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Measuring Strain Variation of Pretreated Wood during Drying Using an Optical Measurement System

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Surfacing, steaming and freezing are widely used pretreatment methods to improve the drying rate and to reduce drying defects of wood. In this study, Douglas fir (*Pseudotsuga menziesii*) wood samples were treated with steaming or freezing, and the resulting drying behaviors such as drying rate, drying strain and drying defects were investigated and compared with those of control wood using an optical measurement system and a digital image correlation (DIC) method.

In the case of steaming pretreatment, the observed drying rate was faster and drying strain was milder than control wood. However, there were almost no differences between control and pre–frozen wood regarding the drying behaviors.

Tangential strain (ϵ_t) of steam–treated wood was larger than that of control and freeze–treated wood. Moreover, the effect of pretreatment was not uniform over the entire wood specimen. The drying check position could be approximately predicted by the analyzing of the strain ratio (μ) and strain velocity (v) graphs during the final drying period.

Key words: optical measurement system, presteaming, prefreezing, strain ratio, strain velocity, DIC, *Pseudotsuga menziesii*

INTRODUCTION

Several pretreatment methods such as surfacing, steaming and freezing are widely used to improve the drying rate of wood and to reduce drying defects generated during wood drying. It has been reported that the surfacing pretreatment could contribute to the elimination of small checks on the wood surface, which could expand to internal checks (Wengert and Baltes, 1971; McMillen and Baltes, 1972). Many researchers have reported that steaming pretreatment can improve the moisture transfer rate by eliminating water soluble extractives, which behave as obstacles in the liquid flow pathways such as pit, tracheid and vessel (Ellwood and Erickson, 1962; Mackay, 1971; Holmes and Kozlik, 1989; Kang, 1991, 1992; Matsumura *et al.*, 1999; Haslett and Dakin, 2001). It was clarified that the moisture transfer rate was improved by freezing pretreatment because the freezing caused microscopic checks on the wood surface resulting in enlarged flow pathways (Glossop, 1994; Ilic, 1995, 1999; Soma *et al.*, 2000). Simpson (1975, 1976) estimated the steaming pretreatment effect on the drying behavior of red oak, which is a refractory species,

and reported that the drying rate of pretreated red oak wood was over 50% faster than control wood. On the other hand, Harris *et al.* (1989) reported that the drying rate of wood pretreated with steam was only slightly faster than the control wood and became nearly identical after approximately one–third of the entire drying period.

With the development of an optical measurement technique using digital image correlation (DIC), the strain distribution of the wood surface during wood drying could be visualized (Kang *et al.*, 2011a, 2011b, 2013). In this study, drying strain distributions of pretreated specimens were estimated, and the drying strain ratio (μ) and strain velocity (v) of the entire wood specimen and localized positions were estimated.

MATERIALS AND METHODS

Sample specimens

North American Douglas fir (*Pseudotsuga menziesii*), which is widely used as a construction material in Korea, is chosen for the species of wood sample board. The dimensions of the flat sawn board were 30 (R) × 120 (T) × 500 (L) mm, and the board was cut at a wood mill in Incheon, Korea at a green condition. The board was transferred to an experimental site, which prevented moisture variation. Subsequently, the board was cut into three pieces in the longitudinal direction, and these three small specimens were used as the control, steaming pretreatment freezing pretreatment samples.

Pretreatments

The specimen used for steaming pretreatment was

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in placed in an autoclave at a temperature of 100°C for two hours. For freezing pretreatment, the specimen was placed in a refrigerator at a temperature of -20°C for three days, and then defrosted at room temperature over a one-day period. After the pretreatments, those specimens were immersed in a water tank with the control sample specimen for 24 hours to release stress caused by the pretreatments.

End coating

Generally, in a DIC system, good images are obtained when the contrast between pixels is high, because the DIC system tracks a pixel subset composed of tens to hundreds of pixels on the measuring surface. To obtain a clean image, usually black and white spots are sprayed on the sample surface. In this study, we developed a new spreading emulsion comprising 100–200 mesh charcoal powder and white diatomite powder mixed and dissolved in a PVAc adhesive resin. By spraying this emulsion, we can produce a subset on the observing surface of the sample specimen and can prevent moisture evaporation from the observed sample surface. The cross surfaces were sprayed with the emulsion and tangential surfaces were coated with PVAc resin to prevent moisture evaporation. As a result, the moisture transportation of the sample board was induced in only one direction from the top surface to the bottom surface of the board.

Kiln drying

All specimens were stacked in a 50°C oven and the weight of the specimens was estimated periodically with a digital balance with 0.1-g accuracy. However, there was no humidity controller in the oven. The moisture content and drying rate were calculated from the water content weight and oven-dry weight. Here, the oven dry-weights of the specimens were obtained after the specimens reached a constant weight at the temperature of 103±2.

Stress distribution monitored with an optical measurement system

The DIC system used in this study was an ARAMIS Model 3D5M (GOM mbH, 38160 Braunschweig, Germany). This system mainly consisted of 2 CCD cameras (2,448×2,050 pixels), a camera controller and a computer image processing unit. The strain ratio distribution of the wood can be continuously visualized as a contour map and numerical data during wood drying by the use of a DIC system.

As shown in Figure 1, three different strain ratio distributions of the cross sectional surfaces were analyzed and compared to the control specimen. Here, sections A, R and T represent the entire area of the sample specimen, its center and its left side, respectively. Therefore, section R denotes a quarter section and section T describes a diagonal surface of the sample specimen. The drying speed of section T was slower than that of section R because the sample specimen was a flat, sawn board. The ray tissue contributes to effective moisture transport in the radial direction. Therefore, more drying

defects usually originated on section T than section R during the final drying period. For the comparison of drying defect origination during the final drying period, we selected these two positions for optical observation.

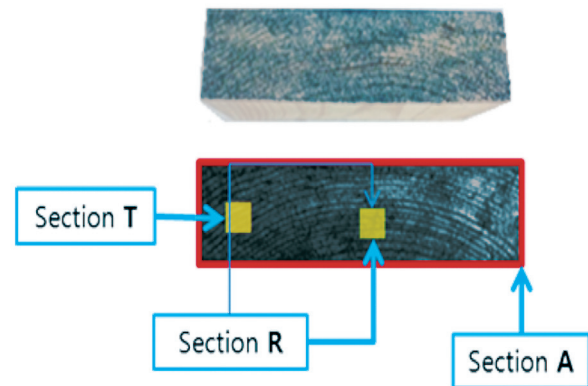


Fig. 1. Cross-section photos of an end-coated specimen with speckles (upper) and sections for DIC analysis (lower).

Calculation of strain ratio and strain velocity

The DIC program obtains the strain ratio distribution via the quantitative analysis of local displacement vectors and local surface strain tensors. The major displacement elements, e_y and e_x , approximately agreed with each radial direction and tangential direction displacement, respectively. In the case of local position, the major displacement elements were described as e_1 and e_2 . Here, during the drying, e_1 describes less shrink in the radial direction and e_2 denotes more shrink in the tangential strain ratio.

The strain ratio between radial and tangential directions, μ , was obtained using equation [1].

$$\mu = e_1 / e_2 \dots\dots\dots [1]$$

Drying defect development could be influenced by the displacement velocity and strain velocity. Strain velocity, v , was obtained from strain ratio change (de) per time change (dt), as shown in equation [2].

$$v = de / dt \dots\dots\dots [2]$$

RESULTS AND DISCUSSION

Drying curves

Moisture content changes with the drying time of control, pre-frozen and pre-steamed sample specimens are shown in Figure 2. The initial moisture contents of the control, pre-steamed and pre-frozen samples were 35.6%, 79.0% and 33.0%, respectively. The initial moisture content of the pre-frozen treated wood did not change during the treatment, but that of the pre-steamed sample was remarkably increased. Although the initial moisture contents of the three specimens were different in the initial drying stage, the moisture content of all specimens decreased linearly with drying time. Finally, all specimens reached nearly the same moisture content during the final drying stage.

The drying rate of the pre-steamed sample at the initial drying stage was 5% MC/hr, which was the fastest

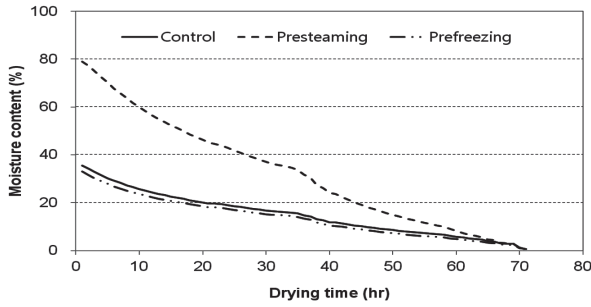


Fig. 2. Drying curves of pre-steamed, pre-frozen and control specimens.

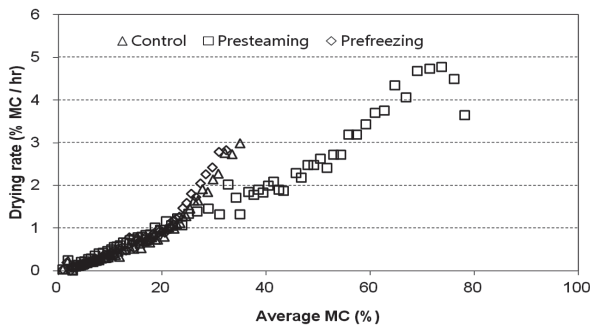


Fig. 3. Plots of drying rates vs. average MC for pre-steamed, pre-frozen and control specimens.

drying rate among three specimens, as shown in Figure 3. However, this trend changed when the drying rate of the pre-steamed sample was lower than those of control and pre-frozen samples at the moisture content of approximately 35%. The drying rates of the three specimens were nearly identical at the moisture range of 25% to 0%.

Strain ratio distributions

From the continuously estimated strain ratio distribution graph, in order to compare values at the same moisture content, we compared the strain ratio distribution graph with moisture content change, as shown in Figure 4. Here, we compared e_2 values among the treatments because estimation in the tangential direction is easier than the radial direction since the tangential direction displacement ratio of e_2 was larger than the radial

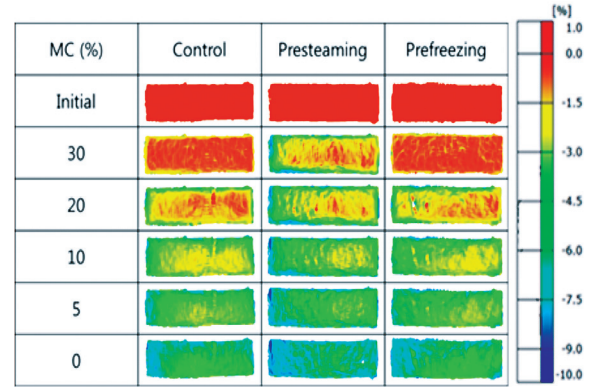


Fig. 4. Distribution contours of the minor principle strains for pre-steamed, pre-frozen and control specimens.

direction displacement ratio e_1 . The strain ratio distribution graphs of the control and pre-frozen samples changed similarly with moisture content, but those of the pre-steamed sample began to shrink at higher moisture contents than the other sample specimens because of its higher initial moisture content. This result was previously reported using an optical measurement system: the wood surfaces start to shrink despite the moisture content of a specimen was above the fiber saturation point (Kang *et al.*, 2011a, 2011b).

Strains (e_1 and e_2)

Average strain ratios of sections A, R and T described in Figure 1 are shown in Figures 5 and 6 as a function of average moisture content. During the initial drying period, the strain showed a positive value over the fiber saturation point, which means that the wood swells even though it is drying. Swelling was observed in the major strain graphs in Figure 5. However, in the minor strain graphs of Figure 6, swelling was only slightly observed in the tangential direction. This indicates that wood shrank in the tangential direction while it swelled in the radial direction during the initial drying period, which is known as a Poisson effect. These observations could not be made without optical measurement using the DIC system.

The radial direction strain ratios of three sections for the pretreatment methods show no significant differ-

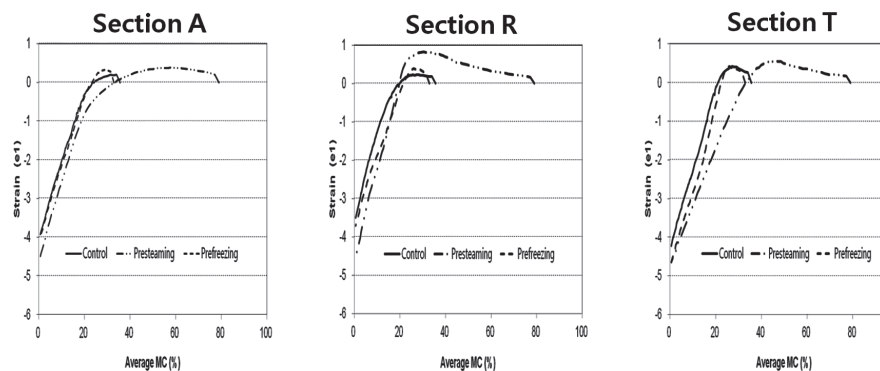


Fig. 5. Plots of major principle strain vs. average MC for the three sections of pre-steamed, pre-frozen and control specimens.

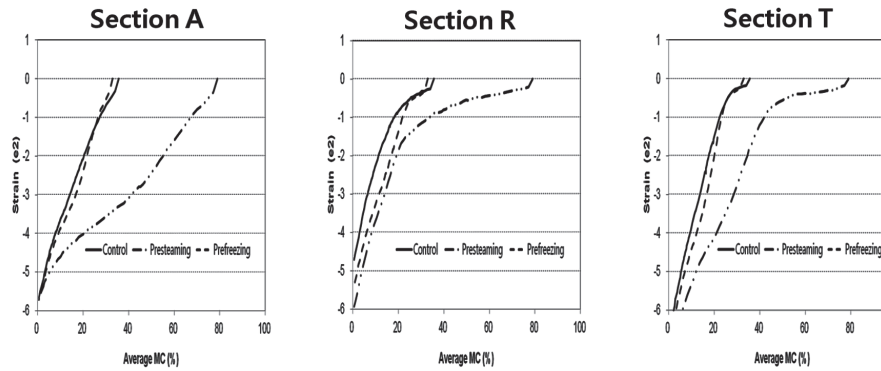


Fig. 6. Plots of minor principle strain vs. average MC for the three sections (A, R and T) of pre-steamed, pre-frozen and control specimens.

ences, as shown in Figure 5. On the contrary, in the tangential direction, the strain ratio during drying showed significant differences among the pretreatment methods. The tangential strain ratio of the pre-steamed specimen was greater than that of the control and pre-frozen samples at the same moisture condition. It was explained that pre-steaming removes the extractives in the cell wall, such that pre-steaming causes greater shrinkage (Kang, 1992, 1993). In the comparison between section R and section T, the effect of pre-steaming on section T was greater than on section R. At the initial and middle stages of drying, the effect of pre-steaming on strain ratio was significant. However, in the final stage of drying, there is no significant difference on strain ratio among all pretreatments.

Strain ratio (μ)

Strain ratios of the localized sections R and T, which were obtained from equation 1, are shown in Figure 7 as functions of average moisture content. Here, the moisture content range was 0% to 30%. Strain variations of localized region of control and pre-frozen samples were similar, but those of the pre-steamed sample show significant differences. The strain ratio of section R is greater than section T in the moisture content range from 30% to 12%, but this relationship was reversed for moisture contents less than 12%. The strain ratio increased in the

cases of decreasing tangential strain ratio and increasing radial strain ratio. A small strain ratio in the tangential direction means that the sample specimen generates tensile stress. Therefore, there is a possibility of tensile rupture, which should be considered in cases of larger strain ratios. As a result, there is a high possibility of check formation in section R in the moisture content range of 30% to 12% and in section T in the moisture content range below 12%. Booker (1994) demonstrated internal check origination on the edge of the radiata pine board at the final stage of wood drying. This edge region of the board agrees with section T in this study, which is the slowest drying region on the entire wood specimen.

Strain velocity (v)

It is surmised that drying checks would not occur in the case of accumulated strain, but it would occur in the case of abrupt strain increase. To predict the possibility of drying checks, strain velocity graphs are shown in Figures 8 and 9. The maximum value of strain velocity in the radial direction was under 0.3/hr and there is no significant difference among pretreatments in all three regions. However, in the case of the tangential direction, the maximum value of strain velocity in sections A and T reached 0.4/hr with remarkable differences in strain velocity among pretreatments. These results confirm that the tensile stress in the tangential direction causes the

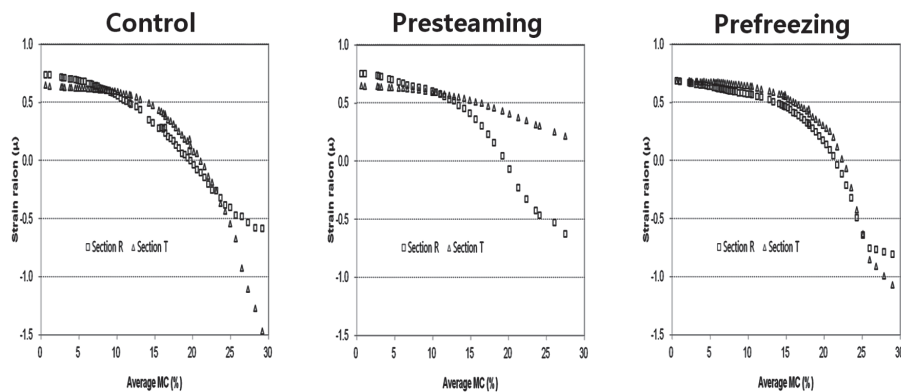


Fig. 7. Plots of strain ratio vs. average MC for two sections (R and T) of pre-steamed, pre-frozen and control specimens.

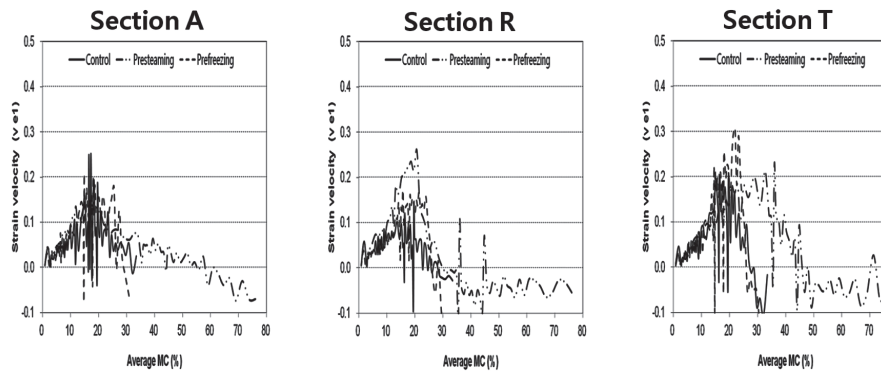


Fig. 8. Plots of major principle strain velocity vs. average MC for the three sections (A, R and T) of pre-steamed, pre-frozen and control specimens.

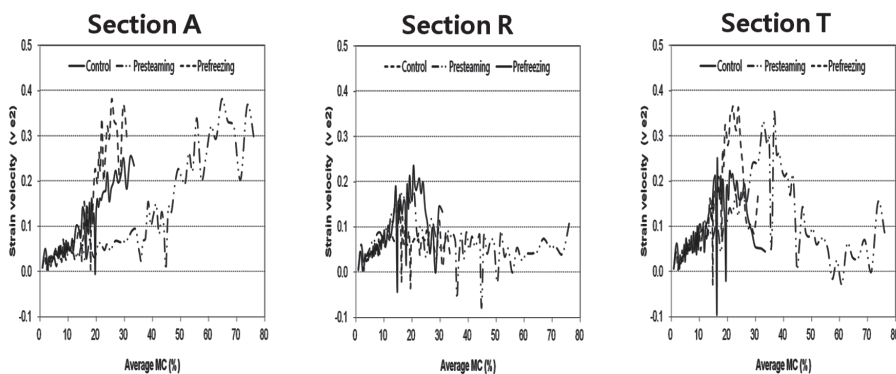


Fig. 9. Plots of minor principle velocity vs. average MC for the three sections (A, R and T) of pre-steamed, pre-frozen and control specimens.

drying checks more than that in the radial direction, and that the possibility of check formation in section T is higher than in section R.

CONCLUSIONS

We estimated the drying behaviors of control, pre-steamed and pre-frozen wood by optical measurement techniques with a DIC (digital image correlation) system.

The spraying emulsion, which was composed of charcoal powder and white diatomite powder mixed and dissolved in PVAc adhesive resin, was appropriate for obtaining a DIC image. The optical measurement system was effective for generating a strain ratio distribution graph during wood drying.

Pre-steaming showed significant differences in wood drying rate and strain ratio, but there was almost no difference observed in the case of pre-freezing. These results may be caused by an insufficient pre-freezing treatment time. Tangential strain ratio (ϵ_t) of the pre-steamed sample was greater than that of the control and pre-frozen samples at the same moisture condition. Considering the effect of pre-steaming, greater results were observed in section T than section R.

From the results of the strain ratio (μ) and strain velocity graph, the possibility of check formation in section T is quite large during the final drying stage.

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