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Relaxation mechanism of residual stress inside logs by heat treatment: choosing the heating time and temperature

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Abstract Some methods to reduce residual stress inside logs have been reported, although the conditions for stress relaxation are not yet clarified. Our study using precise experiments revealed that residual stress relaxation occurs only when both heat and moisture exist inside the logs. We then determined the heating time and temperature required to relax the residual stress inside the logs. Short air-drying treatments did not relax residual stress even though free water in the logs was greatly reduced. The residual stress of the 33-h 80°C-heated bolts was relaxed, whereas that of the 48-h 70°C-heated bolts was not. As for the influence of treatment time, bolts heated at 100°C were relaxed after 18h of treatment. The 13-h heated bolts did not show any relaxation. Therefore, residual stress relaxation occurred rapidly owing to the thermomechanical change of the individual wood components comprising the cell wall. The moisture content inside all the bolts was much higher than the fiber saturation point. This is because relaxation occurs only when the heating temperature is maintained above 80°C for a particular duration of treatment.

Key words Residual stress · Growth stress · Stress relaxation · Heat treatment · Wood drying

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Introduction

Growth stress is generated at the outermost layer of the xylem during secondary growth. This stress is superposed in the tree trunk as it increases in diameter, resulting in residual stress distribution inside the log.[1] As a consequence, there is warp when lumber is sawed and end splits that occur at logging, often decreasing the final yield of the wood product.[2] Therefore, an engineering method for reducing the stress is required because the demand for juvenile wood, which comes from plantation forests and has large growth stress, will increase in the near future.

Many methods have been attempted to reduce residual stress in green logs, with stress relaxation occurring at natural temperatures. The methods include prolonged storage in the open air and under water sprays,[3] burying,[4] soaking in water,[5] and girdling (residual stress relaxation was investigated using girdling treatment of teak). Stress relaxation also occurs at high temperatures induced by boiling,[6] steaming,[7] and smoking.[8–11] Kubler pointed out the importance of heat and water interaction on stress relaxation at high temperatures. He also proposed "hygrothermal recovery" (HTR) for reducing residual stress.[12] Numerous reports have offered relaxation mechanisms at ambient temperature, but it is still open for discussion whether such methods can reduce residual stress. Moreover, how they relax stress is still undefined.

We have evaluated the effect of commercial-scale direct heating treatment on residual stress relaxation for various species (zelkova, Japanese larch, fir, Japanese cedar, oak, ash).[8–11] We suggested that residual stress was reduced when Japanese cedar was treated at temperatures above 80°C (inside the logs) for more than 35h.[8,11] The results derived from these studies support the idea of HTR. However, we have not yet determined the best treatment conditions for stress relaxation because of the difficulty controlling the humidity and temperature of commercial-scale furnaces.[13]

In this study, our focus was on the action of heat and water on residual stress relaxation using precise heating conditions. We first carried out an indoor air-drying experiment to investigate whether the relaxation of residual stress was induced by a decrease in free water without any heating. An in vitro experiment using short bolt samples and an oven with an internal fan was carried out to control the temperature and humidity accurately. Based on the results, the mechanism of HTR that causes stress relaxation is then discussed.

Materials and methods

Species

Six green logs (with bark) of Japanese cedar (*Cryptomeria japonica* D. Don), 25 years of age, 2 m long with a diameter of 12 cm, were prepared as shown in Fig. 1. Log A was used for a control (non-treatment); log B was used for "air-drying"; and logs C, D, E, F, and G were used for "heat treatment under the green condition." They were further divided into several bolts each with a length of 28 cm and were used under various testing conditions.

Variations of released strain and moisture content distribution along the height

For Japanese cedar, the longitudinal growth stress and surface stress show constant values along the height of the log below the branches.[14] However, no studies have measured residual stress along the height of the log. As a preliminary experiment, we checked whether the radial distribution patterns of released strains and moisture content (MC) in a 2-m log were identical. After seven bolts 28 cm length were cut from log A, the bolts were ripped into 5 cm thick diametral planks. Strain gauges 8 mm long were pasted in the longitudinal direction on the plank across the diameter of the log at intervals of 8 mm. Released strains were then measured by cross-cutting the plank above and below the gauges followed by a longitudinal cut at both sides. The released strain is regarded as a direct indicator of residual stress. Finally, sample blocks were obtained where the strain gauges were attached to measure the MC using the oven-dried method.

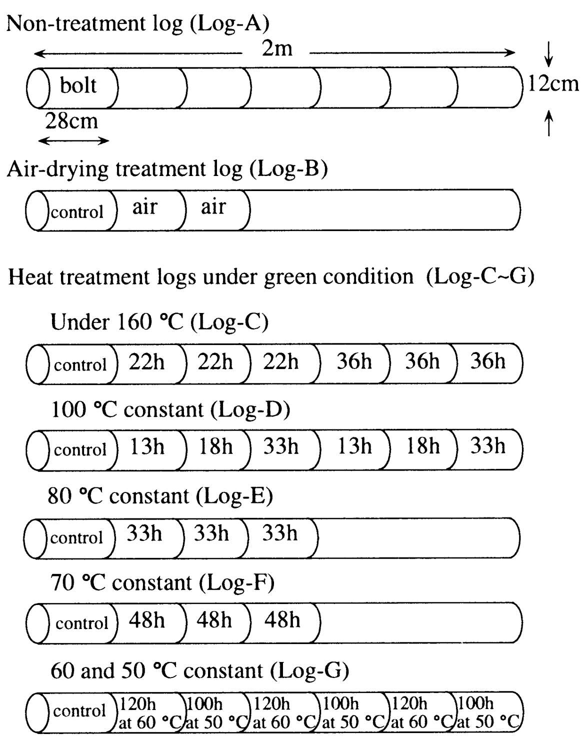

Fig. 1. Seven green logs are prepared for three treatments: non treatment, air-drying, and heat treatment under the green condition

Air-drying treatment

The sample bolts were dried at room temperature and humidity to observe whether the residual stress was changed by the decrease in free water at room temperature. Three bolts were cut from log B (Fig. 1); one bolt was the control, and the other two bolts were used for indoor air-drying at 20°C for 2 weeks. Before air-drying, the bark was peeled off to shorten the drying time. The released strain and MC distribution were then measured.

Heat treatment under the green condition

The faces of all bolts were sealed with silicone rubber to prevent water evaporation during the heat treatment (Fig. 2). In vitro experiments were then performed using an experimental oven with an internal fan (to maintain better control of the temperature under the green condition during treatment). Six treatment conditions were adopted to investigate the interaction of heat and water on residual stress relaxation. We present only one result for each condition, but we tried each condition at least three times.

For log C bolts, heat was applied gradually for 24 h until the temperature of the oven reached 160°C. This

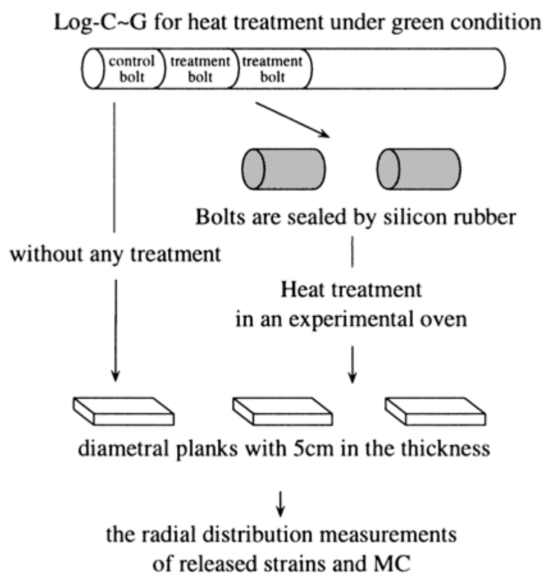

Fig. 2. Procedure for testing a sample by heat treatment under the green condition

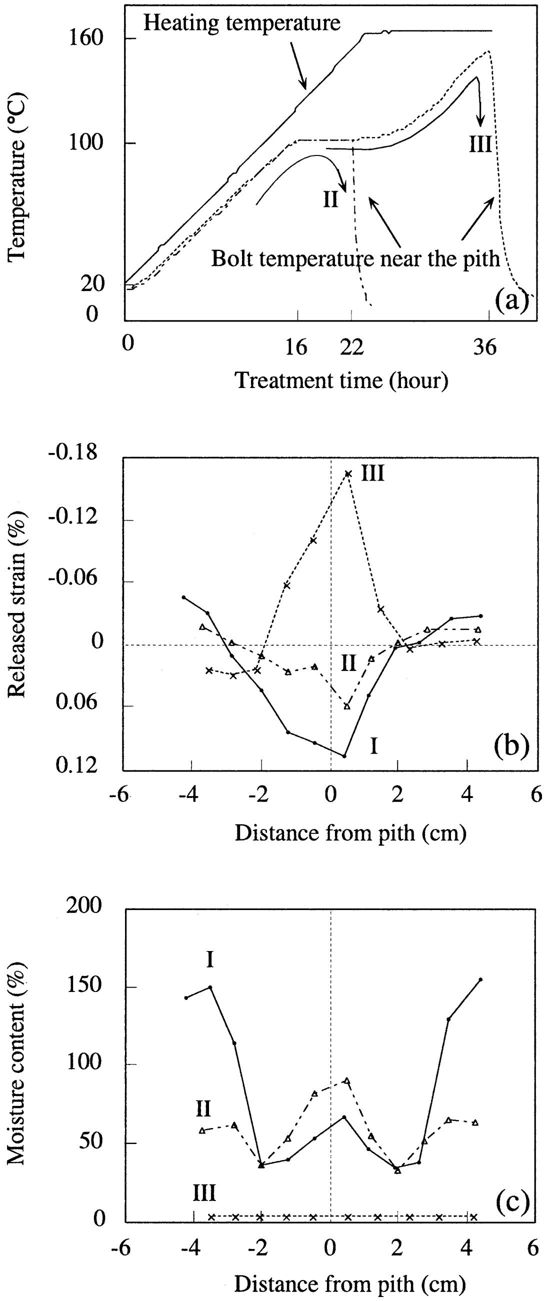

Fig. 3a–c. Heat treatment under the green condition. **a** Heating temperature (*solid line*) and bolt temperatures near the pith (*broken lines*) under 160°C (log C). **b, c** Radial distribution of released strain and the moisture content, respectively, under 160°C (log C). *I*, control bolt without any treatment; *II*, 22-h-treated bolt; *III*, 36-h-treated bolt

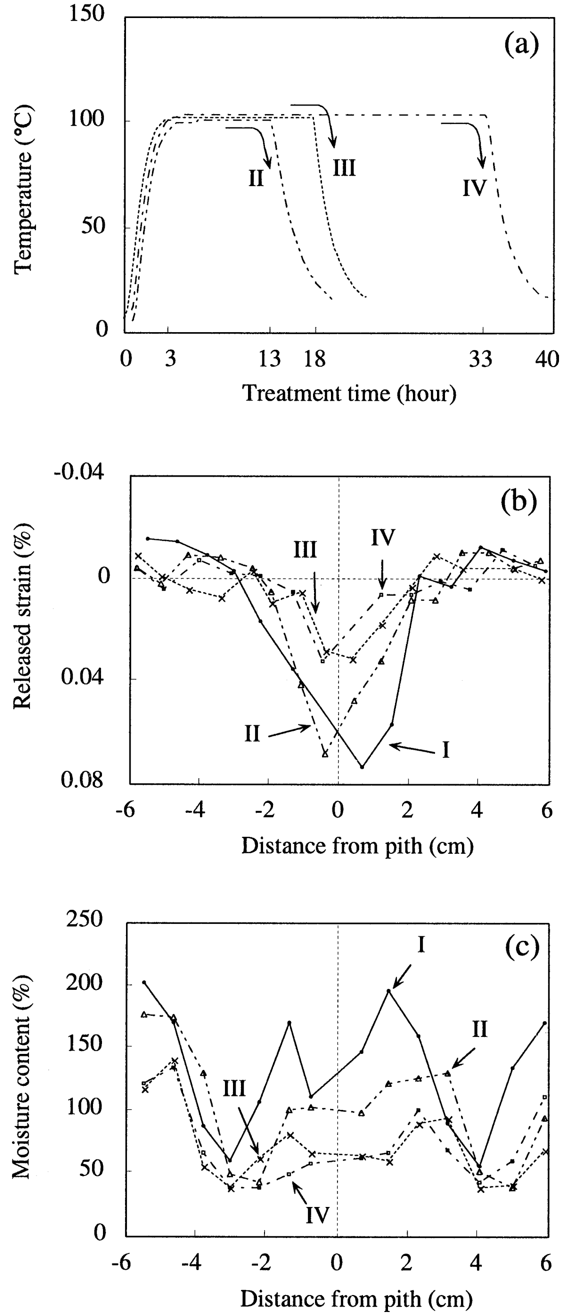

Fig. 4a–c. Heat treatment under the green condition at constant 100°C (log D). **a** Bolt temperature near the pith. **a, b** Radial distribution of released strain and MC, respectively. *I*, control bolt without any treatment; *II*, 13-h-treated bolt; *III*, 18-h-treated bolt; *IV*, 33-h-treated bolt

temperature was maintained for the total treating time of 36 h (Fig. 3a). This heating schedule was established in a previous study,[8] which showed that residual stress was reduced enough under these conditions without drying splits on the surface of Japanese cedar logs. The distribution across the diameter of released strain and MC were measured at 22 and 36 h for each bolt. For log D bolts the temperature was immediately raised to 100°C and was kept there for 33 h (Fig. 4a). The bolts were subjected to measurement of released strain and MC after 13, 18, and 33 h of treatment. For log E bolts the temperature was immediately raised to 80°C and was maintained for 33 h (Fig. 5a). For log F bolts the temperature was increased to 70°C and was kept there for 48 h (Fig. 6a). Finally, for log G bolts the temperature was raised to 60° and 50°C and was kept there for 120 and 100 h, respectively (Fig. 7a).

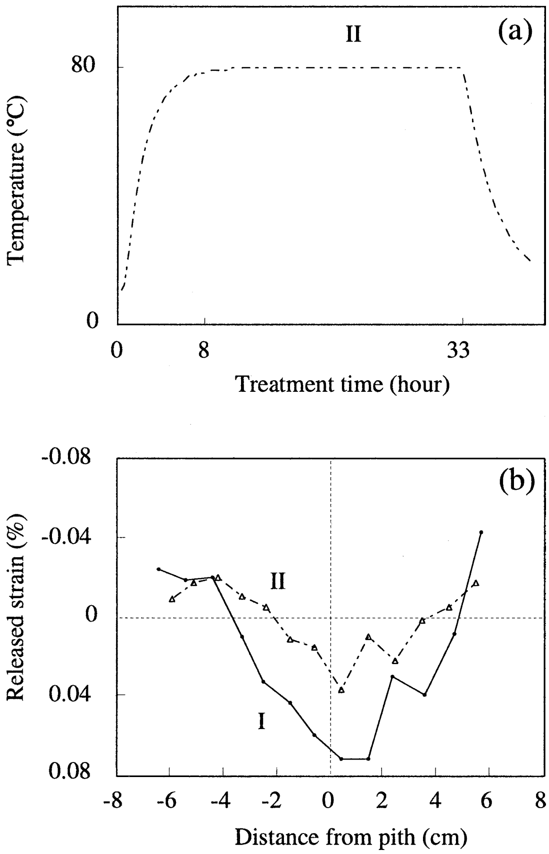

Fig. 5a,b. Heat treatment under the green condition at constant 80°C (log E). Bolt temperature near the pith (**a**) and radial distribution of the released strain (**b**). *I*, control bolt without any treatment; *II*, 33-h treated bolt

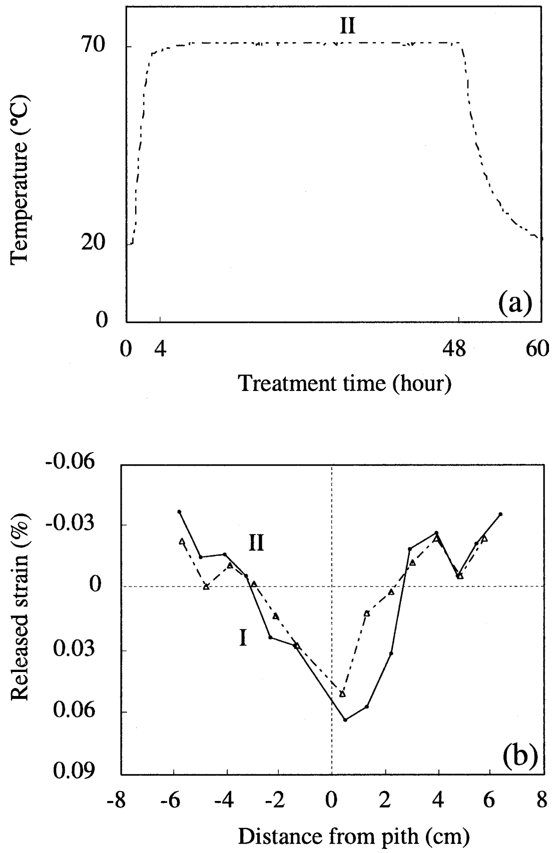

Fig. 6a,b. Heat treatment under the green condition at constant 70°C (log F). Bolt temperature near the pith (**a**) and radial distribution of the released strain (**b**). *I*, control bolt without any treatment; *II*, 48-h treated bolt

Results and discussion

Variations of released strain and MC distribution in the bolts along the height

The radial distribution pattern of released strain and MC are identical along the 2-m logs (Fig. 8). The strain was somewhat less than our previous results.[11] Moreover, the transition point where the stress changes from tensile to compression is closer to the pith than the theoretical point.[1] This is because small amounts of residual stress were released during cross-cutting and were disturbed during lumber preparation. However, the released strain inside the planks prepared from log A in the same manner showed a pattern identical to that seen in Fig. 8a.

Based on this result, we confirmed that the longitudinal released strain pattern is the same among bolts cut from the same log. These distributions of released strain can be considered the control (that not attributed to heat treatment). Also the MCs in the bolts were identical, and they were larger in the sapwood and heartwood regions than in the intermediate wood. This MC pattern is common in planted Japanese cedar.

Air-drying treatment

Figure 9 shows the radial distribution of released strain and MC after air-drying treatment. Curve I represent the control, and curves II and III are the patterns after 2 weeks of air-drying. The residual stress was not reduced, although the MC of the bolts closely approached the fiber saturation point, as shown by curves II and III. Without heating, there was no relaxation of residual stress even after the free water in the logs was greatly reduced. After considering our results and those of previous researchers,[3–5] we concluded that residual stress relaxation at ambient temperatures did not take place because of the decrease in free water but was due to the prolonged treatment time.

Heat treatment under the green condition

Figure 3a shows that there was a stable period inside the green bolts once the temperature reached 100°C (curves II and III) due to evaporation of free water inside the sealed bolts. Hence the pressure inside the bolts was equal to the atmospheric pressure at 100°C, although silicone rubber sealed all the faces of the bolts. The results for the released strain and the MC are shown in Fig. 3b and Fig. 3c,

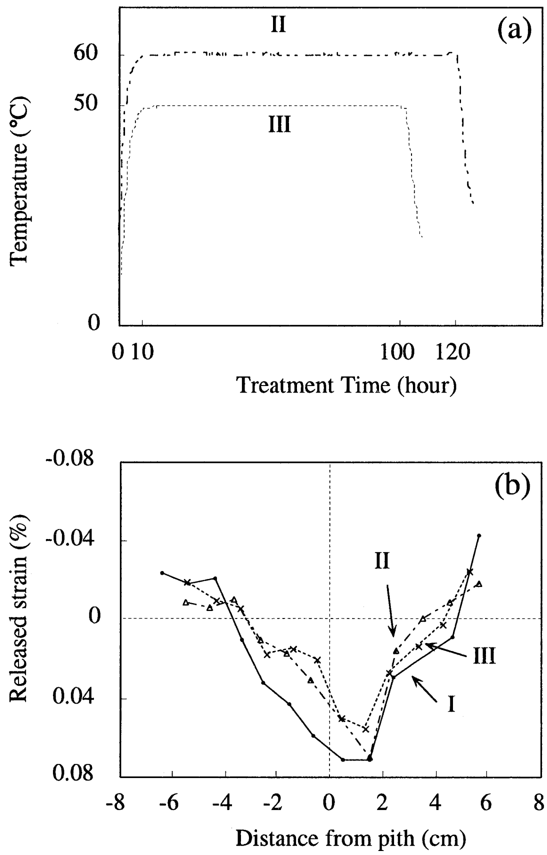

Fig. 7a,b. Heat treatment under the green condition at constant 60° and 50°C (log G). Bolt temperature near the pith (**a**) and radial distribution of the released strain (**b**). *I*, control bolt without any treatment; *II*, 120-h treated bolt at 60°C; *III*, 100-h treated bolt at 50°C

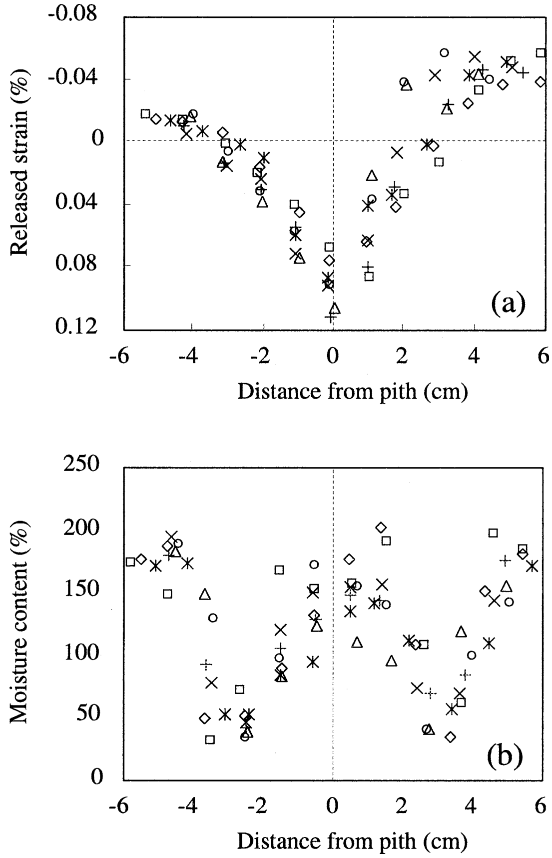

Fig. 8. Radial distribution of released strain (**a**) and moisture content (**b**) along the height in log A. Seven bolts are cut from the same 2 m green log and are measured. *Squares*, 0.14 m from the bottom end; *diamonds*, 0.42 m from the bottom end; *, 0.7 m from the bottom end; +, 0.98 m from the bottom end; ×, 1.26 m from the bottom end; *circles*, 1.54 m from the bottom end; *triangles*, 1.82 m from the bottom end

respectively. The released strain was lower in the 22-h treated bolts (curve II) than in the control (curve I); the MC was also reduced but was still higher than the fiber saturation point after treatment (Fig. 3b,c).

In the 36-h treated bolts (curve III), water had dried up completely owing to the prolonged heat treatment (Fig. 3c). Finally, after 36 h of heat treatment (curve III) the released strain distribution took an inverse shape compared to the control (Fig. 3b). In general, this is attributed to generation of drying stress, which is related to the drying set. We suspect that the difference in longitudinal shrinkage between juvenile and mature wood induces inverse residual stress after drying.

Figure 4b shows that the released strain of both 18-h treated bolts (curve III) and 33-h treated bolts (curve IV) was smaller than that of the control (curve I). Those two (curves III and IV) had the same amount of reduction despite different treatment times. Therefore, we concluded that once the residual stress was relaxed no further relaxation occurs even if the treatment is prolonged. For the 13-h treated bolt (curve II), the stress was not yet reduced. Relaxation began only after 18 h of treatment (curve III). Thus, the rapid relaxation of residual stress was believed to be caused by the thermomechanical change of the individual wood components comprising the cell wall.

Log E was treated at 80°C constantly for 33 h. Figure 5b shows that there was less strain released in the treated bolt (curve II) than in the control (curve I). On the other hand, relaxation did not occur with 70°C treatment (Fig. 6). Figure 4b shows that the residual strain was already relaxed within 15 h after the bolt temperature reached 100°C (curve III). In Fig. 5b it had relaxed within 25 h after the temperature reached 80°C. In Fig. 6b, however, it was not relaxed within 44 h after it reached 70°C. In the case of 60°C (curve II) and 50°C (curve III) treatment, the residual strain did not relax even though the treatment time was extended (Fig. 7). This suggests that residual stress relaxation occurs only at 80°C and higher. The MC distribution at 80°, 70°, 60°, and 50°C treatment was nearly equal to that of the control and was much higher than that of fiber saturation point.

The relaxation mechanism can now be explained by the thermal-softening properties of the wood components. Studies of these properties in isolated wood components suggest that the relaxation is associated with lignin[15,16] or both lignin and hemicellulose.[17] If the stress relaxation is associated only with lignin, it should occur as soon as the wood's temperature reaches the lignin-softening point,

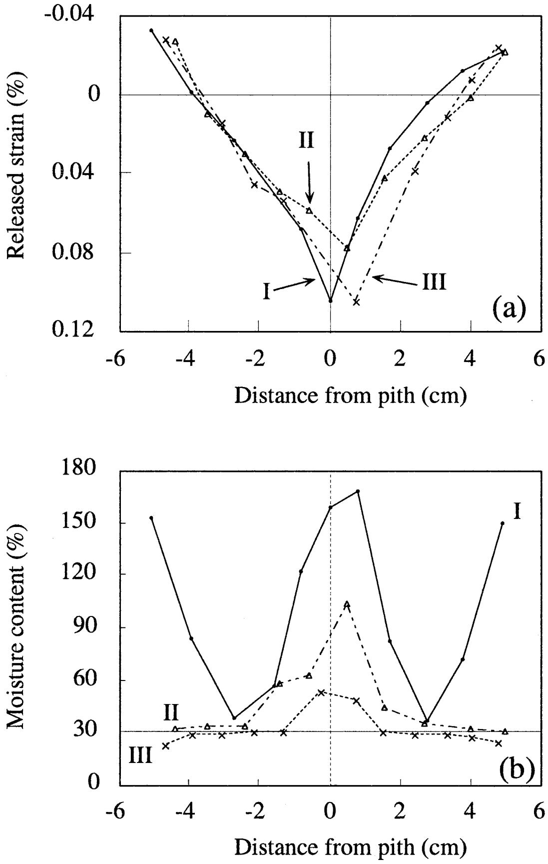

Fig. 9. Radial distribution of released strain (**a**) and moisture content (**b**) during air-drying treatment (log B). *I*, control bolt without any treatment; *II*, *III*, air-drying treatment bolts for 2 weeks

around 80°C; but, residual stress relaxation requires some extra of heating time, as shown in the present study. Ishiguri et al.[18] and Maruyama et al.[19] reported that the pH value of sugi was acidified by heat treatment. Therefore, we concluded that stress relaxation is associated not only with lignin softening but also with degradation of the matrix substance of the cell walls. Tejada et al. discussed similar findings.[17] In contrast, Furuta et al.[20] suggested that stress relaxation was caused by the irreversible change due to the cohesion state of cell wall components.

Our previous studies of direct heat treatment support the idea of HTR. We believe that the generation of HTR during direct heating treatment involves the following mechanism: When green logs with bark are directly exposed to extremely hot gases coming from wood fuels, the logs are completely coated with soot. This coating, in addition to the bark, prevents the water from evaporating inside the logs. As a result, internal HTR of the logs is generated. The in vitro experiment allowed us to control the temperature and moisture accurately in the oven. To simulate the soot coating, the bolts were completely sealed with silicon rubber. Measurements revealed that residual stress relaxes only when both heat and moisture exist in the logs. This proves that the generation of HTR causes residual stress relaxation.

Conclusions

Short air-drying treatments did not relax residual stress even though free water in the logs was greatly reduced. Based on our results and the stress relaxation at ambient temperature, residual stress relaxation without heating did not take place because of the decreased free water but because of the prolonged treatment time.

The bolts heated at 100°C for 18 and 33 h had the same amount of reduction despite different treatment times (Fig. 4). Therefore, we concluded that once the residual stress was relaxed no further relaxation occurred even after prolonging the treatment. Stress was not reduced in bolts heated at 100°C for 13 h. Thus, residual stress relaxation occurred suddenly owing to the thermomechanical change of the individual wood components comprising the cell wall.

Residual stress in the bolts heated at more than 80°C relaxed (Figs. 4, 5), whereas the bolts heated to less than 70°C did not (Figs. 6, 7). This is because relaxation occurs only when the heating temperature is above 80°C and is maintained for about 15 h. The results of our in vitro experiment revealed that residual stress relaxation occurs only when both heat and moisture exist in the logs.

If stress relaxation is associated with lignin alone, it should occur as soon as the wood's temperature reaches the lignin softening point. In our study, this did not occur: Relaxation was seen only when a particular treatment time was applied. Moreover, once stress relaxation was achieved, there was no further relaxation even if the treatment time was extended. Therefore, we concluded that stress relaxation is associated not only with lignin softening but also with degradation of the matrix substance comprising the cell walls.

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