greatly in heartwood by smoke-heating but not in sapwood.

(2) E/ρ increased in both heartwood and sapwood by smoke-heating, the increase ratio being about 9%.

(3) G/ρ decreased slightly in both heartwood and sapwood by smoke-heating.

(4) Tan δ increased in heartwood by smoke-heating, while almost no change was observed in sapwood.

(5) E/G increased in both heartwood and sapwood by smoke-heating. Eρ increased largely in heartwood, while it did not in sapwood.

These results obtained here suggested that the acoustic properties of wood could be improved by smoke-heating.

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