J Wood Sci (2009) 55:161–168
DOI 10.1007/s10086-008-1012-2

ORIGINAL ARTICLE

**Kana Yamashita · Yasuhiko Hirakawa · Hiroshi Nakatani
Motoyoshi Ikeda**

Tangential and radial shrinkage variation within trees in sugi (*Cryptomeria japonica*) cultivars

Received: September 17, 2008 / Accepted: December 5, 2008 / Published online: February 17, 2009

Abstract The transverse shrinkage variation within trees was examined for five sugi cultivars. The within-tree trends of tangential shrinkage (α_T) were different by cultivar, whereas radial shrinkage (α_R) increased from pith to bark in most cultivars. The tangential/radial shrinkage ratio (α_T/α_R) decreased from pith to bark in most cultivars, because the radial variation of α_R was larger than that of α_T. The cultivars showed significant differences among cultivars in α_T, α_R, and α_T/α_R, but the difference among cultivars for α_T/α_R was smaller. The relationships between transverse shrinkage and microfibril angle (MFA), basic density (BD), tree ring parameters, and modulus of elasticity were examined. The α_T and α_R showed positive relationships with BD, latewood percentage, latewood density, and modulus of elasticity, and negative relationships with MFA and ring width. The relationships with earlywood density were weak. Sugi exhibited variation in transverse shrinkage within stem and among cultivars, with the variation affected by MFA, density, and tree ring parameters.

Key words Transverse shrinkage · Microfibril angle · Density · Tree ring parameters · *Cryptomeria japonica*

K. Yamashita (✉) · Y. Hirakawa
Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba 305-8687, Japan
Tel. +81-29-829-8300; Fax +81-29-874-3720
e-mail: zaikana@ffpri.affrc.go.jp

H. Nakatani
Forest Products Research Laboratory, Toyama Prefectural Agricultural, Forestry, and Fisheries Research Center, Toyama 939-0311, Japan

M. Ikeda
Forestry Research and Instruction Station of Kumamoto Prefecture, Kumamoto 860-0862, Japan

Part of this article was presented at the 56th Annual Meeting of the Japan Wood Research Society, Akita, Japan, August 2006, and the 57th Annual Meeting of the Japan Wood Research Society, Hiroshima, Japan, August 2007

Introduction

Sugi (*Cryptomeria japonica* D. Don) is a major plantation species in Japan and is mainly used for construction lumber. Recently, various kiln-drying methods such as high-temperature drying have been developed to shorten drying time and prevent surface check.[1] However, there is little information about the variation of transverse shrinkage and its anisotropy within stem and among trees in sugi,[2–4] even though shrinkage is a means of assessing the dimensional stability of wood.[5]

The most important factor affecting shrinkage is wood density, because wood shrinks by an amount that is proportional to the moisture lost from the cell wall.[6] However, density is a rough indicator because the correlations between volumetric shrinkage and density are not consistent within stem[7–9] and the effects of density are different for tangential and radial shrinkage.[9–12] Tangential shrinkage is about twice as great as radial shrinkage, which cannot be explained in simple terms. One theory to explain transverse shrinkage anisotropy is the earlywood–latewood interaction caused by the larger transverse shrinkage of latewood than earlywood.[13] Tangential shrinkage is largely controlled by the changes in latewood, because latewood is strong enough to force earlywood to comply with it. Radial shrinkage, on the other hand, is a summation of the weighted contributions of earlywood and latewood. The earlywood–latewood interaction has been clarified by measuring the shrinkage of earlywood and latewood separately[13–15] and by observing cell deformations microscopically.[16–20]

Microfibril angle (MFA), which is the angle at which cellulose microfibrils are oriented, is also an important factor affecting transverse shrinkage.[21–26] Because crystalline cellulose is strong, stiff, and does not absorb moisture, the wood shrinks very little in the direction that is parallel to cellulose microfibrils. Therefore, longitudinal shrinkage increases and transverse shrinkage decreases with the increase of MFA.

The variations in MFA,[27–30] density,[8,31] and tree ring structures[32–35] within stem and among cultivars are expected to affect transverse shrinkage in sugi. We examined the radial and height trends of tangential shrinkage, radial shrinkage, and the tangential/radial shrinkage ratio in stems of five sugi cultivars. The relationships of transverse shrinkage with MFA, density, tree ring structures, and modulus of elasticity were examined.

Materials and methods

Materials

The five sugi cultivars used in this study were: boka-sugi, yabukuguri, aya-sugi, ryuunohige, and kumotooshi (Table 1). Disks were cut at different heights above the ground (Table 1) and used to measure shrinkage, basic density, MFA, and tree ring parameters (Fig. 1). Logs between the disks were used to measure modulus of elasticity. Sample trees were the same as those used in the previous study on longitudinal shrinkage.[36]

Transverse shrinkage, basic density, and MFA

Tangential (α_T) and radial shrinkage (α_R) from green to oven-dry were measured at two, three, or four radial positions from pith to bark using the transverse shrinkage specimens with dimensions of 30 (T) × 30 (R) × 5 (L) mm. The tangential/radial shrinkage ratio (α_T/α_R) was obtained as α_T divided by α_R. Basic density (BD) and ring number from the pith were obtained for each shrinkage specimen. The MFA of the S_2 layer was measured at different radial and height positions using the transverse shrinkage specimens from five trees in each cultivar.[36]

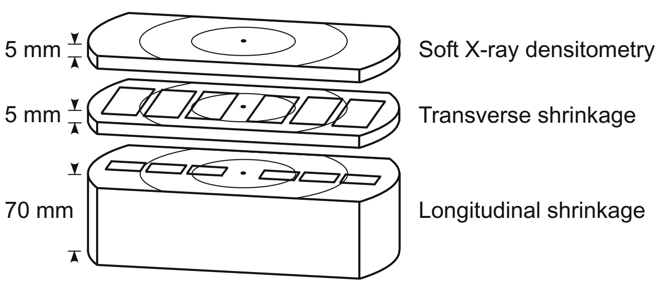

Fig. 1. Method of cutting specimens. A diametric strip was taken from a disk. A cross section for transverse shrinkage specimens and a strip for longitudinal shrinkage specimens[36] were taken in green condition. Basic density and microfibril angle were measured using shrinkage specimens. A cross section for soft X-ray densitometry was taken in air-dry condition

Tree ring parameters

Soft X-ray negatives were taken of 5-mm-thick cross sections after conditioning at 20°C and 60% relative humidity (RH). The negatives were scanned to obtain density profiles (microdensitometer 3CS, Joyce Loebl). The four tree ring parameters: earlywood density (EWD), latewood density (LWD), ring width (RW), and latewood percentage (LWP) were calculated for the rings where each shrinkage specimen was sampled. The earlywood and latewood was divided at 550 kg/m^3.

Modulus of elasticity

The dynamic modulus of elasticity (E_{fr}) of log was measured by tapping the logs in the green condition.[36]

Statistical analysis

The variation of transverse shrinkage within stem and among cultivars was statistically evaluated (JMP5.01 software package, SAS Institute). About 2% of the specimens were excluded from the analysis because they contained knots. The difference among the radial and height positions within stem were examined by *t*-test and correlation analysis between ring number and shrinkage at each height. The differences among cultivars were examined by one-way analysis of variance (ANOVA) and the Tukey-Kramer HSD test at two heights (1.4–1.7 m and 5.8–6.2 m). The shrinkage values of the first and second disks were averaged for boka-sugi, aya-sugi, and ryuunohige, because they were sampled at heights that were different from those for yabukuguri and kumotooshi (Table 1).

The relationships between transverse shrinkage (α_T, α_R, and α_T/α_R) and MFA, BD, EWD, LWD, RW, and LWP were evaluated using correlation analysis for each cultivar and for the combined five cultivars. Furthermore, the relationships were evaluated for the inner part (IP) with the innermost specimens near the pith and the outer part (OP) with the outermost specimens near the bark, respectively. The relationships between transverse shrinkage and E_{fr} of logs were examined using the transverse shrinkage averaged from both ends of each log.

Table 1. Stand locations, tree ages, numbers of trees (*n*), and heights of sampling disks of the five sugi cultivars

Cultivar	Stand location	Tree age (years)	*n*	Heights of sample disks (m)
Boka-sugi	Takaoka, Toyama	36	42	0.6, 2.8, 4.4, 6.2
Yabukuguri	Kahoku, Kumamoto	42	10	1.4, 3.6, 6.0, 8.2
Aya-sugi	Kahoku, Kumamoto	49	30	0.4, 2.6, 4.4, 5.8, 8.0
Ryuunohige	Kikuchi, Kumamoto	52	30	0.6, 2.6, 4.4, 5.8, 8.0
Kumotooshi	Kikuchi, Kumamoto	55	10	1.4, 3.6, 6.0, 8.2

Results

Tangential and radial shrinkage

The within-tree trends of α_T were different among the five cultivars (Fig. 2). In boka-sugi and yabukuguri, α_T decreased from pith to bark at the stem base, but increased from pith to bark in the upper stem. The α_T of the outer stem was smaller than α_T of the inner stem at a height of 0.6 m in boka-sugi ($P < 0.01$), and larger above 4.4 m in height in boka-sugi and at 8.2 m in height in yabukuguri ($P < 0.01$). In boka-sugi, α_T was negatively correlated with ring number at a height of 0.6 m, but was positively correlated above 4.4 m in height ($P < 0.01$). In aya-sugi, α_T was constant at a height of 0.4 m, but increased and then decreased from pith to bark above 2.6 m in height. In ryuunohige, α_T decreased from pith to bark, with negative correlations against ring number ($P < 0.01$) at all heights. In kumotooshi, α_T was constant, with no significant difference between radial positions.

The within-tree trends of α_R showed similarities and differences with the α_T trends (Fig. 2). In boka-sugi, α_R decreased from pith to bark at the stem base, and increased from pith to bark in the upper stem, which was similar to its α_T trend. In the other four cultivars, α_R increased from pith to bark and with height in the outer stem, which were different with their α_T trends. In these cultivars, α_R of the outer stem was significantly larger than α_R of the inner stem ($P < 0.01$), and α_R was positively correlated with ring number ($P < 0.01$) except at a height of 0.4 m in aya-sugi and 0.6 m in ryuunohige. The specific radial shrinkage, α_R divided by BD, also increased from pith to bark and increased with height in the outer stem.

The within-tree trends of α_T/α_R were the opposite of those for α_R (Fig. 2). In boka-sugi, α_T/α_R was relatively constant from pith to bark. In the other four cultivars, α_T/α_R generally decreased from pith to bark and with height in the outer stem. In these cultivars, α_T/α_R was negatively correlated with ring number ($P < 0.01$), and α_T/α_R of the outer stem was significantly smaller than that of the inner stem ($P < 0.01$).

There were significant differences among cultivars in both α_T and α_R (Table 2). The α_T and α_R values were the largest in kumotooshi, followed by ryuunohige and yabukuguri, and the smallest in aya-sugi and boka-sugi. The α_T/α_R ratio also showed significant difference among cultivars, but the difference was small (Table 2).

Relationships between shrinkage and MFA, basic density and tree ring parameters

Both α_T and α_R were positively correlated with BD, LWD, and LWP, and negatively correlated with MFA and RW for the combined samples of the five cultivars (Fig. 3). Both α_T

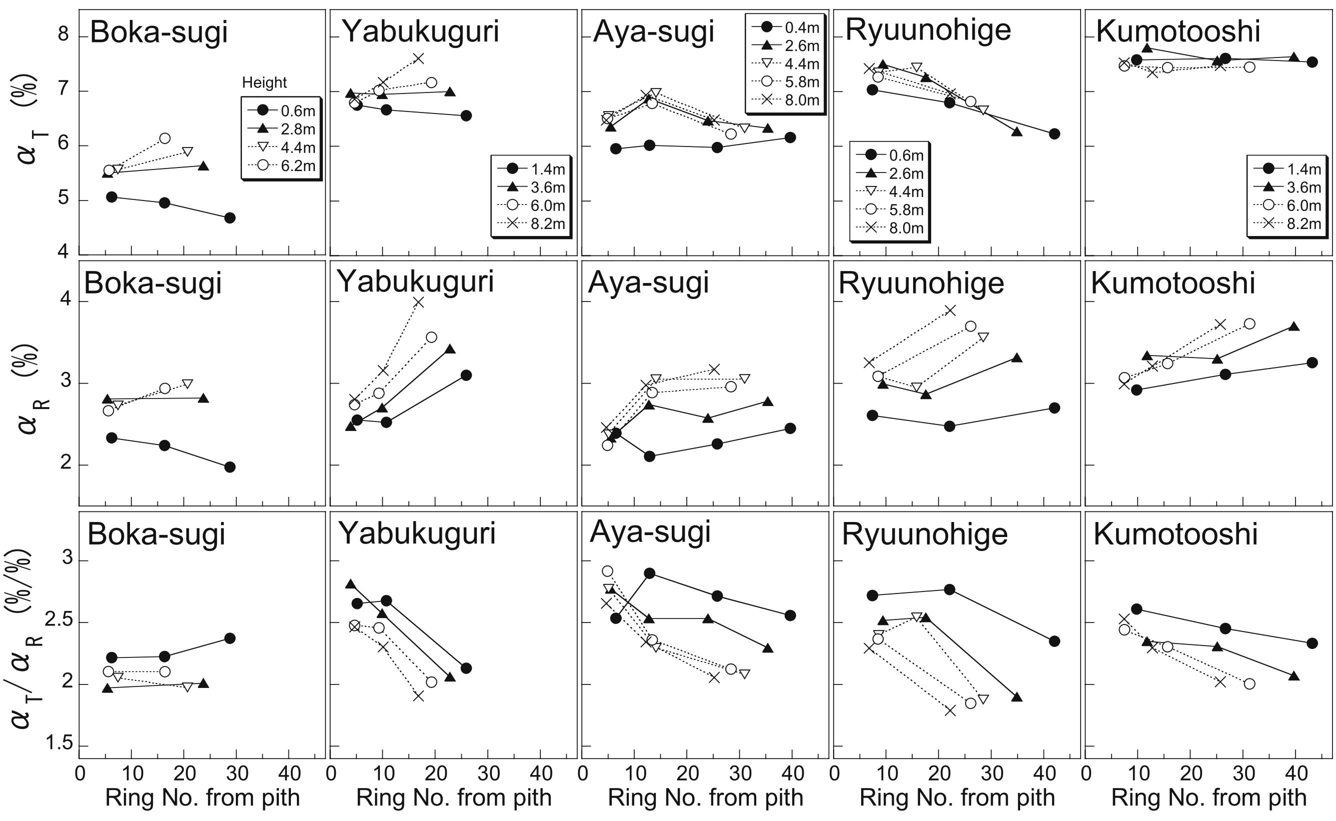

Fig. 2. Radial profiles of tangential shrinkage (α_T), radial shrinkage (α_R), and tangential/radial shrinkage ratio (α_T/α_R) at different heights of the five sugi cultivars

Table 2. Transverse shrinkage (α_T, α_R, and α_T/α_R) of the five sugi cultivars at two heights

Cultivar	Height 1.4–1.7 m			Height 5.8–6.2 m		
	Disk	IP	OP	Disk	IP	OP
Tangential shrinkage (α_T) (%)						
Boka-sugi	5.22 d	5.30 d	5.16 c	5.85 c	5.56 c	6.15 b
Yabukuguri	6.60 b	6.75 b	6.56 b	7.00 a	6.79 b	7.17 a
Aya-sugi	6.27 c	6.16 c	6.25 b	6.50 b	6.50 b	6.22 b
Ryuunohige	6.78 b	7.23 a	6.26 b	7.08 a	7.27 a	6.82 a
Kumotooshi	7.58 a	7.58 a	7.54 a	7.27 a	7.35 a	7.22 a
Radial shrinkage (α_R) (%)						
Boka-sugi	2.49 c	2.58 c	2.40 d	2.80 c	2.67 c	2.94 b
Yabukuguri	2.71 b	2.55 bcd	3.10 ab	3.08 b	2.74 bc	3.56 a
Aya-sugi	2.46 c	2.37 d	2.61 c	2.70 c	2.24 d	2.96 b
Ryuunohige	2.86 b	2.76 ab	3.01 b	3.39 a	3.08 a	3.70 a
Kumotooshi	3.09 a	2.92 a	3.25 a	3.31 a	3.02 ab	3.66 a
Tangential/radial shrinkage ratio (α_T/α_R)						
Boka-sugi	2.13 c	2.10 b	2.19 bc	2.10 c	2.11 c	2.10 a
Yabukuguri	2.48 ab	2.65 a	2.13 bc	2.31 b	2.48 b	2.03 ab
Aya-sugi	2.60 a	2.65 a	2.43 a	2.46 a	2.92 a	2.12 a
Ryuunohige	2.40 b	2.65 a	2.11 c	2.12 c	2.37 b	1.85 b
Kumotooshi	2.47 ab	2.61 a	2.33 ab	2.22 bc	2.44 b	1.98 ab

There were significant differences among the cultivars by one-way analysis of variance in each position at each height ($P < 0.001$). Values in the same column with different letters were significantly different by the Tukey-Kramer HSD test ($P < 0.05$)
Disk, mean of the radial positions from pith to bark; IP, inner part of stem; OP, outer part of stem

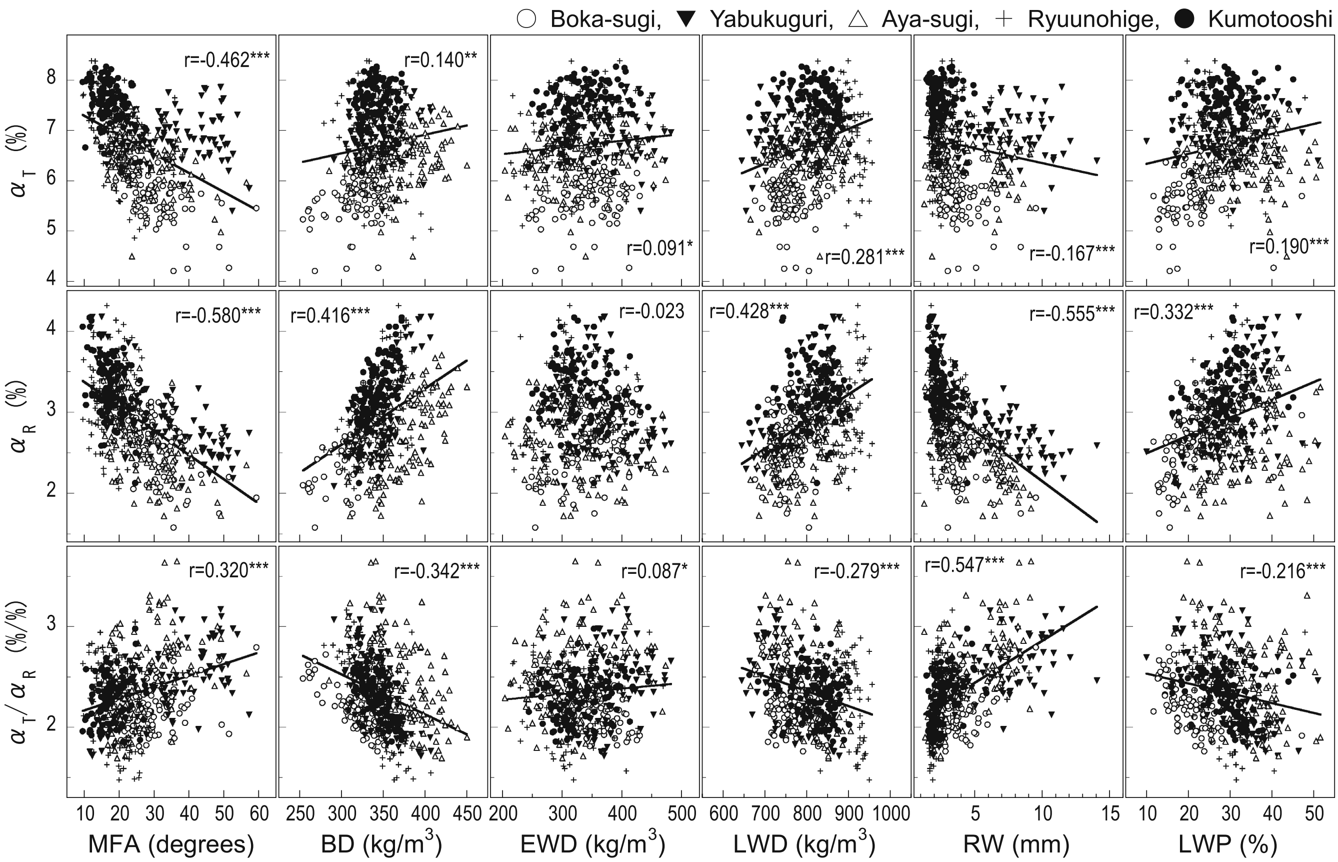

Fig. 3. Relationships between transverse shrinkage (α_T, α_R, and α_T/α_R) and microfibril angle (*MFA*), basic density (*BD*), earlywood density (*EWD*), latewood density (*LWD*), ring width (*RW*), and latewood percentage (*LWP*). *Thick lines* are the relationships of the combined samples of the five cultivars. *Triple asterisk*, $P < 0.001$; *double asterisk*, $P < 0.01$; *asterisk*, $P < 0.05$

and α_R were correlated with MFA for each of the cultivars (Fig. 4A) and both of IP and OP (Fig. 4B). The correlations with BD and tree ring parameters were higher in α_R than in α_T (Figs. 3, 4) and tended to be higher in OP than in IP (Fig. 4B). The correlations of α_T with BD and tree ring parameters varied by cultivar (Fig. 4A). The correlations of α_R with BD, RW, and LWP were significant for each of the cultivars, but those with EWD and LWD varied by cultivar (Fig. 4A). When the correlations of α_T were examined for IP and OP separately, LWD and RW were significant both for IP and OP, BD and LWP were significant only for OP, and EWD was not significant for IP or OP (Fig. 4B). For α_R, LWD and RW were significant both for IP and OP, whereas BD, EWD, and LWP were significant only for OP (Fig. 4B).

The α_T/α_R ratio was positively correlated with MFA and RW, and negatively correlated with BD, LWD, and LWP, which was the inverse of the relationships for α_T and α_R (Figs. 3, 4). The correlations of α_T/α_R with MFA were lower than those of α_T and α_R with MFA.

The correlations between BD and the tree ring parameters for the combined cultivars were the highest in LWP ($r = 0.716$, $P < 0.001$) followed by EWD ($r = 0.191$, $P < 0.001$), LWD ($r = 0.131$, $P = 0.003$), and the lowest in RW ($r = -0.100$, $P = 0.023$). The order was different from the correlations between transverse shrinkage (α_T, α_R) and the tree ring parameters (Figs. 3, 4).

Relationship between shrinkage and modulus of elasticity

The α_T and α_R were positively correlated with E_{fr} of logs for each of the cultivars (with the exception of α_T for kumotooshi) and for the combined cultivars ($P < 0.01$) (Fig. 5, Table 3). The α_T/α_R ratio was negatively correlated with E_{fr} of logs ($P < 0.01$) for each of the cultivars. The correlation for the combined cultivars was low, because α_T/α_R was smaller in boka-sugi at the same level of E_{fr} of logs. The correlation for the combined cultivars was significant when boka-sugi was excluded ($P < 0.01$).

Table 3. The coefficients of correlation between transverse shrinkage (α_T, α_R, and α_T/α_R) and modulus of elasticity of log ($n = 405$)

Cultivar	α_T	α_R	α_T/α_R
Boka-sugi	0.709***	0.692***	–0.301***
Yabukuguri	0.604**	0.831***	–0.691***
Aya-sugi	0.563***	0.780***	–0.630***
Ryuunohige	0.646***	0.881***	–0.494***
Kumotooshi	–0.229	0.575**	–0.737***
All	0.867***	0.759***	0.088[a]

*** $P < 0.001$, ** $P < 0.01$
[a] $r = -0.675$*** without boka-sugi

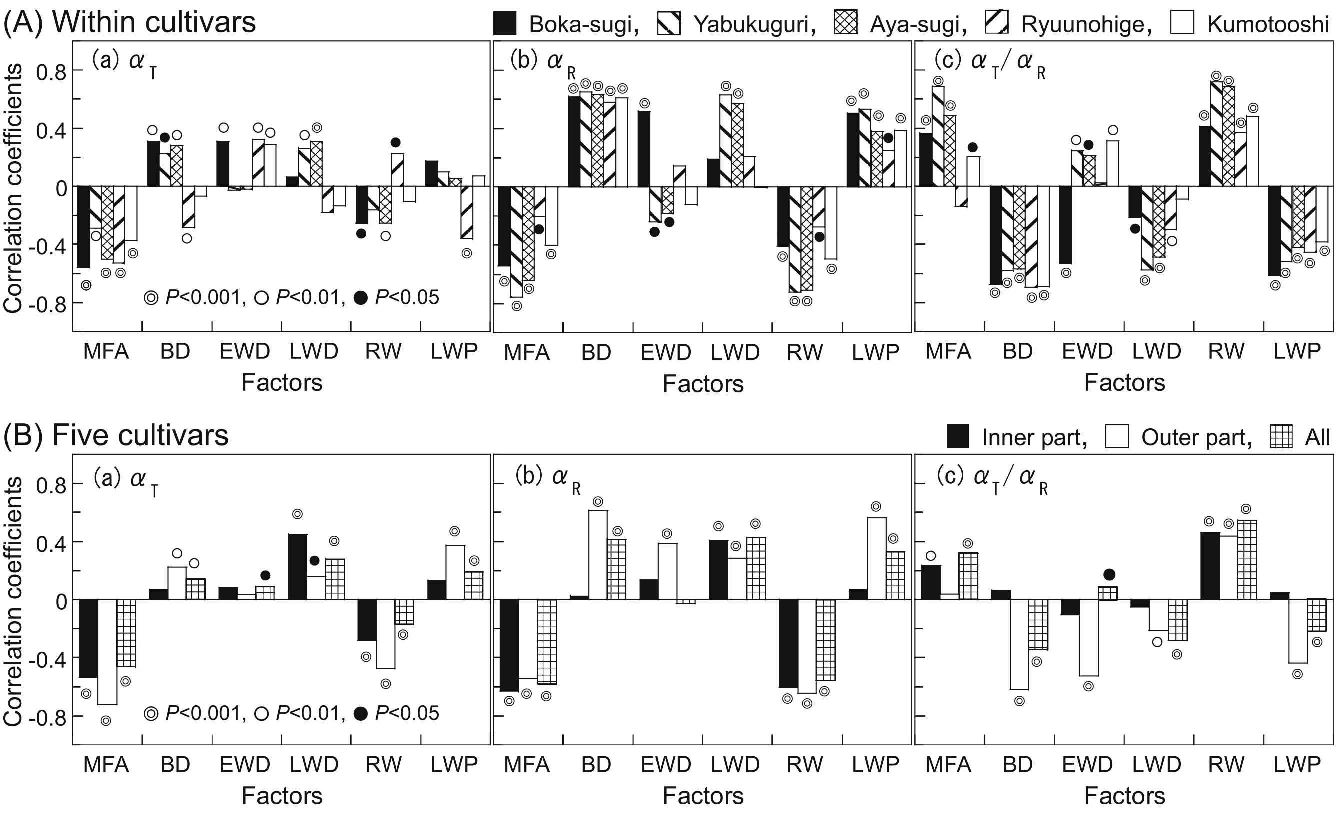

Fig. 4A,B. The correlation coefficients between transverse shrinkage (α_T, α_R, and α_T/α_R) and MFA, BD, EWD, LWD, RW, and LWP for **A** each cultivar and **B** combined samples of the five cultivars

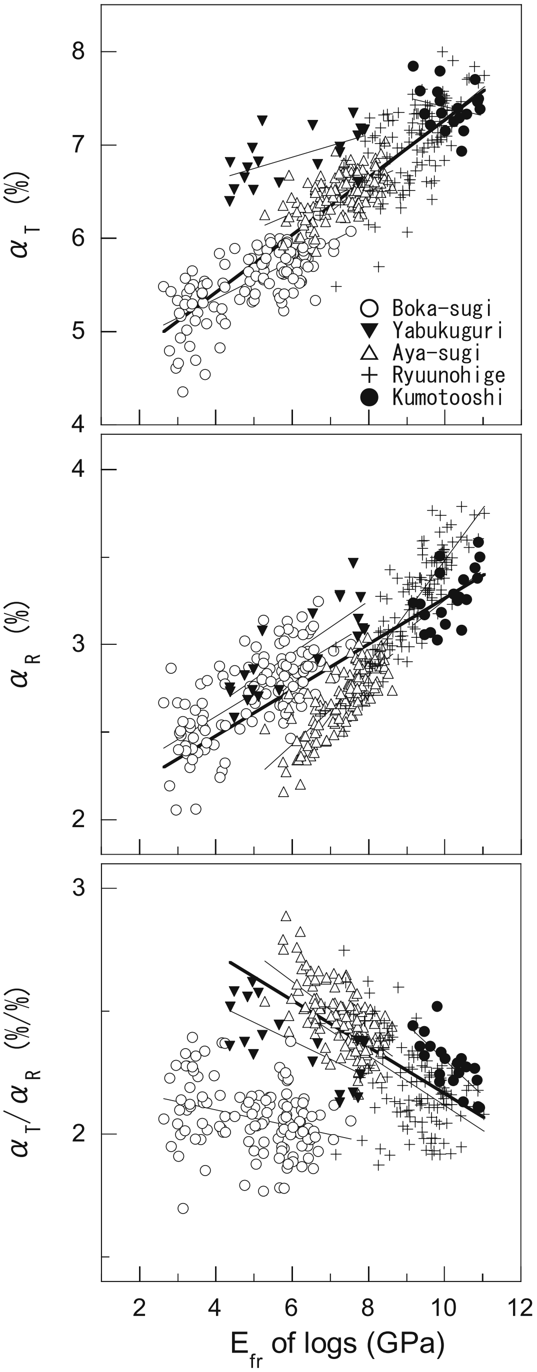

Fig. 5. Relationships between transverse shrinkage (α_T, α_R, and α_T/α_R) and modulus of elasticity (E_{fr}) of logs. *Narrow lines* are relationships for each cultivar. *Thick lines* are relationships for the combined samples of the five cultivars for tangential and radial shrinkage, and of the four cultivars except boka-sugi for tangential/radial shrinkage ratio

Discussion

Tangential and radial shrinkage variation within stems and among cultivars

The within-tree trends of transverse shrinkage might be different by species. Kaburagi[37] showed that volumetric shrinkage was large in the outer stem of *Larix*, *Abies*, and *Pinus*, and large in the inner stem of *Fraxinus*, *Populus*, and *Picea*. In *Pinus*, tangential and radial shrinkage were reported to be larger in the outer wood than in the inner wood.[10,12,38–39] In *Populus tremula*, it was reported that tangential shrinkage was smallest near the pith and rather uniform, whereas radial shrinkage decreased at first and then increased strongly from pith to bark.[40] In sugi, Zhu et al.[4] showed that both tangential and radial shrinkage were larger in mature wood than in juvenile wood, and that they were smaller at lower heights. We found that the within-tree trends of α_T varied by cultivar, whereas α_R increased from pith to bark and with height to a greater or lesser extent in most of the cultivars (Fig. 2). In contrast, α_T/α_R decreased from pith to bark and decreased slightly with height. The opposite trends of α_R and α_T/α_R might have occurred because the within-tree variation of α_R was larger than that of α_T.

Fukazawa[8] showed the differences in volumetric shrinkage among sugi cultivars. We found significant differences among cultivars both for α_T and α_R (Table 2). The difference among cultivars was larger in the inner part of the stem for α_T, and larger in the outer part of the stem for α_R.

These variations of transverse shrinkage within stem suggest that the shrinkage behavior and drying-stress distribution within the lumber might differ depending on where the lumber is sawn in the log. The difference in transverse shrinkage among cultivars suggests the amount of shrinkage, the drying stress, and the incidence of drying defects such as cracks or deformations might differ among lumber sawn from different cultivars. If the lumber was sorted by shrinkage properties and appropriate drying schedules were applied to each group, it is expected that the drying yield would increase and the cost and energy consumption would decrease. The significant correlations between transverse shrinkage and E_{fr} of logs (Fig. 5, Table 3) suggest that it might be possible to sort lumber with large transverse shrinkage by measuring the modulus of elasticity. The correlations might have occurred because MFA and density, which have large variation within sugi trees, had significant effects both on transverse shrinkage and modulus of elasticity.

In this study, the shrinkage specimens were not taken within 20 mm of the pith or the third growth ring to avoid knots. In the zone near the pith, the MFA might be larger, density might be higher, and anatomical features such as tracheid diameter and wall thickness might be different from areas away from the pith. Therefore, we would expect the shrinkage behavior of lumber containing pith to be different, which is a topic for future investigation.

Factors affecting tangential and radial shrinkage

The factors that contribute to transverse shrinkage might vary depending on the anatomical structure and its variation within each species. The variations of the tangential and radial shrinkage within stem and among sugi cultivars showed the common and different trends, which suggested that they were affected by common and different factors.

Both α_T and α_R were correlated with MFA (Figs. 3, 4). It suggests that MFA is an important factor for tangential and radial shrinkage in sugi. The effect of MFA might be different by species depending on its variation within species. In *Eucalyptus globulus*, it is reported that MFA had an effect only on tangential shrinkage, but not on radial shrinkage.[26] Both α_T and α_R were correlated with basic density, and the correlation of α_R was higher than that of α_T (Figs. 3, 4), which was the same result shown for multiple species[11] and for sugi.[3] This might be because radial shrinkage was influenced by the total amount of cell wall including earlywood and latewood, whereas tangential shrinkage was largely controlled by the changes in latewood. The effects of tree ring parameters were different between tangential and radial shrinkage. Among the tree ring parameters, LWD showed the highest correlation for tangential shrinkage, and RW showed the highest correlation for radial shrinkage. The correlations of transverse shrinkage (α_T and α_R) with LWD were higher than those with EWD (Figs. 3, 4), even though EWD was more strongly related to basic density than LWD. These results suggest that not only density but also tree ring parameters are important factors for transverse shrinkage in sugi.

The correlations of transverse shrinkage with basic density and tree ring parameters varied among the cultivars (Fig. 4A). The correlations with BD and LWP were higher in the outer part of the stem than in the inner part of the stem (Fig. 4B). These findings suggest that factors affecting the transverse-shrinkage variation are not consistent among cultivars or within stem in sugi.

The within-tree trends of transverse shrinkage were not completely explained by the six factors examined in this study. Radial shrinkage increased from pith to bark even in the cultivars in which density decreased. One probable explanation is that the earlywood–latewood interaction might vary depending on tree ring structure. In the outer stem, earlywood tracheid exhibits larger cell size and thinner cell wall than in the inner stem; therefore, the shape of earlywood tracheid might be more easily deformed. Watanabe et al.[16] showed that the difference in shrinkage anisotropy among species greatly depended on the transverse cell shape. Another probable explanation is ray restraint. Although the rays are small in conifers, they might still have a significant restraining effect on radial shrinkage.[5] Fujiwara and Nakayama[41] reported that the number of rays is largest near the pith at the base of the stem, and decreases to a constant level from pith to bark and decreases with height within the sugi stem, which was the opposite trend of radial shrinkage observed in this study. In *E. globulus*, it was suggested that the expected higher proportion of ray tissue in young developing trees might offer greater radial restraint during drying.[42] There are other factors affecting transverse shrinkage such as the differences of microfibril orientation[21] and lignin content[43] between the tangential and radial walls, but the variations of these properties have not been investigated.

The effects of seed source and growing condition on transverse shrinkage have been evaluated in other species. Koshy and Lester[44] found no significant genetic effect for transverse shrinkage in Douglas fir, but suggested that the large variation within and among trees might be improved by stand management. McAlister and Clark[38] reported the effect of stand, but not the effect of seed source in Loblolly pine. Yang et al.[42] reported that the stand effect was significant both for tangential and radial shrinkage, but there was a provenance effect only for tangential shrinkage in *E. globulus*. This study showed MFA, density, and tree ring parameters were the main indicators of the transverse shrinkage variation in sugi. It has been shown that MFA is highly heritable,[27–30] while density and tree ring structures are affected by both genetic and environmental conditions.[31–35] Therefore, we expect that the transverse shrinkage of sugi might be improved by breeding and stand management.

Conclusions

Sugi cultivars showed significant differences in tangential shrinkage, radial shrinkage, and tangential/radial shrinkage ratio within a stem. The radial and height trends of tangential shrinkage were different among cultivars, while the radial shrinkage increased and the tangential/radial shrinkage ratio decreased with radius and height in the stems of most cultivars.

The microfibril angle was one of the most important indicators of both tangential and radial shrinkage. Density and tree ring parameters such as latewood density, ring width, and latewood percentage were indicators of radial shrinkage, and to a lesser extent tangential shrinkage. The effect of earlywood density on transverse shrinkage was limited.

There were close relationships between tangential and radial shrinkage and modulus of elasticity of logs. It might be possible to use the modulus of elasticity for sorting lumbers with large shrinkage during drying in sugi.

Acknowledgments We thank Mr. Jiro Akutsu for preparing the specimens for shrinkage and soft X-ray densitometry. We thank Dr. Trevor Jones for soft X-ray densitometry. We thank Dr. Trevor Jones and Dr. Naohiro Kuroda for suggestions regarding the manuscript.

References

1. Kuroda N (2007) Development of fundamental research on drying of boxed-heart square timber of sugi (*Cryptomeria japonica*) (in Japanese with English summary). Mokuzai Gakkaishi 53:243–253
2. Fukuhara Y, Matsuo T, Okada A (1983) On the wood quality of the thinned tree of sugi (in Japanese with English summary). Bull Utsunomiya Univ Forest 19:45–54
3. Ikeda M (1998) Relationship between shrinkage and growth rate of Sugi wood with same diameter (in Japanese). Bull Kyushu Branch Jpn Forest Soc 51:179–180
4. Zhu J, Takata K, Iijima Y, Hirakawa Y (2003) Growth and wood quality of sugi (*Cryptomeria japonica*) planted in Akita prefecture I. Variation of some wood quality indices within tree stems (in Japanese with English summary). Mokuzai Gakkaishi 49:138–145
5. Panshin AJ, De Zeeuw C (1980) Textbook of wood technology, 4th edn. McGraw-Hill, New York, pp 207–212

6. Skaar C (1988) Wood–water relations, Springer, Berlin Heidelberg New York, pp 122–176
7. Kaburagi Z (1962) Forest-biological studies on wood quality (Report 15). On the volumetric shrinkage of Todo-fir – the apparent value and its relationship to the bulk-density (in Japanese with English summary). Bull Gov Forest Exp Stat 144:53–96
8. Fukazawa K (1967) The variation of wood quality within a tree of *Cryptomeria japonica* D. Don (in Japanese with English summary). Res Bull Fac Agric Gifu Univ 25:47–128
9. Yao J (1969) Shrinkage properties of second-growth southern yellow pine. Wood Sci Technol 3:25–39
10. Choong ET, Fogg PJ (1989) Differences in moisture content and shrinkage between innerwood and outerwood of two shortleaf pine trees. Forest Prod J 39:13–18
11. Watanabe U, Norimoto M (1996) Shrinkage and elasticity of normal and compression woods in conifers. Mokuzai Gakkaishi 42:651–658
12. Dumail JF, Castera P (1997) Transverse shrinkage in maritime pine juvenile wood. Wood Sci Technol 31:251–264
13. Pentoney RE (1953) Mechanisms affecting tangential vs. radial shrinkage. J Forest Prod Res Soc 3:27–32, 86
14. Kaburagi Z (1950) Forest-biological studies on the wood quality. Report 1. On the moisture content, the bulk density of the early- and late-wood of green Todo-fir grown at Nopporo district in Hokkaido and their shrinkage (in Japanese with English summary). Bull Gov Forest Exp Stat 46:37–70
15. Watanabe U, Norimoto M, Fujita M, Gril J (1998) Transverse shrinkage anisotropy of coniferous wood investigated by the power spectrum analysis. J Wood Sci 44:9–14
16. Watanabe U, Fujita M, Norimoto M (1998) Transverse shrinkage of coniferous wood cells examined using replica method and power spectrum analysis. Holzforschung 52:200–206
17. Murata K, Ito M, Masuda M (2001) An analysis of the swelling behavior of various woods using an optical microscope and a digital image correlation method (DIC) (in Japanese with English summary). J Soc Mater Sci Jpn 50:397–402
18. Murata K, Masuda M (2006) Microscopic observation of transverse swelling of latewood tracheid: effect of macroscopic/mesoscopic structure. J Wood Sci 52:283–289
19. Mikajiri N, Matsumura J, Okuma M, Oda Kazuyuki (2001) Observation by LV-SEM of shrinkage and anisotropy of tracheid cells with desorption (in Japanese with English summary). Mokuzai Gakkaishi 47:289–294
20. Sakagami H, Matsumura J, Oda K (2007) Shrinkage of tracheid cells with desorption visualized by confocal laser scanning microscopy. IAWA J 28:29–37
21. Barber NF, Meylan BA (1964) The anisotropic shrinkage of wood. A theoretical model. Holzforschung 18:146–156
22. Harris JM, Meylan BA (1965) The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. Holzforschung 19:144–153
23. Cave ID (1972) A theory of the shrinkage of wood. Wood Sci Technol 6:284–292
24. Yamamoto H, Sassus F, Ninomiya M, Gril J (2001) A model of anisotropic swelling and shrinking process of wood. Wood Sci Technol 35:167–181
25. Abe K, Yamamoto H (2006) Behavior of the cellulose microfibril in shrinking woods. J Wood Sci 52:15–19
26. Yang JL, Ilic J, Evans R (2003) Interrelationships between shrinkage properties, microfibril angle, and cellulose crystallite width in 10-year-old *Eucalyptus globulus*. New Zeal J Forest Sci 33:47–61
27. Hirakawa Y, Fujisawa Y (1996) The S_2 microfibril angle variations in the vertical direction of latewood tracheids in sugi (*Cryptomeria japonica*) trees (in Japanese with English summary). Mokuzai Gakkaishi 42:107–114
28. Hirakawa Y, Yamashita K, Nakada R, Fujisawa Y (1997) The effects of S_2 microfibril angles of latewood tracheids and densities on modulus of elasticity variations of sugi tree (*Cryptomeria japonica*) logs (in Japanese with English summary). Mokuzai Gakkaishi 43:717–724
29. Yamashita K, Hirakawa Y, Fujisawa Y, Nakada R (2000) Effects of microfibril angle and density on variation of modulus of elasticity of sugi (*Crypromeria japonica*) logs among eighteen cultivars (in Japanese with English summary). Mokuzai Gakkaishi 46: 510–522
30. Nakada R, Fujisawa Y, Hirakawa Y (2003) Effects of clonal selection by microfibril angle on the genetic improvement of stiffness in *Cryptomeria japonica* D. Don. Holzforschung 57:553–560
31. Tsushima S, Koga S, Oda K, Shiraishi S (2006) Effects of initial spacing on growth and wood properties of sugi (*Cryptomeria japonica*) cutting cultivars (in Japanese with English summary). Mokuzai Gakkaishi 52:196–205
32. Yahata H, Miyajima H, Sairinji T, Huruie H, Kodama T, Yuruki T, Yamamoto H, Kubota S, Watanabe K, Nogami K, Kuroki H (1987) Wood quality variations of native cultivars and the clones of plus trees in the experimental areas of cultivars of *Cryptomeria japonica* in Kyushu (in Japanese with English summary). Bull Kyushu Univ Forest 57:149–173
33. Fujisawa Y, Ohta S, Tajima M (1993) Wood characteristics and genetic variations in sugi (*Cryptomeria japonica*) II. Variation in growth ring components among plus-trees clones and test stands. Mokuzai Gakkaishi 39:875–882
34. Fujisawa Y, Ohta S, Akashi T (1995) Wood characteristics and genetic variation in sugi (*Cryptomeria japonica*) IV. Variation in growth ring features of plus-tree clones in relation to the initial planting space (in Japanese with English summary). Mokuzai Gakkaishi 41:631–639
35. Kubo T, Jyudo S (1996) Some characteristics of the annual ring structure related to wood density variation in sugi (*Cryptomeria japonica*). Mokuzai Gakkaishi 42:1156–1162
36. Yamashita K, Hirakawa Y, Nakatani H, Ikeda M (2009) Longitudinal shrinkage variations within trees in sugi (*Cryptomeria japonica*) cultivars. J Wood Sci 55:1–7
37. Kaburagi Z (1956) Forest-biological studies on wood quality. (Report 13) On the volumetric shrinkage of wood of the planted trees grown at Nopporo district in Hokkaido (in Japanese with English summary). Bull Gov Forest Exp Stat 90:109–144
38. McAlister RH, Clark A (1992) Shrinkage of juvenile and mature wood of loblolly pine from three locations. Forest Prod J 42:25–28
39. Cown DJ, McConchie DL, Young GD (1991) Radiata pine wood properties survey. FRI Bull 50:1–50
40. Kärki T (2001) Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz Roh Werkst 59:79–84
41. Fujiwara S, Nakayama Y (1978) Distribution of rays and total number of ray cells in stem of sugi (*Cryptomeria japonica* D. Don) (in Japanese with English summary). Mokuzai Gakkaishi 24: 841–845
42. Yang JL, Fife D, Ilic J, Blackwell P (2002) Between-site and between-provenance differences in shrinkage properties of 10-year-old *Eucalyptus globules* Labill. Aust Forest 65:220–226
43. Boyd JD (1974) Anisotropic shrinkage of wood: identification of the dominant determinants. Mokuzai Gakkaishi 20:473–482
44. Koshy MP, Lester DT (1994) Genetic variation of wood shrinkage in a progeny test of coastal Douglas-fir. Can J Forest Res 24: 1734–1740