論　文（Original article）

Wood properties of *Picea koyamae*: within-tree variation of grain angle, tracheid length, microfibril angle, wood density and shrinkage

Kana YAMASHITA[1)*], Toshio KATSUKI[2)],
Kouji AKASHI[3)] and Yoshitaka KUBOJIMA[1)]

Abstract

The within-tree variations of wood properties including grain angle, tracheid length (TL), microfibril angle (MFA), wood density, tree ring parameters and shrinkage, which influence the physical characteristics, were investigated with a native tree of a threatened species, *Picea koyamae*. The grain was S-helix in the inner rings and the grain angle reached a maximum of 4° – 6° at ring numbers 5 – 9 followed by a slow decline toward the bark. TL of latewood increased from pith to bark, ranging from 0.86 mm to 4.95 mm. MFA of latewood rapidly decreased from the pith outward to ring number 10 followed by a gradual decrease and then remained almost constant. MFA ranged from 2.2° to 42.0°. Mean wood density declined rapidly from the pith outward to ring number 10, then remained constant with annual fluctuations. Mean wood density was closely correlated with latewood percentage and earlywood density. Longitudinal shrinkage was higher, and transverse shrinkage was lower in the core wood than in the outer wood. The difference in shrinkage between the core wood and the outer wood was thought to be affected by MFA. Twisting and warping might be large in the core part of the stem because the grain angle and MFA and their variations were large, but might be small in the outer part of the stem. The within-tree variation patterns and the values of these wood properties of *P. koyamae* were comparable with those of other *Picea* species, thus the wood is expected to be usable, the same as other *Picea* species.

Key words : *Picea koyamae*, spiral grain, tracheid length, microfibril angle, wood density, tree ring structure, shrinkage

Introduction

Picea koyamae Shiras. (Pinaceae) (Yatsugatake-touhi) is a tree species endemic to the subalpine and mountain zone at altitudes of 1102 – 2028 m in Nagano and Yamanashi prefectures, Japan (Katsuki et al., 2008). It grows straight up to 34 m in height. Since there are only a few populations of native trees, it is listed as a vulnerable category of species by the Japanese government and as an endangered species by IUCN (International Union for Conservation of Nature). Not only are the native trees conserved, but also the trees have been planted in Nagano and Saitama prefectures (about 46 ha) and these are expected to supply wood in future.

Picea is an important forest resource in the Northern hemisphere. The wood is valuable for many products such as pulp wood, construction lumber and musical instruments, because of its lightness combined with the required stiffness and strength, and good resonance qualities. In Japan, *P. glehnii* (Aka-ezomatsu) is distributed in Hokkaido and Iwate prefecture, and *P. jezoensis* var. *jezoensis* (Ezomatsu) is distributed in Hokkaido. The wood qualities of both native trees and plantation trees of *P. glehnii* have been studied, because it is expected to be a favorable plantation species in cold temperate areas (Kawaguchi et al., 1986a; Kawaguchi et al., 1986b; Kawaguchi et al., 1986c; Nobori et al., 1991; Akutsu, 1997a; Akutsu, 1997b; Akutsu & Iizuka, 1998; Iizuka et al., 1999; Iizuka et al., 2000; Iizuka et al., 2001). In comparison, there is little information about the wood quality of other *Picea* species such as *P. koyamae*, *P. jezoensis* var. *hondoensis* (Touhi), *P. maximowiczii* (Himebara-momi), *P. alcoquiana* (Ira-momi) and *P. torano* (Hari-momi) except their anatomical features (Sudo, 1968; Anagnost et al., 1994).

Wood properties change rapidly within the stem in the area from the pith outward and the extent of the area depends on the properties (Zobel & Sprague, 1989).

原稿受付：平成 21 年 9 月 16 日 Received 16 September 2009　原稿受理：平成 21 年 12 月 14 日 Accepted 14 December 2009
1) Department of wood properties, Forestry and Forest Products Research Institute (FFPRI)
2) Forest Bio Research Center, Forestry and Forest Products Research Institute (FFPRI)
3) Iida City Museum
* Department of wood properties, Forestry and Forest Products Research Institute (FFPRI), 1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan; e-mail: zaikana@ffpri.affrc.go.jp

Fortunately, we could obtain logs of a native tree of *P. koyamae* that was more than 100 years old. In order to examine whether the wood of *P. koyamae* can be used like that of other *Picea* species, we measured grain angle, tracheid length, microfibril angle, wood density, tree ring parameters and shrinkage which are the most basic properties affecting physical characteristics such as dimensional stability and strength properties. The strength properties and color were reported in another paper (Kubojima et al., 2009).

Materials and methods

Sample tree

The sample tree of *Picea koyamae* was a dominant tree in a Larix-Picea natural forest on a volcanoclastic material at Karamatsu-Sawa on Mt. Nishidake (Fujimi, Nagano, Japan). The altitude, latitude and longitude were 1690 m, 35°56'31''N (WGS 84) and 138°19'10''E (WGS 84), respectively. The tree was rotten at the base and had snapped at 1 m above the ground during a typhoon in 2007. In that year, the tree was 30.0 m tall and 53.0 cm in diameter at breast height. The number of rings at 4 m was 107. Disks of 30-cm thickness were taken at 8, 12, 14, and 18 m, and strips from pith to bark were taken in four directions (Fig. 1). The disks were not perfect circles but were eccentric. We separated the direction with the longest radius (C) from the other three directions (A, B, and D) in the analysis, because direction C was considered to have compression wood by visual observation and by the peculiar values of measured properties.

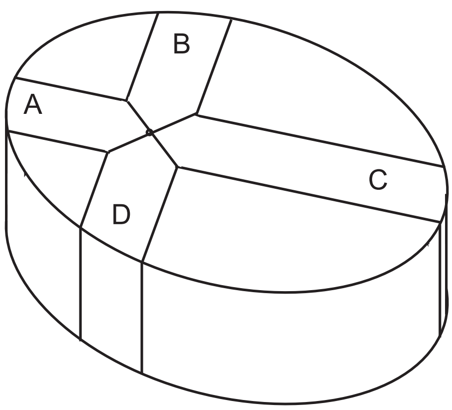

Fig. 1. Directions of the wood property measurements. Two strips (A and C) were taken from the two opposing radii in the direction with the largest diameter. Two strips (B and D) were taken from the two opposing radii in the direction perpendicular to the former strip. The radius was the largest in direction C and the smallest in direction A.

Grain angle

Grain angle was measured by the procedure outlined by Nakagawa (1972). A strip from pith to bark having parallel cross faces was prepared. Parallel base lines passing through the pith were drawn on both cross faces. The specimen was split on one cross face through the base line in the longitudinal direction. The distances from the base line to the split line on the other face were measured at each ring boundary on a four-times enlarged image. The grain angle was calculated as the arctangent of the ratio of the measured distance and the specimen thickness (25 mm).

Tracheid length and microfibril angle

Small chips cut from latewood were macerated in a solution of acetic acid and hydrogen peroxide at 70ºC (Franklin, 1945). The lengths of 50 tracheids per annual ring were measured, and their mean was calculated as tracheid length (TL).

A thin tangential section was cut from the last formed latewood, and the angles between the tangential slit-like pit apertures and the axis of the tracheid were measured (Hirakawa & Fujisawa, 1995). Photo 1 shows the agreement of the directions between slit-like pit aperture and the microfibril orientation stained by the iodine crystals in S_2 layer of a latewood tracheid of *P. koyamae*. The average of 30 tracheids per annual ring was obtained as microfibril angle in the S_2 layer of the tracheid wall (MFA).

Photo 1. The agreement of the directions between slit-like pit aperture (arrow) and the iodine crystals in a latewood tracheid in *Picea koyamae*.

X-ray densitometry

A cross section from pith to bark with 2-mm thickness was prepared from an air-dried strip. After conditioning at 20ºC and 65% RH, a soft X-ray negative was taken (4 min., 14 mA, 20 kV) and scanned to obtain the density profile using a Dendro2003 (Walesch Electronic). The seven tree ring parameters of ring width (RW), earlywood width (EWW), latewood width (LWW), latewood percentage (LWP), mean wood density (MD), earlywood density (EWD) and latewood density (LWD) were calculated for each ring. The boundary between earlywood and latewood was set at 550 kg/m^3 (Nobori et al., 1991).

Shrinkage

Longitudinal shrinkage specimens having dimensions of 20 mm (T) × 5 mm (R) × 50 mm (L) along the grain and transverse shrinkage specimens having dimensions of 20 mm (T) × 20 mm (R) × 5 mm (L) were taken at different radial positions from pith to bark. The lengths of the specimens were measured in the green condition (lg) and in the oven-dry condition (lo). Shrinkage from green to oven-dry condition (α) was obtained using the following equation:

$$\alpha = (lg - lo) / lg \times 100\ (\%)$$

Basic density (BD) was obtained as the oven-dry weight per green volume.

In order to examine the factors affecting wood density and shrinkage, the core wood (CW) and the outer wood (OW) were separated at ring number 15 from the pith (Zhu et al., 1998). Ring number 15 was included in OW. The OW was divided into two groups, directions A, B and D (OW_{ABD}) and direction C (OW_C).

Results and discussion

Grain angle

The grain was S-helix in the inner rings (Fig. 2). Grain angle increased from the pith, reached a maximum and then decreased toward the bark (Fig. 2a). The grain angle of each ring at the four heights ranged from 8.5° to –6.5°. The average grain angle of the four directions reached a maximum angle of 3.7° – 6.0° at ring numbers 5 – 9 followed by a slow decline (Fig. 2b). The radial patterns and the values were similar among heights.

The radial pattern of grain angle and the grain angle of *P. koyamae* were similar to those of other *Picea* species. Ohkura (1958) reported that the grain started with S-helix in the core part of the stem turning into Z-helix in the outer part in *P. jezoensis* var. *hondoensis*, *P. jezoensis* var. *jezoensis* and *P. glehnii*, and the maximum angles of twist were 3°, 5° and 2°, respectively. Spiral grain causes twisting during drying of sawn timber and plywood, and reduces the strength of timber (Harris, 1989). The boards sawn near the pith would induce twisting in *P. koyamae* as well as in other *Picea* species (Okura et al., 1963).

Tracheid length and microfibril angle

First, the trends from pith to bark were observed in direction A in which the radius was shortest. TL increased rapidly in the core part, and gradually in the outer part (Fig. 3a). TL reached 4.1 – 4.6 mm at ring number 60 and kept increasing thereafter. TL of each ring ranged from 0.86 mm to 4.95 mm. The radial trends and the values were similar between directions A, B and D, and among heights (Fig. 3a, b). When a logarithmic function was fitted, the ring number where the annual rate of increase reached 1%, which was

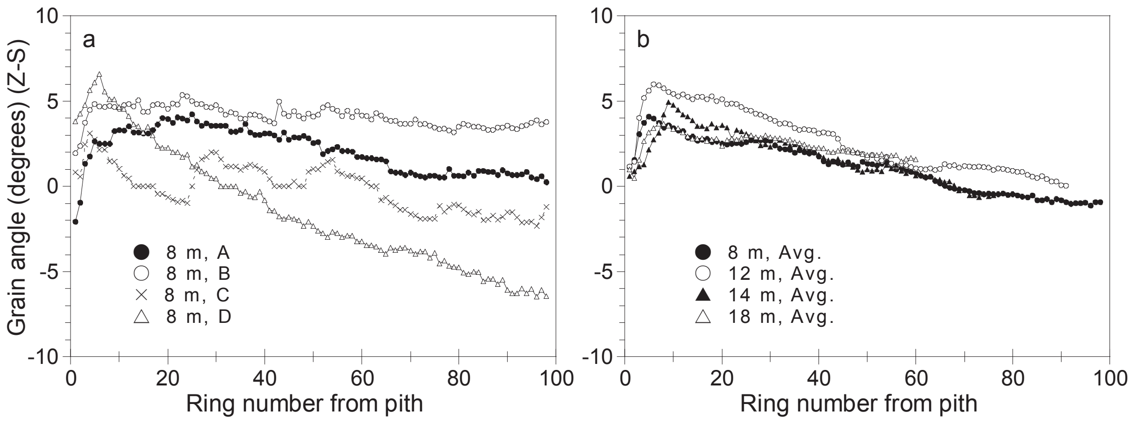

Fig. 2. Radial trend of grain angle. a) Four directions at 8 m above the ground. b) Average of four directions at 8 m, 12 m, 14 m and 18 m above the ground. The minus (Z) grain angle is the deviation to the right of the upper extremity of the longitudinal axis of a tree as viewed by an observer on the ground, and plus (S) grain angle is to the left.

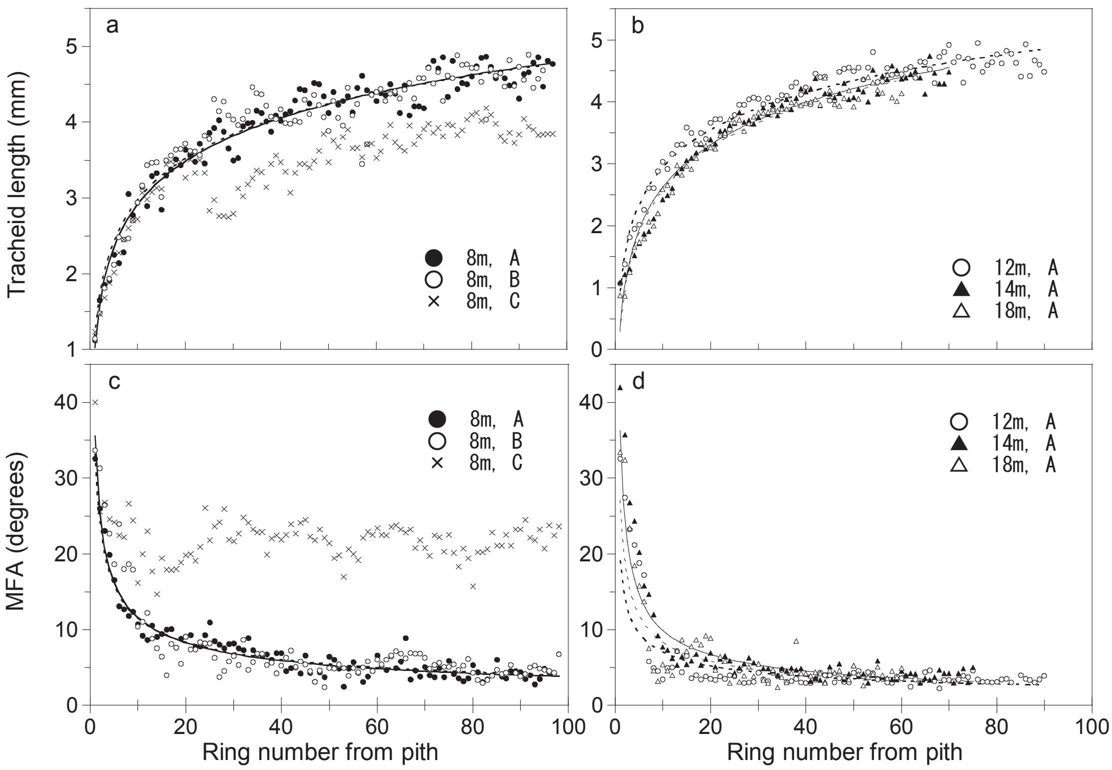

Fig. 3. Radial trends of tracheid length (a, b) and MFA (c, d). Directions A , B and C at 8 m above the ground (a, c), and direction A at 12 m, 14 m and 18 m above the ground (b, d) are shown.

Table 1. Regression equations between ring number and tracheid length and MFA

Height (m)	Direction	Tracheid length	MFA
8	A	Y_{TL}=1.024+1.892Log(X) R^2=0.944	Y_{MFA}=5.16+35.8/X R^2=0.796
12	A	Y_{TL}=0.953+1.994Log(X) R^2=0.955	Y_{MFA}=2.87+38.0/X R^2=0.814
14	A	Y_{TL}=0.351+2.274Log(X) R^2=0.960	Y_{MFA}=3.63+48.6/X R^2=0.880
18	A	Y_{TL}=0.296+2.282Log(X) R^2=0.965	Y_{MFA}=3.69+38.1/X R^2=0.808

X: ring number from pith; Y_{TL}: tracheid length; Y_{MFA}: MFA.

proposed as the boundary of juvenile wood and mature wood by Shiokura (1982), was 24 – 28 where the distances from the pith were 60 – 92 mm and TL were 3.6 – 3.7 mm (Table 1). The radial trend of *P. koyamae* and the values of TL were comparable to those of other *Picea* species such as *P. jezoensis* var. *jezoensis* (Shiokura, 1971), *P. glehnii* (Kawaguchi et al., 1986b) and *P. abies* (Zobel & Sprague, 1998; Mäkinen, 2007).

MFA was at a maximum in the first-formed rings, decreased rapidly to ring number 10, then remained almost constant (Fig. 3c). MFA reached 3.5° – 5.8° at ring number 60. MFA of each ring ranged from 2.2° to 42.0°. The radial trends and the values were similar between directions A, B and D, and among heights (Fig. 3c, d). Among a fractional function, logarithmic function and exponential function, a fractional function was the most suitable (Table 1). When a fractional function was fitted, the ring number where the rate of decrease per 5 years reached 2.5°, which was proposed as the MFA boundary of juvenile wood and mature wood by Hirakawa and Fujisawa (1995), was 10 – 12 where the distances from the pith were 30 – 49 mm and MFA were 6.3° – 9.3°. The radial trend of *P. koyamae* was similar to that of *P. abies* (Sahlberg et al., 1997; Lindström et al., 1998; Brändström, 2001). The latewood MFA of *P. koyamae* at ring number 60 was close to the latewood MFA of *P. glehni* (5.9°) and *P. jezoensis* (3.7°) (Hori et al., 2002).

MFA was fairly constant after ring number 20 – 30, although TL kept increasing after ring number 30. The areas of rapid change in the core part and the rate of change were different between TL and MFA (Fig. 3), as reported in other species such as *P. abies* (Brändström, 2001) and *Larix kaempferi* (Takimoto, 2001).

Wood density and tree ring parameters

First, the trends from pith to bark and difference between the core wood (CW) and the outer wood (OW_{ABD}) were examined except in direction C. Wood density and tree ring parameters changed rapidly in the core part. RW, EWW, LWW, LWP, MD and EWD of CW were larger than those of OW_{ABD} (Table 2). Their decline curves from pith to bark exhibited slight differences (Fig. 4). RW and EWW reached a maximum in ring numbers 4 – 8 then declined slowly. LWW and LWP were high in the first few rings and fluctuated thereafter. MD and EWD were at a maximum in the first or second ring, declined rapidly to ring number 10 and fluctuated by annual ring thereafter. On the other hand, LWD of CW was smaller than that of OW_{ABD} (Table 2). The radial trends and values of the ring parameters were similar between directions A, B and D, and among heights.

Among the tree ring parameters, LWP and EWD showed the highest correlations with MD, and LWW also showed a high correlation (Fig. 5, Table 3). Some

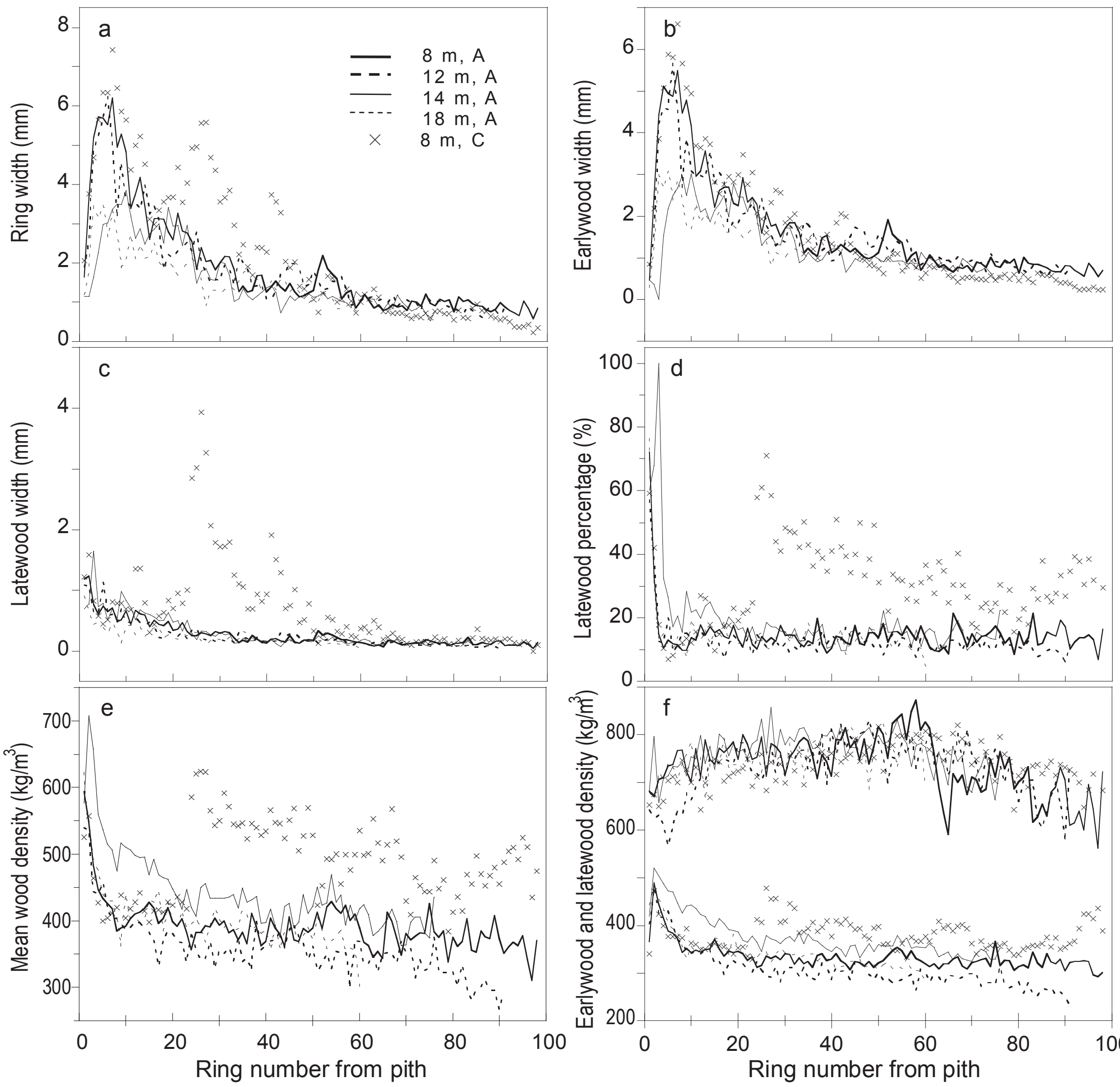

Fig. 4. Radial trends of ring width (a), earlywood width (b), latewood width (c), latewood percentage (d), mean wood density (e) and earlywood and latewood density (f). Direction A at 8 m, 12 m, 14 m and 18 m above the ground, and direction C at 8 m above the ground are shown.

Table 2. Averages of tree ring parameters with standard deviations

Position within stem	RW (mm)	EWW (mm)	LWW (mm)	LWP (%)	MD (kg/m^3)	EWD (kg/m^3)	LWD (kg/m^3)
CW	3.58±0.06[a]	2.80±0.05[a]	0.78±0.03[a]	25.7±0.9[a]	471±5[a]	396±3[a]	719±3[b]
OW_{ABD}	1.46±0.03[c]	1.24±0.03[b]	0.22±0.02[c]	14.6±0.5[c]	390±3[b]	332±2[c]	733±2[a]
OW_C	1.77±0.06[b]	1.12±0.05[b]	0.65±0.03[b]	32.3±0.8[b]	482±4[a]	371±3[b]	728±3[ab]

RW: ring width; EWW: earlywood width; LWW: latewood width; LWP: latewood percentage; MD: mean wood density, EWD: earlywood density; LWD: latewood density. CW: core wood with ring number less than 15; OW_{ABD}: outer wood with ring number larger than equal 15 in directions A, B and D; OW_C: outer wood with ring number larger than equal 15 in direction C. There were significant differences among the positions within the stem by one-way analysis of variance in RW, EWW, LWW, LWP, MD, EWD ($P < 0.001$) and LWD ($P < 0.05$). Values in the same column with different letters were significantly different by the Tukey-Kramer HSD test ($P < 0.05$).

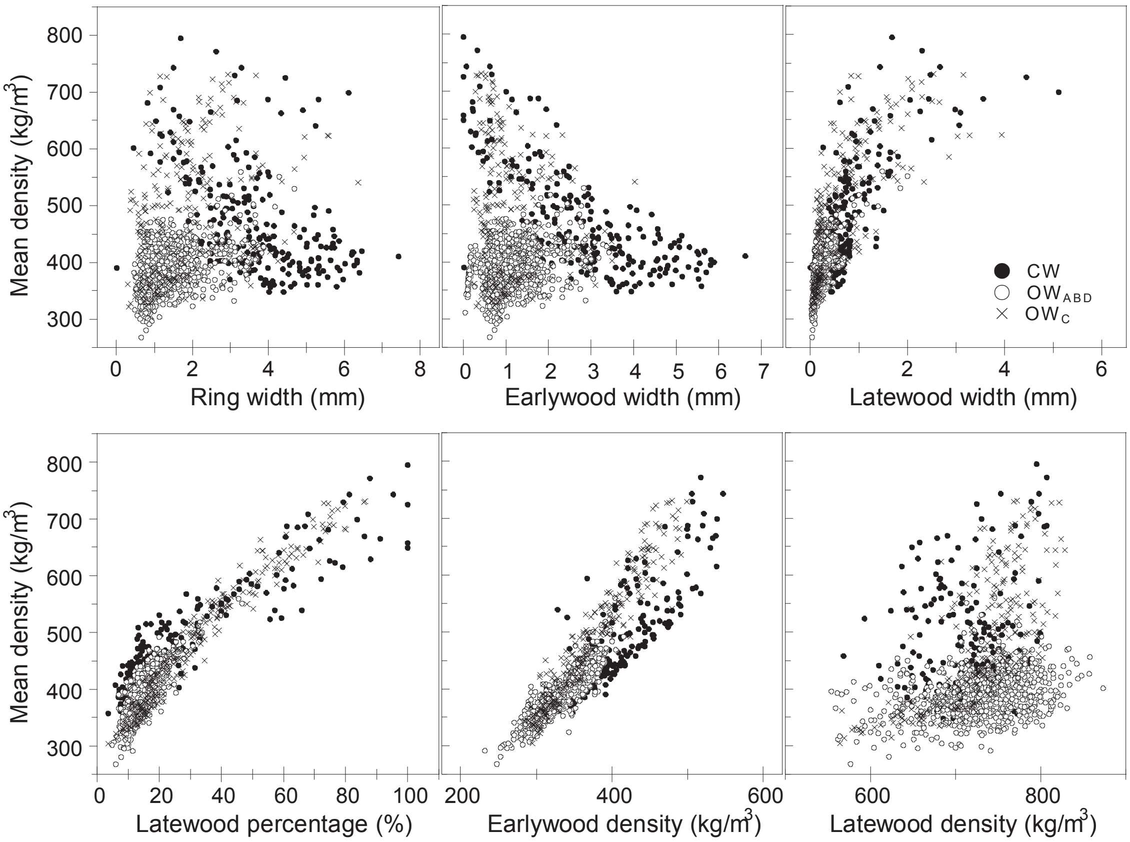

Fig. 5. Relationships between tree ring parameters and mean wood density of the core wood (CW), the outer wood in directions A, B and D (OW_{ABD}) and the outer wood in direction C (OW_C).

Table 3. Correlation coefficients between mean wood density and tree ring parameters

Position within stem	RW	EWW	LWW	LWP	EWD	LWD
All	0.261***	-0.057*	0.770***	0.919***	0.907***	0.265***
CW	-0.403***	-0.700***	0.728***	0.915***	0.871***	0.071
OW_{ABD}	0.334***	-0.169***	0.726***	0.971***	0.957***	0.696***
OW_C	0.376***	0.276	0.611***	0.772***	0.910***	0.342***

***: $P < 0.001$; **: $P < 0.01$; *: $P < 0.05$. RW, EWW, LWW, LWP, MD, EWD, LWD, CW, OW_{ABD}, and OW_C are the same as in Table 2.

parameters exhibited different correlations in the core wood and the outer wood: the correlation with EWW was much higher in CW than OW_{ABD}, and the correlation with LWD was significant in OW_{ABD}, but not in CW.

The radial trends of the ring parameters of *P. koyamae* were similar to those of other *Picea* species. The mean wood density was high near the center of the stem, the same as for other *Picea* species (Zobel & Sprague, 1998). In *P. glehnii*, it was shown that the radial trends were similar between RW and EWW and between EWD and MD, and that LWP and EWD affected MD (Nobori et al., 1991). The parameters showing high correlations with density of *P. koyamae* were also the same as those of *P. glehnii* (Akutsu & Iizuka, 1998).

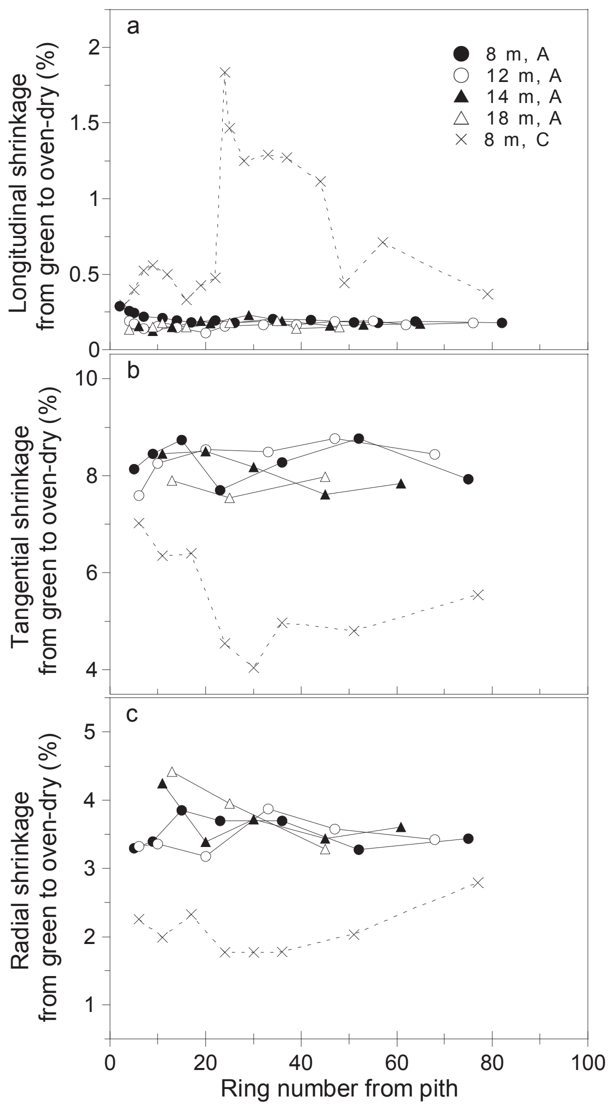

Fig. 6. Radial trends of longitudinal (a), tangential (b) and radial (c) shrinkage. Direction A at 8 m, 12 m, 14 m and 18 m above the ground, and direction C at 8 m above the ground are shown.

Shrinkage

The shrinkages along the three directions (α_L, α_T, and α_R) were almost constant with radius in directions A, B and D (Fig. 6). Statistically, α_L, BD and MFA of CW were significantly larger, and α_T and α_R of CW were significantly smaller than those of OW_{ABD} (Table 4). The radial trends and the values were similar between directions A, B and D, and among heights.

The radial trends were similar with those of other *Picea* species. Kawaguchi & Takahashi (1986a) reported that BD, α_L and α_R were larger, and α_T was smaller within 3 cm from the pith compared with those in the outer part, although their radial variation was small in *P. jezoensis* var. *jezoensis* and *P. glehni*, which was similar to our result of *P. koyamae* except that α_R was smaller at the core part. Saranpää(1994) reported that the longitudinal shrinkage decreased from the pith towards the outer rings in *P. abies*. The shrinkage values were also comparable with those of other *Picea* species, although BD, α_T and α_R were a little smaller than those of *P. jezoensis* var. *hondoensis* sampled in Koumi, Nagano (Table 4) (Wood Technology and Wood Utilization Division, 1982; Kawaguchi & Takahashi 1986a).

Wood properties in the direction with the longest radius

Direction C had the longest radii and its wood properties were different from those of the other directions. In direction C, TL was shorter (Fig. 3a), MFA was larger (Fig. 3c) and RW, LWW, LWP, MD and EWD were higher (Fig. 4, Table 2) than those of the other directions at each height. The α_L, BD and MFA of OW_C were larger, and α_T and α_R of OW_C were smaller than those of CW and OW_{ABD} (Fig. 6, Table 4). The differences were probably caused by compression wood (Panshin & De Zeeuw, 1970). The grain angle of direction C was not peculiar compared with those of the other directions (Fig. 2).

Factors affecting shrinkage

Wood shrinkage generally increases in proportion to wood density since the shrinkage amount is proportional to the amount of the cell wall material. However, α_T and α_R of CW and OW_C were much smaller than those of OW_{ABD} even though the wood density was higher in CW and OW_C (Fig. 7, Table 5). The relationship between BD and transverse shrinkage was negative in CW and OW_C, which was also shown in compression wood of Todo-fir (*Abies sachalinensis*) (Kaburaki, 1952).

Generally, longitudinal shrinkage increases and transverse shrinkage decreases with the increase of MFA, since the region consisting of non-crystalline cellulose

Table 4. Shrinkage, basic density (BD) and MFA of native trees of P. koyamae and other Picea species

Species	Position within stem	α_L (%)	α_T (%)	α_R (%)	α_T/α_R (%/%)	BD (kg/m^3)	MFA (degree)
P. koyamae	CW	0.37±0.03^b	7.25±0.20^b	3.05±0.11^b	2.45±0.07^a	350±5^b	16.0±0.5^b
	OW_{ABD}	0.18±0.03^c	7.98±0.15^a	3.43±0.08^a	2.34±0.05^a	328±4^c	7.2±0.5^c
	OW_C	0.93±0.05^a	4.89±0.22^c	2.10±0.12^c	2.35±0.07^a	419±6^a	21.3±0.7^a
P. jezoensis	HW	0.19	8.52	4.78		373	
var. *hondoensis*[1)]	SW	0.21	8.93	4.32		343	
P. jezoensis	HW	0.18	9.51	4.11		348	
var. *jezoensis*[2)]	SW	0.18	9.02	3.87		350	
P. jezoensis var. *jezoensis*[3)]		0.16	8.1	4.6		370	
P. glehnii[2)]	HW	0.19	7.90	3.41		382	
	SW	0.18	7.61	2.97		355	
P.glehnii[3)]		0.22	7.9	3.8		381	

Sampling sites were 1): Koumi, Nagano (Wood Technology and Wood Utilization Division, 1982); 2): Shintoku, Hokkaido (Wood Technology and Wood Utilization Division, 1982) and 3): Ikutora, Hokkaido (Kawaguchi & Takahashi, 1986a). CW, OW_{ABD}, OW_C are the same as in Table 3. HW: heartwood; SW: sapwood. MFA was measured in the ring where the dimension was measured. There were significant differences among the position within the stem by one-way analysis of variance in α_L, α_T, α_R, BD and MFA (P < 0.001). Values in the same column with different letters were significantly different by the Tukey-Kramer HSD test (P < 0.05).

and hemicellulose shrinks in the direction orthogonal to the crystalline cellulose (Skaar, 1988). In *P. koyamae*, the correlation between MFA and shrinkage was positive in α_L and negative in α_T and α_R, which suggested that MFA affected the shrinkage variation within a tree. Therefore, the large longitudinal shrinkage and small transverse shrinkage in CW and OW_C were supposed to have been affected by large MFA, but not by high density.

The core wood and the compression wood would cause problems such as warp and crook in lumber and waviness in veneer, which require care when the wood is used. However, the area of core wood having large MFA was small (within 10 years from pith where the distances from the pith were about 50 mm). On the other hand, since MFA and its variation were quite small in the outer wood, the outer wood was expected to cause less warp and crook, and to exhibit high elasticity and small internal damping (loss tangent) (Hori, 2002; Kubojima, 2009).

The wood properties of planted trees of *P. koyamae* require future study. In *P. glehnii*, it was reported that there was little difference between a native tree and a vigorous plantation-grown tree in the juvenile-wood area, specific gravity, shrinkage and mechanical property (Kawaguchi et al., 1986b), and that shrinkage of planted trees did not vary much by growth rate or wood density (Akutsu, 1997b). Furthermore, knots and resin pockets, which we did not examine in this study, also need to be considered in forest management since they might affect the lumber quality.

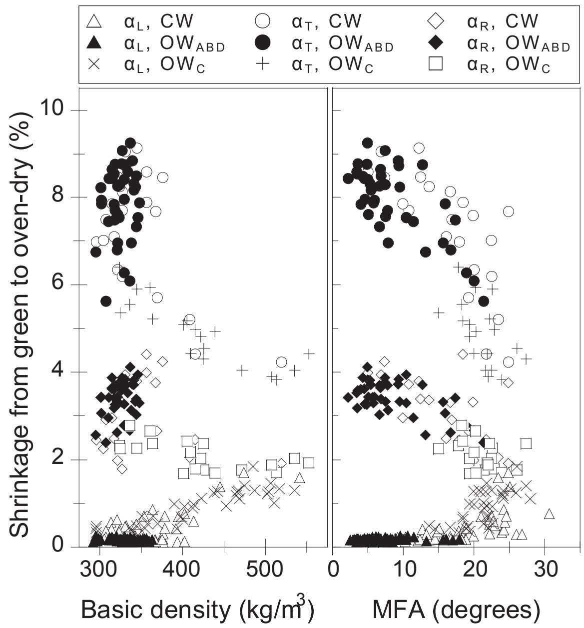

Fig. 7. Relationships between basic density and MFA, and shrinkage of the core wood (CW), the outer wood in directions A, B and D (OW_{ABD}) and the outer wood in direction C (OW_C).

Table 5. Correlation coefficients between basic density (BD), MFA and shrinkage

Position within stem	α_L BD	α_L MFA	α_T BD	α_T MFA	α_R BD	α_R MFA	BD and MFA
All	0.857***	0.743***	-0.760***	-0.819***	-0.585***	-0.766***	0.561***
CW	0.692***	0.625***	-0.615**	-0.744***	-0.177	-0.661***	0.262*
OW_{ABD}	-0.197	0.178	0.083	-0.686***	0.254	-0.553***	-0.090
OW_C	0.879***	0.677***	-0.862***	-0.527*	-0.617	-0.318	0.530***

CW, OW_{ABD}, OW_C are the same as in Table 2. The numbers of samples were CW: 58, OW_{ABD}: 76 and OW_C: 35 for α_L, and CW: 22, OW_{ABD}: 40 and OW_C: 19 for α_T and α_R. ***: $P < 0.001$; **: $P < 0.01$; *: $P < 0.05$.

Conclusions

The within-tree pattern and the values of grain angle, tracheid length, MFA, wood density, tree ring parameters and shrinkage of *P. koyamae* were comparable with those of other *Picea* species. Therefore, the wood of *P. koyamae* is expected to be usable, the same as other *Picea* species. Grain angle, MFA and wood density rapidly changed from the pith to ring number 10. The core wood is expected to cause twisting and warping. On the other hand, the outer wood is expected to cause less twisting and warping and to exhibit high strength because the grain angle, MFA and their variations were small.

Acknowledgements

We are grateful to the Nanshin District Forest Office for providing the sample tree. We are grateful to Mr. Kiyoto Motojima, Chubu regional Forest Office and Mr. Tomoyuki Nishimura, NPO Morinoza for their support during sampling. We thank Dr. Trevor Jones and Dr. Takeshi Fujiwara for their suggestions regarding the manuscript. This work was partially supported by grant from Chubu regional Forest Office (project of conservation for *Picea koyamae*) and Grant-in-Aid for Young Scientists (B) (No. 20780132).

References

Akutsu H. (1997a) Testing of wood quality in plus-tree of *Picea glehnii* - Basic density and slope of grain -, Transactions of the meeting in Hokkaido branch of the Japanese forestry society, **45**, 31–34 (in Japanese).

Akutsu H. (1997b) Testing of wood qualities of *Picea glehnii* plantation (I) Wood qualities of general planted trees, Journal of the Hokkaido Forest Products Research Institute, **11**(3), 1–5 (in Japanese with English summary).

Akutsu H. and Iizuka K. (1998) Testing of wood qualities of *Picea glehnii* plantation (II) Wood qualities of plus-tree clones, Journal of the Hokkaido Forest Products Research Institute, **12**(2), 13–21 (in Japanese with English summary).

Anagnost S. E., Meyer R. W. and De Zeeuw C. (1994) Confirmation and significance of Bartholin's method for the identification of the wood of *Picea* and *Larix*, IAWA J., **15**(2), 171–184.

Brändström J. (2001) Micro- and ultrastructural aspects of Norway spruce tracheids: A review, IAWA J., **22**(4), 333–353.

Franklin G. L. (1945) Preparation of thin section of synthetic resins and wood-resin composites, and a new maceration method for wood, Nature, **3924**, p.51.

Harris J. M. (1989) Spiral grain and wave phenomena in wood formation, Springer-Verlag, 57-76.

Hirakawa Y. and Fujisawa Y. (1995) The relationships between microfibril angles of the S_2 layer and latewod tracheid lengths in elite sugi tree (*Cryptomeria japonica*) clones. Mokuzai Gakkaishi **41**(2), 123–131 (in Japanese with English summary).

Hori R., Müller M., Watanabe U. Lichitenegger H. C., Fratzl P. and Sugiyama J. (2002) The importance of seasonal differences in the cellulose microfibril angle in softwoods in determining acoustic properties. J. Mater. Sci. **37**, 4279–4284.

Iizuka K., Akutsu H. and Itahana N. (1999) Clonal variation of wood quality in the grafted plus-trees of *Picea glehnii*, J. Jpn. For. Soc., **81**, 325–329 (in Japanese with English summary).

Iizuka K., Hayashi E. and Itahana N. (2000) Comparative analysis of growth and wood quality of *Picea glehnii* plus-tree-clones growing in various seed orchards, J. Jpn. For. Soc., **82**, 80–86 (in Japanese with English summary).

Iizuka K., Ubukata M. and Sakamoto S. (2001) Geographic variations of growth and basic density in *Picea glehnii*, J. Jpn. For. Soc., **83**, 53–57 (in Japanese with English summary).

Kaburagi Z. (1952) Forest-biological studies on the wood quality. (Report 4) On the moisture content, the bulk-density in green lumber and the shrinkage of the compression wood of Todo-fir, FFPRI Bulletin, **52**, 53–78 (in Japanese with English summary).

Katsuki T., Akashi K., Tanaka S., Iwamoto K. and Tanaka N. (2008) An estimation of the present distribution of *Picea koyamae* and *P. maximowiczii* using climatic and geological factors, Jpn. J. For. Environ., **50**(1), 25–34 (in Japanese with English summary).

Kawaguchi N. and Takahashi M. (1986a) The properties of natural Ezomatsu and Todomatsu, Journal of the Hokkaido Forest Products Research Institute, **412**, 1–4 (in Japanese).

Kawaguchi N., Takahashi M. and Okubo I. (1986b) The qualities of plantation-grown Akaezomatsu (I), Journal of the Hokkaido Forest Products Research Institute, **416**, 1–10 (in Japanese with English summary).

Kawaguchi N., Takahashi M. and Okubo I. (1986c) The qualities of plantation-grown Akaezomatsu (II), Journal of the Hokkaido Forest Products Research Institute, **419**, 1–9 (in Japanese with English summary).

Kubojima Y., Katsuki T., Akashi K., Yamashita K., Suzuki Y. and Tonosaki M. (accepted in 2009) Radial variations in wood properties of a threatened species, *Picea koyamae*, Mokuzai Gakkaishi (in Japanese with English summary)

Lindström H., Evans. J. W. and Verrill S. P. (1998) Influence of cambial age and growth conditions on microfibril angle in young Norway Spruce (*Picea abies* [L.] Karst.), Holzforschung, **52**, 573–581.

Mäkinen H. (2007) Predicting wood and tracheid properties of Norway spruce, Forest Ecol. Manag., **241**, 175–188.

Nakagawa S (1972) Distribution of spiral grain within stem and the spirality pattern on *Larix leptolepis* Gordon, Bull. Gov. For. Exp. Sta., **248**, 97-120 (in Japanese with English summary).

Nobori Y., Nagata Y., Houjima R., Tomaki K., Kohda H. and Chiba S. (1991) Wood density analysis of *Picea glehnii* by X-ray densitometry, J. Jpn. For. Soc., **73**, 339–343 (in Japanese with English summary).

Ohkura S. (1958) On the macroscopic features of twisted fibre in trees, J. Fac. Agri. Shinshu Univ., **8**, 59–100 (in Japanese with English summary).

Okura S., Ozawa K. and Takagaki N. (1963) On the twisting warp of wood. IV. Twisting warp of boards in relation to fiber directions, Mokuzai Gakkaishi **9**(4), 121–124 (in Japanese with English summary).

Panshin A. J. and De Zeeuw C. (1970) Textbook of wood technology. 3rd edition, McGraw-Hill Company, 289–300.

Sahlberg U., Salmén L. and Oscarsson A. (1997) The fibrillar orientation in the S2-layer of wood fibres as determined by X-ray diffraction analysis, Wood Sci. Technol., **31**, 77–86.

Saranpää P. (1994) Basic density, longitudinal shrinkage and tracheid length of juvenile wood of *Picea abies* (L.) Karst., Scand. J. For. Res., **9**(1), 68–74.

Shiokura T. (1971) Studies on juvenile wood (Part 4) The influence exerted by the early growth control on the variation in average tracheid length in the radial direction across tree trunks of EZO-spruce (*Picea jezoensis* Carr.) and TODO-fir (*Abies sachalinensis* Mast.), Journal of Agricultural Science Tokyo Nogyo Daigaku **16**(2): 99-104 (in Japanese with English summary).

Shiokura T. (1982) Extent and differentiation of the juvenile wood zone in coniferous tree trunks, Mokuzai Gakkaishi **28**(2), 85–90 (in Japanese with English summary).

Skaar C. (1988) Wood-water relations, Springer-Verlag, 122–176.

Sudo S. (1968) Anatomical studies on the wood of species of *Picea*, with some considerations on their geographical distribution and taxonomy, Bull. Gov. For. Exp. Sta., **215**, 39–130.

Takimoto H. (2001) Koujurei Karamatsu zai no MFA no jukannnaihendou (Within annual and from pith to bark variations in the microfibril angles of S2 layer of old age plantations of Japanese larch), Master thesis of Shinshu University, 66p (in Japanese).

Wood technology and wood utilization division (1982) Properties of the Japanese important woods. Table of the properties of woods, FFPRI Bulletin, **319**, 85–126 (in Japanese).

Zhu J., Nakano T., Hirakawa Y (1998) Effect of growth on wood properties for Japanese larch (*Larix kaempferi*): Differences of annual ring structure between corewood and outerwood, J. Wood Sci. **44**, 392–396.

Zobel B. J. and Sprague J. R. (1998) Juvenile wood in forest trees, Springer-Verlag, 21–112.

ヤツガタケトウヒの木材特性： 繊維傾斜角、仮道管長、ミクロフィブリル傾角、木材密度、および収縮率の樹幹内変動

山下 香菜 [1)*], 勝木 俊雄 [2)], 明石 浩司 [3)], 久保島 吉貴 [1)]

要 旨

絶滅危惧種ヤツガタケトウヒの天然木において、物理的性質に影響を及ぼす木材特性である繊維傾斜角、仮道管長、晩材のミクロフィブリル傾角 (MFA)、密度、年輪構造および収縮率の樹幹内変動を調べた。樹幹内側の木理は S らせんで、繊維傾斜角の 4 方位平均値は、5 – 9 年輪目で最大値 4° – 6° になった後に、樹皮に向かって緩やかに減少した。晩材の仮道管長は、0.86 – 4.95 mm で、髄から外側にむかって増加した。晩材の MFA は、2.2° – 42.0° で、髄付近で大きく、10 年輪目まで急減した後、徐々に減少し、ほぼ一定になった。平均密度は、髄から 10 年輪目まで急減した後、年輪間変動を伴ってほぼ一定であり、晩材率および早材密度との間に高い相関を示した。樹幹内側では樹幹外側に比べて、軸方向収縮率が大きく、横断面収縮率が小さかった。樹幹内外における収縮率の違いは、MFA の影響を受けていると考えられた。樹幹内側では、繊維傾斜角と MFA およびそれらの材内変動が大きいために狂いが大きいが、樹幹外側では、繊維傾斜角と MFA およびそれらの材内変動が小さいために、狂いが小さいと考えられた。これらの木材特性の樹幹内変動傾向および特性値は、他のトウヒ属とほぼ同じであったことから、ヤツガタケトウヒの木材を、他のトウヒ属と同様に利用することができると考えられた。

キーワード：ヤツガタケトウヒ、らせん木理、仮道管長、ミクロフィブリル傾角、木材密度、年輪構造、収縮率

1) 森林総合研究所木材特性研究領域
2) 森林総合研究所森林バイオ研究センター
3) 飯田市美術博物館
＊森林総合研究所木材特性研究領域　〒 305-8687　茨城県つくば市松の里 1 e-mail: zaikana@ffpri.affrc.go.jp