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Piao, Jinji
Laboratory of Wood Material Technology, Division of Biomaterial Science, Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University

Fujimoto, Noboru
Laboratory of Wood Material Technology, Division of Biomaterial Science, Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University

Yamamoto, Yasushi
Yamamoto Vinita Co., Ltd

Nagata, Soji
Yamamoto Vinita Co., Ltd

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Hybrid Kiln Drying System with Radio Frequency Heating for Hinoki Boxed–Heart Timber with Round Edges

Jinji PIAO[1], Noboru FUJIMOTO*, Yasushi YAMAMOTO[2] and Soji NAGATA[2]

Laboratory of Wood Material Technology, Division of Biomaterial Science, Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan
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To avoid the formation of checks during the drying of hinoki (*Chamaecyparis obtusa* Endl.) boxed–heart timber with round edges, a comparative investigation on the kiln drying and the hybrid drying, the high temperature and low humidity (HT/LH) treatment stage combined with radio frequency (RF) heating, was carried out in this study. The results showed that the hybrid drying could effectively prevent the occurrence of both surface checks and internal checks in the hinoki boxed–heart timber with round edges. Moreover, the hybrid drying time was significantly shortened to 15 hours. The combination of RF heating at the stage of HT/LH treatment resulted in at least following beneficial consequences: reduction of the surface temperature decreasing, attenuation of the tensile stress, promotion of the internal drying, relaxation of the moisture gradient, and inhibition on the extreme drying stress. Therefore, a wood drying strategy with high speed, free of both surface and internal checks could be realized through hybrid drying.

INTRODUCTION

During the drying of the boxed–heart timbers, surface checks often form due to obvious anisotropic shrinkage (Kanagawa, 1985). Consequently, it is necessary to develop a drying method that can effectively restrain the formation of surface checks. One currently used drying method can prevent almost all surface checking of some species of wood through treatment at the high temperature and low humidity (HT/LH) to form a large drying–set on the wood surface (Fujimoto *et al.*, 1994; Yoshida *et al.*, 2000). However, it is difficult for this treatment to prevent surface checking in the hinoki (*Chamaecyparis obtusa* Endl.) boxed–heart timber with round edges.

In our previous studies, both radio frequency heating (RF) and microwave heating have been used to dry the heavy timbers of sugi, with the advantages of reduced processing times, consistent quality, and simplified process control. Because radio frequency heating or microwave heating occurs simultaneously throughout the thickness of the timber, the inner layer moisture content (MC) of the sugi round timber or sugi boxed–heart timber was dropped far more significant by these two methods than by the kiln drying (Piao *et al.*, 2006; 2007; 2007).

To prevent surface checking, the effects of RF heating combined with the HT/LH treatment stage during kiln drying were evaluated in this study, in order to explore a new drying strategy for the drying of hinoki boxed–heart timber with round edges.

[1] Laboratory of Wood Material Technology, Division of Biomaterial Science, Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University, Fukuoka 812–8581, Japan
[2] Yamamoto Vinita Co., Ltd, Yao–shi, Osaka, 581–0075, Japan
* Corresponding author (E–mail: fujipon@agr.kyushu–u.ac.jp)

MATERIALS AND METHODS

Materials

Hinoki boxed–heart timbers with round edges were selected for drying tests in this experiment. The dimensions of each timber was 120 mm in thickness × 120 mm in width × 500 mm in length. Before testing, 20–mm thick cross sections at the points of 100 mm from the end of the timbers were sampled, and the initial MCs in the cross section were measured by oven–dry method. The remainder of the specimen at the length of 400 mm was used for the drying test after coating one end with silicone.

Drying system

Figure 1 shows the hybrid kiln drying system with

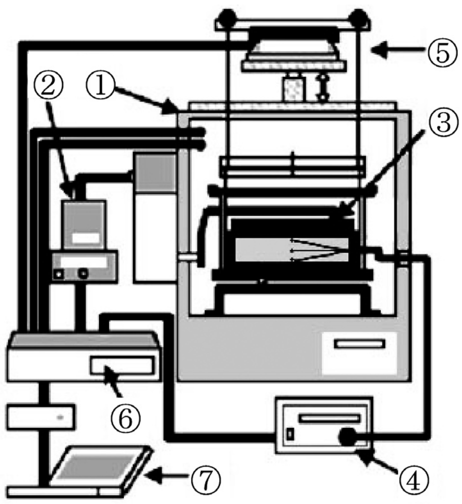

Fig. 1. Hybrid kiln drying system with RF heating.
① Constant temperature & humidity chambers ② RF generator ③ Electrode plates ④ Optical fiber thermometer ⑤ Load cell ⑥ Controller ⑦ Notebook computer

RF heating. The RF generator (YAMAMOTO Vinita) was installed in a constant temperature and humidity machine for this study. The radio frequency used was 13.56 MHz. The load woods were placed between the charged (+) and grounded (−) electrode plates. After separating the woods and electrode plates with wood strips of 10 mm thickness, the wood and electrode plates were fastened by rope. A load cell was installed on the top of the machine to lift the fastened set of woods for weighing during drying. Three optical fiber thermometers preset in holes drilled in the wood were used to measure the temperature of the top surface, center and bottom surface. The center temperature of the wood was maintained around 105–110 °C by the operating system. During drying, the weights and temperatures of the wood were recorded every minute and logged into a computer.

Drying methods

Table 1 shows the drying methods, kiln drying and hybrid drying, as well as the drying time under each drying stage. In this study, the HT/LH treatment stage com-

Table 1. Drying condition and total drying time

		Steaming DBT–95 °C, WBT–95°C (h)	HT/LH (DBT–120 °C, WBT–90 °C) / RF heating (h)	DBT–90 °C, WBT–60 °C (h)	Total drying time (h)
Hybrid drying	H1	12	12 / 4.8	–	24
	H2	6	12 / 4.7	–	18
Kiln drying	H3	12	12 / 0	21	45
	H4	6	12 / 0	23	41

Note: HT/LH – high temperature and low humidity

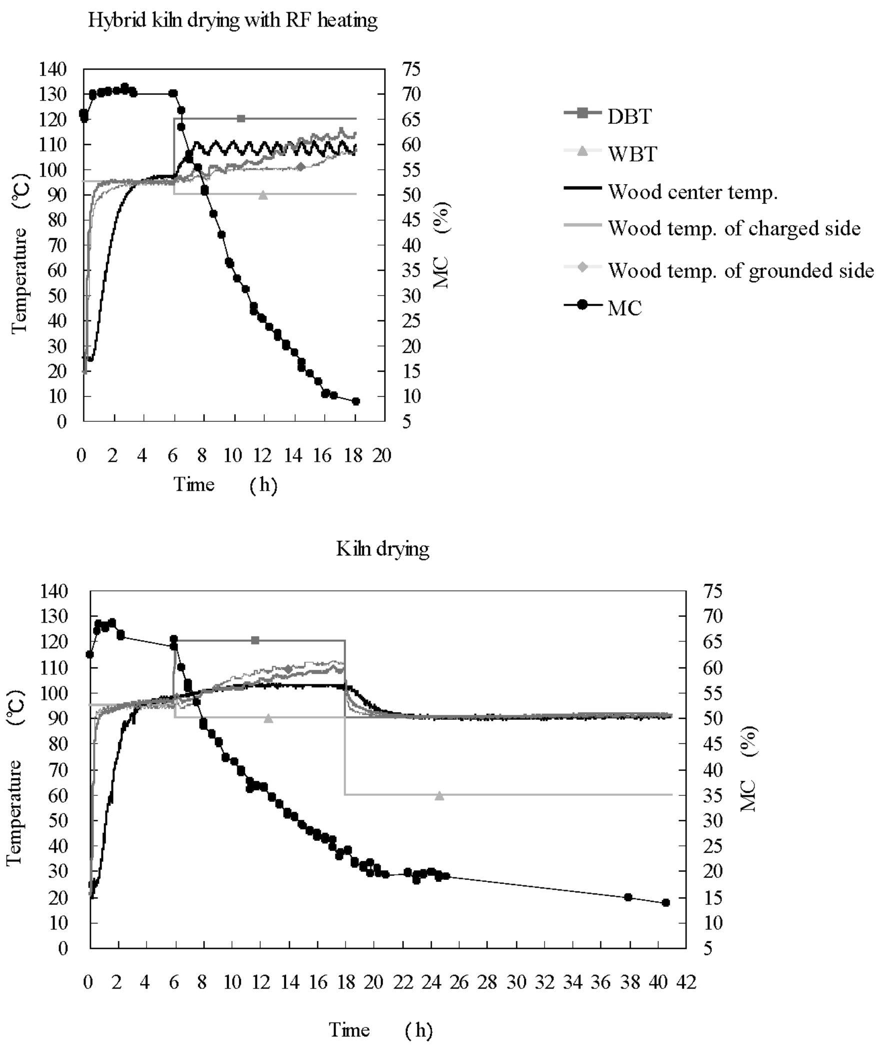

Fig. 2. Drying curve.

bined with or without RF heating was comparatively carried out for drying hinoki boxed–heart timber with round edges. The timbers were first treated with 95 °C steaming for 6 or 12 hours, followed by HT/LH treatment (DBT 120 °C, and WBT 90 °C) for 12 hours. In this stage of the hybrid drying, RF heating was combined with the HT/LH treatment. An additional step under DBT 90 °C and WBT 60 °C continued until reaching a final MC below 15%. For the timbers treated with combined drying, this additional step is unnecessary because the final MC has already decreased to below 15% by the combined RF heating.

Measurements

The MC distributions of the cross section were measured before and after drying. To determine the temperature of wood during drying process, the timbers were drilled three holes of 60 mm in depth at different positions on the timbers: 5 mm deep to the top surface and bottom surface, respectively, as well as the center. Each hole was set with one optical fiber thermometer and then sealed with silicon. The wood weights during drying were obtained every 30 min by the load cell that was preset on the top of the machine with constant temperature and humidity. After drying, other factors such as surface checks, internal checks, and released strains in the direction of the width, were measured according to previously described methods.

RESULTS AND DISCUSSION

Temperature of timbers and drying curves

During the kiln drying and the hybrid drying, the wood temperatures were measured continuously and the drying curves were drawn. One representative result is shown in Fig. 2. It can be seen that the total hybrid drying time was shortened significantly due to the combination with RF heating, compared to the kiln drying. The total drying time is only 15 hours, including 6 hours for steaming treatment, in the case of hybrid drying from green to a final MC below 15%. After steaming treatment for 4–5 hours, the temperature in the wood center increased to 95 °C. During the stage of HT/LH treatment, hybrid drying quickly increased the center temperature up to 100 °C within 16–20 min. In the subsequent stage, the center temperature remained at a high temperature range of 105–110 °C due to the RF heating. However, it took more than 3–4 hours to elevate the center temperature up to 100 °C at the HT/LH treatment stage of kiln drying, which remained constant until the end of this stage. These results indicated that during the kiln drying, only the wood surface could be dried quickly, while during the hybrid drying, the wood center remains a relatively higher temperature and the internal moisture can quickly move out to the surface. As a result, the moisture gradient between the center and the surface of wood became very gentle during the hybrid drying.

Moisture content distribution

After drying the timbers, the MC distributions across the cross section were monitored and the representative results are shown in Fig. 3. The average MC of the timbers dried by the kiln drying and the hybrid drying reduced from 62.3% and 66.1% to 13.8% and 8.9%, respectively. After the hybrid drying, there seemed to be a slight moisture gradient between the top surface (charged) and the bottom surface (grounded), while there was no obvious moisture gradient between the center and surface of wood, as compared to the kiln drying.

Surface checks, internal checks and the surface released strains

The surface checks and the internal checks were examined after drying the timbers. As shown in the Fig. 4, kiln drying caused clear surface checks. However, hybrid drying resulted in neither observable surface checks nor internal checks.

In addition, the surface released strains after kiln drying and hybrid drying were detected to be 4200 $\mu\varepsilon$ and 2800 $\mu\varepsilon$, respectively, suggesting that the compression stress in kiln drying is higher than that in hybrid drying.

These results are interesting and applicable, and can be reasonably explained by the above experimental results of the temperature distribution and the MC distribution. Under the HT/LH treatment, the wood surface

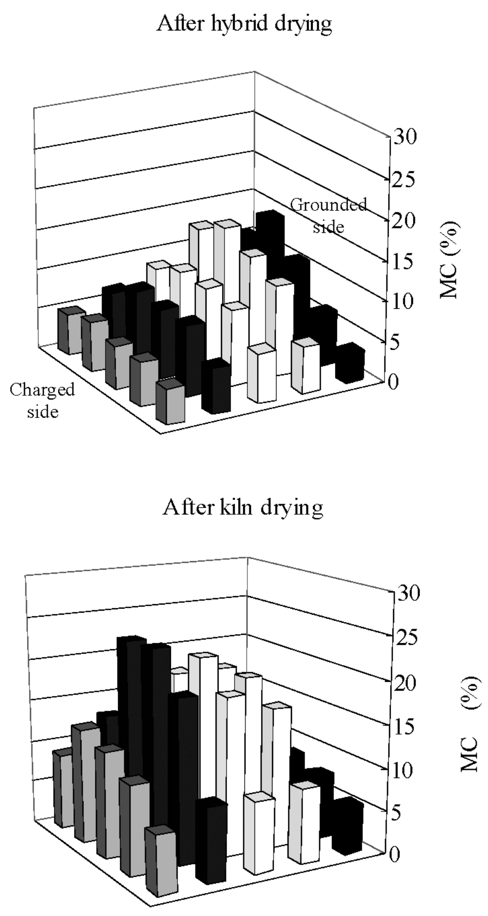

Fig. 3. MC distribution after each drying method.

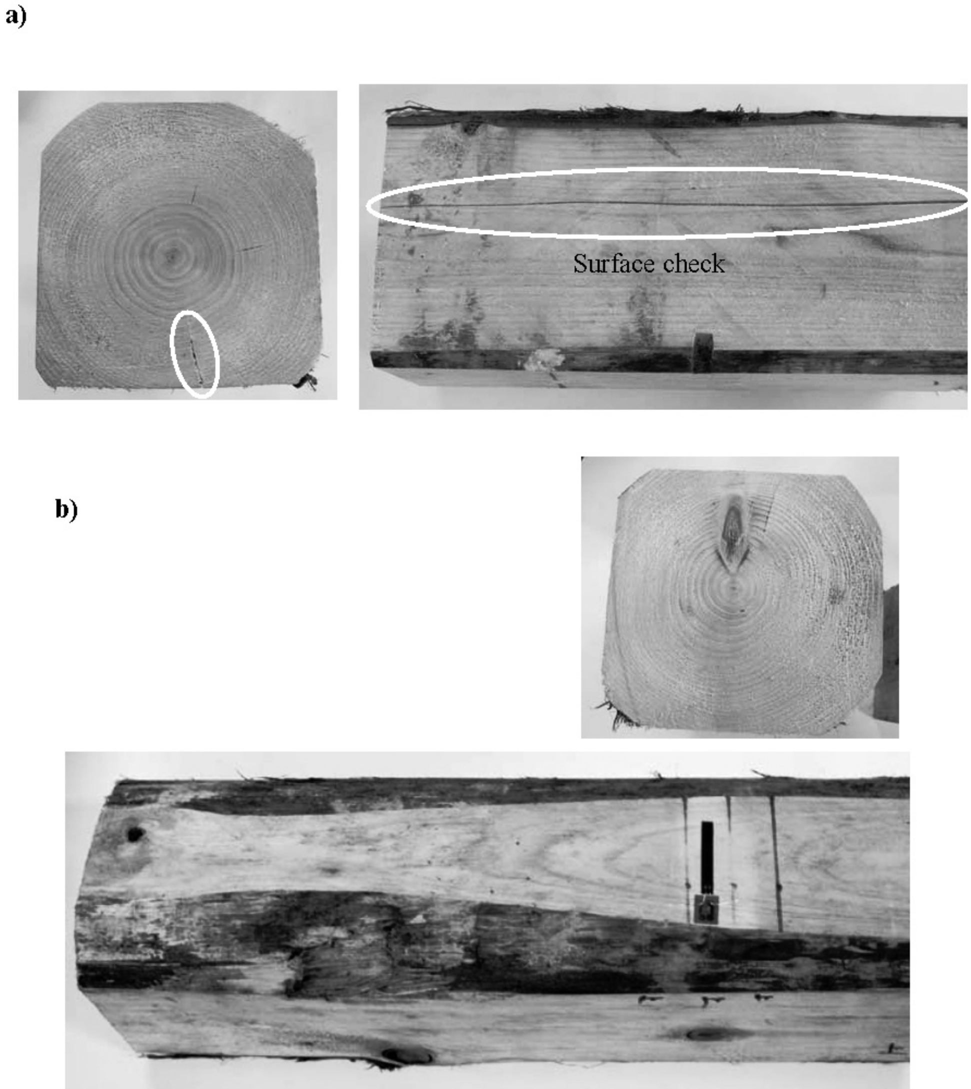

Fig. 4. Typical surface and cross section of timbers after each drying methods.
a) Surface checks on a timber after kiln drying
b) No surface and internal checks after hybrid drying

dried quickly and shrank clearly, leading to formation of tensile stress. Hybrid drying could accelerate the increasing of the surface temperature and subsequently attenuated the tensile stress. Furthermore, hybrid drying could also maintain a high center temperature in the wood and promote the movement of internal moisture towards surface, thereby prevented the formation of extreme MC gradient and drying set.

CONCLUSIONS

The effects of RF heating combined with the HT/LH treatment stage during kiln drying were evaluated and a new drying strategy was established for the drying of hinoki boxed–heart timber with round edges. The conclusions of the study are as below:

1. Hybrid kiln drying system, HT/LH treatment stage combined with RF heating, could effectively prevent the occurrence of both surface checks and internal checks in the hinoki boxed–heart timber with round edges.

2. The hybrid drying time was significantly shortened to 15 hours.

3. The hybrid drying resulted in reduction of the surface temperature decreasing, attenuation of the tension stress, promotion of the internal drying, relaxation of the moisture gradient, and inhibition on the extreme drying stress.

4. The hybrid Kiln drying system with RF heating can be explored as a new drying strategy for the drying of hinoki boxed–heart timber with round edges.

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