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ORIGINAL ARTICLE

Internal-check variation in boxed-heart square timber of sugi (*Cryptomeria japonica*) cultivars dried by high-temperature kiln drying

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Abstract To investigate the wood properties affecting the internal-check variation in boxed-heart square timber of sugi (*Cryptomeria japonica*), two cultivars, yabukuguri and kumotooshi were kiln-dried together by the high-temperature setting method and their internal checks were compared. There was a difference in the area of internal checks between the cultivars. Kumotooshi formed a larger area of internal checks, which was thought to be affected by the larger tangential shrinkage of kumotooshi. The number, total length, and total area of internal checks were significantly correlated with tangential shrinkage. The area of internal checks around the pith was also larger for kumotooshi, which might be affected by the larger tangential shrinkage in the core part of kumotooshi. The results supported that tangential shrinkage should be one of the important properties affecting the internal-check variation of sugi boxed-heart square timber.

Keywords High-temperature setting method · Drying check · Area of internal check · Tangential shrinkage

Introduction

Sugi (*Cryptomeria japonica* D. Don) is a major plantation species in Japan, of which thinned trees are sawn into boxed-heart square timber and used as posts or beams for house construction. Recently, kiln-dried timber has been required to shorten the construction period and prevent dimensional changes from significant shrinkage after completion. However, drying of boxed-heart square timber is not easy, because it is susceptible to drying checks due to shrinkage anisotropy between the tangential and radial directions, and contains the heartwood which is slow in drying.

In order to shorten the drying time and reduce surface checking, various high-temperature kiln-drying methods have been developed as Kuroda reviewed [1]. Yoshida et al. [2] showed that drying the timber surface rapidly in the initial stage of drying under the conditions of high temperature and low relative humidity, induced tension set on the timber surface and produced less surface checking, but formed some large internal checks (high-temperature setting method). Tokumoto et al. [3] showed that the kiln-dried timber surface is stressed in compression, and the core is stressed in tension.

Large internal checks are undesirable for the timber strength properties. Ido et al. [4] showed that internal checks have little effect on bending strength, but have a significant effect on shear strength. Inoue et al. [5] showed that internal checks have a negative effect on the tension strength of Japanese traditional joints. However, information on internal checks is quite limited [6], and there is no knowledge on the effects of cultivars with different wood properties on internal checking during high-temperature kiln drying.

Drying checks are formed where the drying stress in the tangential direction exceeds the tangential tensile strength of the wood. Drying stress is induced by shrinkage differences in the timber during drying, and, it is expected to be

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affected by the moisture gradient, and the transverse shrinkage, and its anisotropy. The moisture gradient varies by the heartwood percentage, and heartwood moisture content, along the stem and among cultivars of sugi [7, 8]. The transverse shrinkage also varies within the stem and among cultivars, depending on the microfibril angle (MFA), density, and tree ring parameters such as the ring width, latewood percentage and latewood density [9]. Therefore, drying checks are also expected to vary along the stem and among cultivars. Our previous research showed that surface checks which formed during conventional kiln drying were different between heights along the stem and among cultivars, and its variation was affected by the shrinkage properties and the heartwood percentage [10].

In this study, we examined the internal checks that appeared in the boxed-heart square timber taken at two heights along the stems of the sugi cultivars, yabukuguri and kumotooshi. We compared the internal checks in timber that was kiln-dried together, because small differences in the drying schedule can affect internal checking with the high-temperature setting method. Shortening the time of the high-temperature setting treatment can reduce internal checking and create larger stress gradients between the surface and the core [11, 12]. In order to observe internal checking, we used a severer schedule than that used in practice. We investigated the relationships between internal checks and the wood properties such as moisture content, transverse shrinkage, density, and tree ring parameters.

Materials and methods

Materials

Two cultivars, yabukuguri and kumotooshi were used. Ten trees of each cultivar were harvested from the same stands (yabukuguri: Kahoku, Kumamoto and kumotooshi: Kikuchi, Kumamoto) and processed at the same time. The age of each cultivar was 42 for yabukuguri and 55 for kumotooshi. The sample trees were also used in our previous studies on shrinkage [9, 13] and bow [14]. Logs were taken at two heights above the ground (lower height, "timber 1"; upper height, "timber 4") (Fig. 1). The sampling heights were 1.5–3.5 m for timber 1 and 6.1–8.1 m for timber 4. The logs were sawn into 2 m-long boxed-heart square timber with 120 mm^2 cross section including pith at the center of each end. Disks of 200 mm thickness were cut at both ends of the logs to measure the fundamental wood properties.

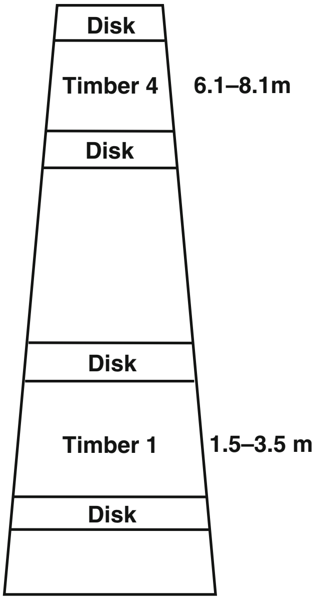

Fig. 1 Sampling heights above the ground

Wood properties

The heartwood percentage (HWP) on the transverse faces was calculated from the heartwood radius and timber dimensions. Tangential and radial shrinkage from the green to oven-dried condition (α_T, α_R) was measured using small clear samples of dimensions 30 (T) mm × 30 (R) mm × 5 (L) mm at 30 mm apart from the pith where internal checks appeared most prominently. Basic density (BD) was measured using small blocks cut at 20 mm intervals from the pith to the edge of timber, and then mean values of them were calculated. The wood properties in two diametrically opposite directions were also averaged for each disk, and mean values of at both ends of timber were calculated. The modulus of elasticity of green timber (MOE$_{GT}$) was measured using the tapping method [15]. The fundamental frequency of longitudinal vibration was obtained with a fast Fourier transform digital signal analyzer (Rion SA-71). The MOE$_{GT}$ was calculated using Eq. (1)

$$MOEGT = 4 \times L^2 \times f^2 \times \rho \qquad (1)$$

where L is length, f is fundamental frequency of longitudinal vibration, and ρ is green density.

The tree ring parameters were measured by soft X-ray densitometry [9]. The ring parameters were ring width (RW), latewood percentage (LWP), earlywood density (EWD), and latewood density (LWD). They were averaged through rings included in each timber. The earlywood and latewood boundary was set at 550 kg/m^3.

Kiln drying

Forty boxed-heart square timbers from different heights and/or cultivars were arranged alternately in the layers of the stack in the kiln (SKIF10LPT, Shinshiba) placed in the Forestry and Forest Products Research Institute. The drying schedule was as follows: steaming (90 °C dry bulb, 90 °C wet bulb, 8 h), drying (120 °C dry bulb, 90 °C wet bulb, 88 h), and conditioning (95 °C dry bulb, 91 °C wet bulb, 24 h). The moisture content of green (MC_{GT}) and dried timber (MC_{DT}) were obtained as water weight per oven-dry wood weight.

Measuring internal checks

After kiln drying, 40-mm-thick transverse slices were taken from the center of the timber length. The transverse-face of each slice was scanned by an image scanner (GT-F600, Epson) and printed out on a white paper. The internal-check outline was traced on the back of the printed paper, and its image was captured by the scanner. The number (NIC), total area (TAIC), and average area (AAIC) of the internal checks were obtained by the image processing program (ImageJ, NIH). The total length of the internal checks (TLIC) was measured using a ruler. The NIC, TAIC, and TLIC were calculated per square meter of green timber transverse area. Furthermore, to evaluate the radial check from the pith (heart checks), the total area of internal checks within a circle of 20 mm radius from the pith (TAICc) was obtained.

Statistical analysis

The differences in the wood properties and the internal checks between the four samples (Y1, Y4, K1, and K4) were examined using one-way analysis of variance (ANOVA) and the Tukey–Kramer honestly significant difference (HSD) test. The relationships between the internal-checking parameters and wood properties were examined using correlation analysis.

Results

Wood properties

The HWP exhibited small variation among the samples (Table 1). Kumotooshi timber 4 (K4) contained the sapwood at the corners, but the other samples were occupied by the heartwood. Timber 1 exhibited higher MC_{GT} than timber 4, since their heartwood moisture contents were higher (Y1, 89 %; Y4, 68 %; K1, 152 %; K4, 108 %). The MC_{DT} was low for all the samples (6.0–9.1 %). The α_T and α_R were smaller for yabukuguri than kumotooshi (Table 2). The MOE_{GT} was lower for yabukuguri than kumotooshi (Table 2). The differences in the transverse shrinkage and MOE_{GT} might be influenced by the MFA difference between the cultivars [9]. The BD was at a similar level (Table 2), but the tree ring parameters were different between the cultivars. The RW was wider and EWD was higher for yabukuguri (Table 3).

Internal checks

After high-temperature drying, surface checking was not observed on the lateral surfaces. On the transverse faces of the slices, taken at the center of the timber length, internal checks were observed in the radial direction (Fig. 2). They were most prominent on the diagonal line from the pith to the corner, and between the pith and the corner. Some checks were short over a few rings, but some were long over many rings.

The internal checks were significantly different among the four sample groups (Y1, Y4, K1, and K4) by ANOVA (NIC, $P < 0.01$; TLIC, $P < 0.05$; TAIC, $P < 0.001$; AAIC, $P < 0.01$; TAICc, $P < 0.001$) (Fig. 3). The number and the total length of internal checks exhibited similar trends. NIC and TLIC were at a similar level for Y1 and K1. Y4 exhibited the smallest NIC and the shortest TLIC. The total area and average are of internal checks exhibited different trends with them. The TAIC was larger for kumotooshi than yabukuguri for both timber 1 and timber 4. When the two cultivars were compared for timber 1 and timber 4, respectively, kumotooshi exhibited larger TAIC ($P < 0.01$) and AAIC ($P < 0.05$) for timber 1, and larger NIC ($P < 0.001$), longer TLIC ($P < 0.01$), and larger TAIC ($P < 0.001$) for timber 4. Among the internal-checking parameters, there were significant correlations between NIC, TLIC, and TAIC ($P < 0.001$) (Table 4).

Table 1 Heartwood percentage (HWP) on the transverse face of the timber and moisture content of the green and kiln-dried timber (MC_{GT}, MC_{DT})

Cultivar	Sample	*N*	*H* (m)	HWP (%)		MC_{GT} (%)		MC_{DT} (%)	
				Mean	SD	Mean	SD	Mean	SD
Yabukuguri	Y1	10	1.5–3.5	100	0.0	58.1	12.9	7.4	2.3
	Y4	10	6.1–8.1	99.8	0.7	40.4	6.6	6.4	1.7
Kumotooshi	K1	10	1.5–3.5	100	0.0	110.0	31.6	6.0	2.2
	K4	10	6.1–8.1	87.6	15.6	66.3	10.1	9.1	1.5

N number of boxed-heart square timbers, *H* height above the ground of the timber source, *SD* standard deviation

Table 2 Tangential shrinkage (α_T), radial shrinkage (α_R), tangential/radial shrinkage ratio (α_T/α_R), basic density (BD), and modulus of elasticity of the green timber (MOE_{GT})

Cultivar	Sample	α_T (%)		α_R (%)		α_T/α_R (%/%)		BD (kg/m^3)		MOE_{GT} (GPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Yabukuguri	Y1	6.88b	0.43	2.51c	0.15	2.75a	0.10	340b	11	2.66c	0.23
	Y4	6.79b	0.39	2.76b	0.14	2.47b	0.12	358a	11	4.98b	0.38
Kumotooshi	K1	7.69a	0.11	3.14a	0.17	2.47b	0.12	350ab	10	9.48a	0.34
	K4	7.49a	0.25	3.09a	0.14	2.44b	0.10	346ab	9	9.60a	0.44

There were significant differences among the samples of Y1, Y4, K1, and K4 for α_T, α_R, α_T/α_R, MOE_{GT} ($P < 0.001$), and BD ($P < 0.01$) using ANOVA. Different letters, a, b, and c show significant differences using the Tukey–Kramer HSD test ($P < 0.05$)

Table 3 Tree ring parameters for ring width (RW), latewood percentage (LWP), earlywood density (EWD), and latewood density (LWD)

Cultivar	Sample	RW (mm)		LWP (%)		EWD (kg/m^3)		LWD (kg/m^3)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Yabukuguri	Y1	5.85a	0.81	32.1a	3.4	356b	23	752c	29
	Y4	4.45b	0.50	34.4a	3.0	383a	22	797b	23
Kumotooshi	K1	2.44d	0.75	32.1a	6.1	347c	44	816a	29
	K4	2.68c	0.15	29.6b	1.9	334c	14	797ab	21

There were significant differences among the samples of Y1, Y4, K1, and K4 for RW, LWP, EWD, and LWD ($P < 0.001$) using ANOVA. Different letters, a, b, c, and d show significant differences using the Tukey–Kramer HSD test ($P < 0.05$)

The internal checks around the pith were prominent for kumotooshi, but not for yabukuguri (Fig. 2). They were observed in all the timber of kumotooshi, but were absent in a few timber of yabukuguri. The TAICc was much larger for kumotooshi than yabukuguri, and the difference was significant by the Tukey–Kramer HSD test ($P < 0.05$) (Fig. 3). When the two cultivars were compared for timber 1 and timber 4, respectively, kumotooshi exhibited larger TAICc for both timber 1 and timber 4 ($P < 0.01$).

Relationships between internal checks and wood properties

The four internal-checking parameters, NIC, TLIC, TAIC, and AAIC, were positively correlated with α_T (NIC, $P < 0.01$; TLIC, $P < 0.05$; TAIC, $P < 0.001$; AAIC, $P < 0.01$) (Table 5). However, the correlations with the other wood properties were different by the parameters. The NIC and TLIC had no significant correlation with the other wood properties, except a negative correlation between NIC and EWD ($P < 0.01$). On the other hand, TAIC and AAIC were positively correlated with MC_{GT} ($P < 0.001$), α_R ($P < 0.01$), MOE_{GT} (TAIC, $P < 0.01$; AAIC, $P < 0.05$), and LWD ($P < 0.05$), and negatively correlated with RW (TAIC, $P < 0.01$; AAIC, $P < 0.05$) (Table 5; Fig. 4). The internal-checking parameters did not have significant correlations with α_T/α_R, BD, and LWP (Table 5).

Discussion

The factors affecting the internal checks

The internal-checking parameters, NIC, TLIC, and TAIC were highly correlated with each other (Table 4), but exhibited differences in variation among the four samples, and in correlations with the wood properties. The TAIC was larger for kumotooshi, both for timber 1 and 4, while NIC and TLIC were not different between the two cultivars for timber 1 (Fig. 3). The TAIC exhibited significant correlations with several wood properties, while NIC was correlated only with α_T and EWD, and TLIC was with α_T (Table 5). These differences in the internal-checking parameters may have occurred because the number and total length of the internal checks (NIC and TLIC) represent the occurrence and propagation of the checks, while the total area of the internal checks (TAIC) represents the amount of shrinkage.

This study compared the internal checks of two sugi cultivars in which the heartwood percentage and basic density were similar, but the transverse shrinkage was different. Kumotooshi exhibited a larger TAIC than yabukuguri, which was considered to be caused by the larger tangential shrinkage of kumotooshi (Table 2) as a result of the high-positive correlation between TAIC and α_T (Table 5; Fig. 4). In our previous study of the conventional kiln drying of boxed-heart square timber, the total length

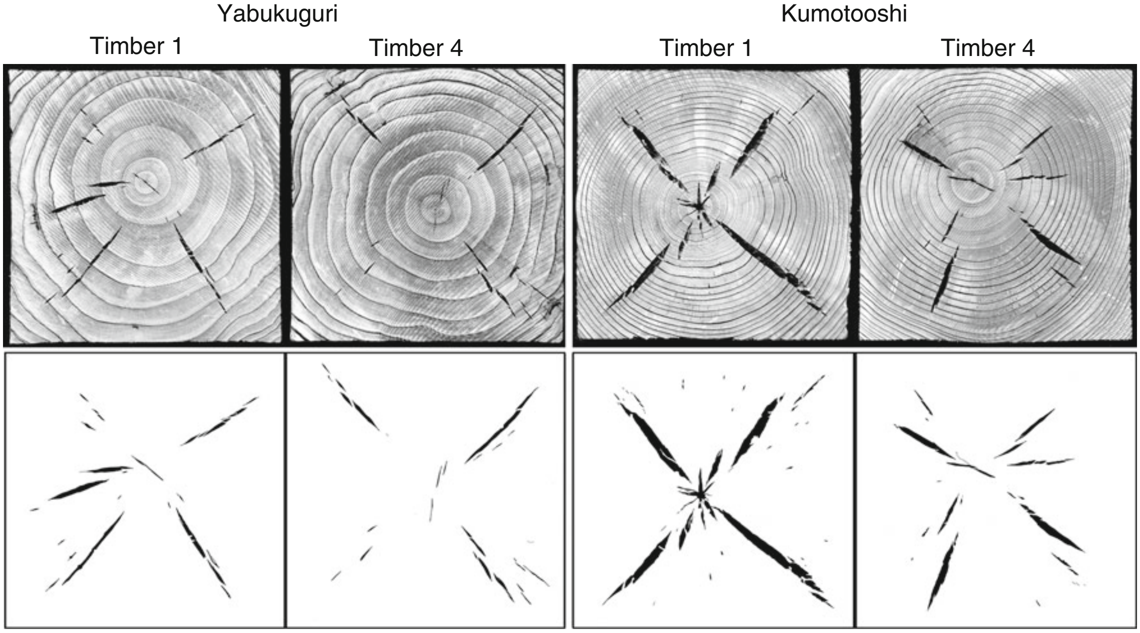

Fig. 2 Typical images of internal checking for yabukuguri and kumotooshi

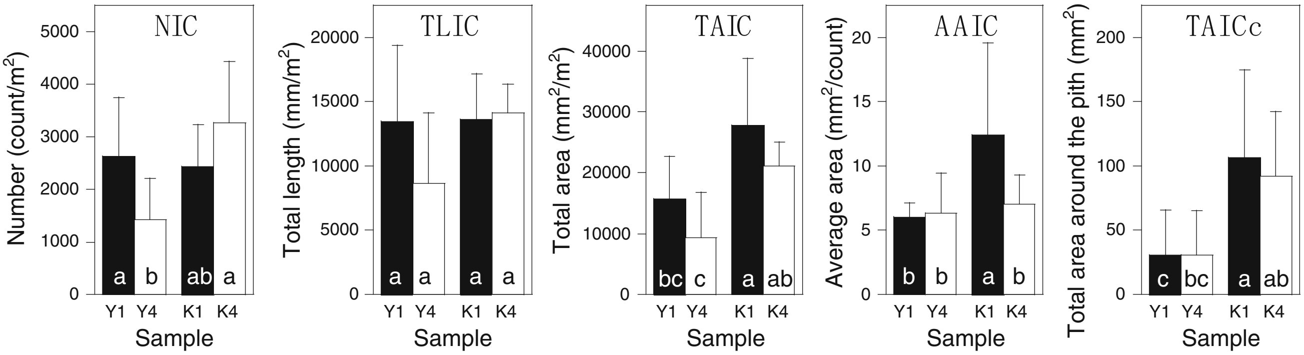

Fig. 3 Mean and standard deviation of the internal-checking parameters. *NIC* number of internal checks, *TLIC* total length of internal checks, *TAIC* total area of internal checks, *AAIC* average area of internal checks, *TAICc* total area of internal checks within 20 mm from the pith. There were significant differences among the four samples using ANOVA (*TAIC* $P < 0.001$, *NIC*, *AAIC*, and *TAICc* $P < 0.01$, *TLIC* $P < 0.05$). Different letters, *a*, *b*, and *c* show significant differences among the samples using the Tukey–Kramer HSD test ($P < 0.05$)

Table 4 Correlation coefficients between the number (NIC), total length (TLIC), total area (TAIC), and average area (AAIC) of the internal checks

	TLIC	TAIC	AAIC
NIC	0.779***	0.565***	−0.158
TLIC		0.786***	0.255
TAIC			0.657***

*** $P < 0.001$

and average length of the surface checks along axis were longer for kumotooshi compared with yabukuguri, which was considered to be affected by the larger tangential shrinkage of kumotooshi [10]. This study showed that the tangential shrinkage is important for not only surface-checking variation but also for internal-checking variation with the high-temperature setting method.

The TAIC was also positively correlated with the MC_{GT} (Table 4; Fig. 4). Kawabe et al. [16] examined the distributions of moisture content and internal stress within logs during vacuum drying with high-frequency heating, and reported that their distributions were different in logs that had different heartwood moisture contents. In this study, the moisture content was higher for kumotooshi than yabukuguri, and the internal stress distribution during drying might have been different between the two cultivars. In order to explain how the moisture content of green timber affects the formation of internal checks, future

Table 5 Correlation coefficients between the internal-checking parameters and wood properties

Internal-checking parameter	MC_{GT}	α_T	α_R	α_T/α_R	BD	MOE_{GT}	RW	LWP	EWD	LWD
NIC	0.164	0.452**	0.221	0.130	0.307	0.242	−0.184	−0.166	−0.427**	−0.096
TLIC	0.278	0.480**	0.176	0.248	−0.274	0.164	−0.112	0.023	−0.255	0.017
TAIC	0.610***	0.658***	0.495**	−0.066	−0.139	0.497**	−0.500**	−0.054	−0.392*	0.361*
AAIC	0.590***	0.423**	0.439**	−0.206	0.099	0.359*	−0.395*	0.085	−0.063	0.386*

NIC number of internal checks, *TLIC* total length of internal checks, *TAIC* total area of internal checks, *AAIC* average area of internal checks

***$P < 0.001$, ** $P < 0.01$, * $P < 0.05$

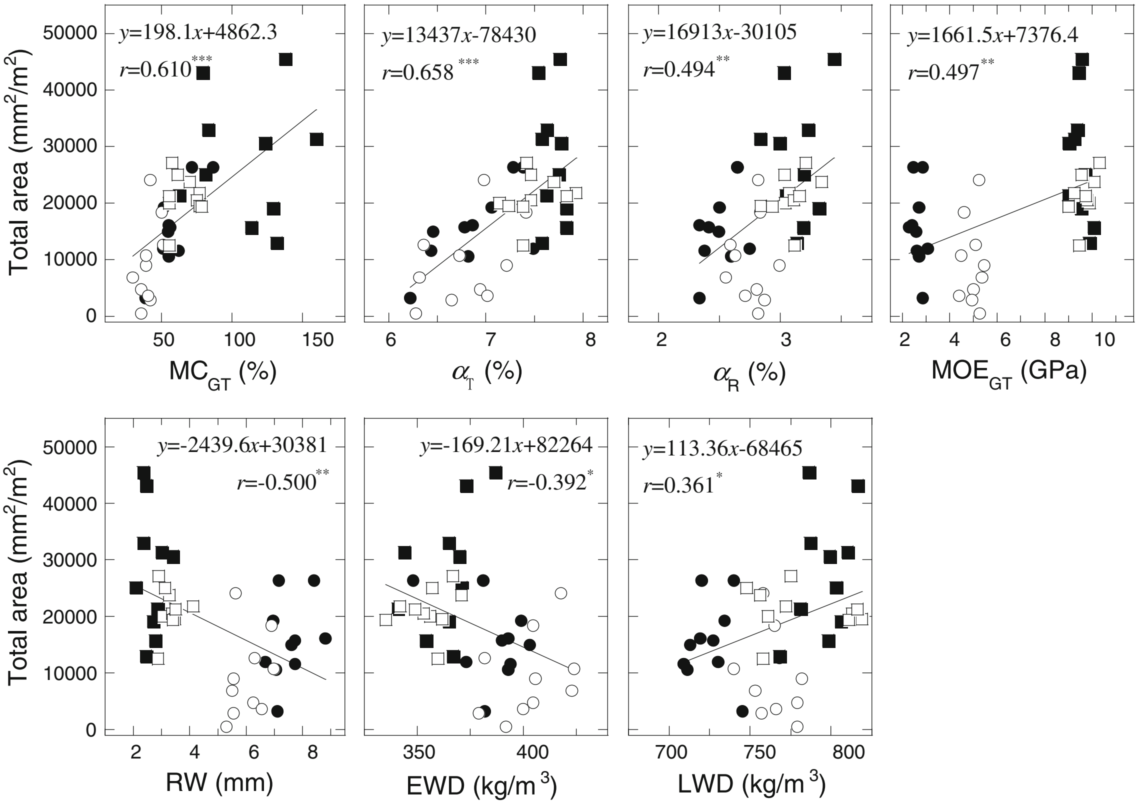

Fig. 4 Relationships between the total area of internal checks and wood properties. *MC_{GT}* moisture content of green timber, α_T tangential shrinkage, α_R radial shrinkage, *MOE_{GT}* the modulus of elasticity of green timber, *RW* ring width, *EWD* earlywood density, *LWD* latewood density, *r* correlation coefficient. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$. *Filled circles*, Y1; *open circles*, Y4; *filled squares*, K1; *open squares*, K4

research is needed that includes the distributions of internal stress and moisture content during drying.

The TAIC was also correlated with tree ring parameters such as the RW, EWD, and LWD (Table 5; Fig. 4). The two cultivars had a similar level of BD, but kumotooshi had narrower RW and lower EWD (Table 3). Drying checks are formed at the latewood, so, it is possible that the narrower RW and lower EWD might have contributed to larger internal checks forming across many rings for kumotooshi, while the higher EWD prevented the internal checks from enlarging in yabukuguri. The positive correlation between TAIC and LWD might have occurred because the tangential shrinkage was larger with higher LWD. In our previous study, the tangential shrinkage exhibited a higher correlation with the LWD than the other tree ring parameters [9].

The factors affecting the radial check from the pith

The radial check from the pith (heart checks) was much larger for kumotooshi than yabukuguri (Figs. 2, 3). In this study, the radial checks from the pith were observed in the

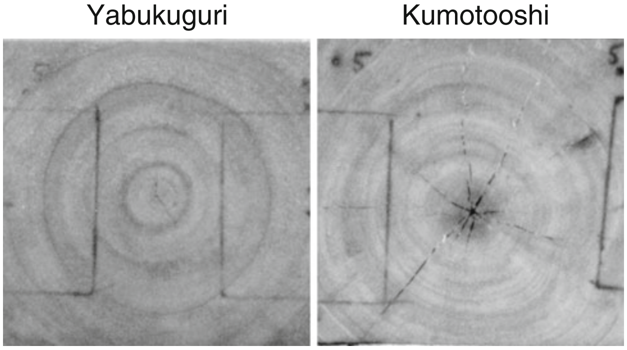

Fig. 5 Heart checks appeared at the pith before drying in green state for slices taken at the butt end of timber 1

green state in the slices prepared for shrinkage measurement, and they were prominent for kumotooshi, but were quite small for yabukuguri (Fig. 5). There are few studies about the growth stress variation among sugi cultivars, but growth stress release is known to be different depending on tree age [17], growth rate [18], and the elastic properties affected by MFA [19]. The growth stress might have been larger for kumotooshi, because its growth rate was slower and its MFA was smaller than in yabukuguri. The heart checks are considered to have enlarged more for kumotooshi during drying, because it had larger tangential shrinkage, especially in the core part of the juvenile wood, owing to its smaller MFA than yabukuguri [9].

Effect of internal checks on strength properties

Large internal checks in cross sections might be longer in the longitudinal direction. Timber containing large internal checks might be undesirable for post or beams, because of the decrease in the shear strength [4]. The shear strength is not required for posts, but with large internal checks it is possible to decrease the buckling strength. Furthermore, large internal checks may affect joint strength [5]. Recently, not only traditional joints but also the joints using nails or metal fittings are also used. The joint strength would decrease if the nails or bolts are inserted into the large internal checks. This study revealed that the occurrence of internal checks might be affected by the timber quality, even in the same drying schedule. The timber which has large tangential shrinkage, and is susceptible to the formation of larger checks, needs more attention in the choice of the drying method.

Conclusions

Boxed-heart square timber of the sugi cultivars yabukuguri and kumotooshi exhibited differences in internal checking, when it was kiln-dried by the high-temperature setting method. The total area of internal checks and the area of radial checks from the pith were larger for kumotooshi than yabukuguri, and were thought to be affected by the larger tangential shrinkage of kumotooshi. Tangential shrinkage is one of the most important factors affecting internal-checking variation, and the timber having larger tangential shrinkage is thought to form a larger area of internal checks.

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