主　論　文　の　要　約

論文題目　　Hygrothermal recovery of wood and its mechanism
（木材の湿熱回復挙動とそのメカニズム）

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During cell wall lignification, trees generate a two-dimensional stress distribution in the thin layer of the newly formed xylem, which is referred to as growth stress. The growth stress comprises an elastic component and a viscoelastic component. The elastic component is instantly released when cutting wood specimens from the xylem; the cut wood specimens often contract or expand. However, even after releasing the elastic component, the viscoelastic component of growth stress, referred to as locked-in growth stress, still remains within the wood cell wall. The locked-in growth stress is released when green wood is heated to a high temperature in the presence of water (hygrothermal treatment), resulting in the irreversible contraction or expansion of the wood. Such an irreversible dimensional change is defined as hygrothermal recovery (HTR). HTR is a possible reason for inducing defects, such as distortions, cracks, and checks, in lumber during kiln drying at high temperatures. Therefore, understanding HTR provides important information for improving the utilization rate of wood and understanding the origin of growth stress in wood cell walls.

The aim of this study is to clarify the mechanism of HTR, the dimension measurement and vibrational properties measurement were the main approaches for the investigations.

In chapter 1, the author firstly reviewed the researches around the growth stress. Definition, measurement method and possible generation mechanisms of growth stress were introduced. Next, the author introduced the growth stress related phenomenon: HTR. The history and recent studies of HTR were introduced. Furthermore, the possible mechanisms of HTR for both softwood and hardwood species were also reviewed. Finally, the author introduced the vibration test for measuring the vibrational properties of wood and its possibility for confirming and clarifying the mechanism of HTR.

In chapter 2, the research subject was the HTR of softwood. The author tried to compare the dimethyl sulfoxide (DMSO) swelling behavior, drying shrinkage behavior with the HTR behavior of wood. The green hinoki compression wood (CW) and normal wood (NW) were hygrothermally treated in water at 100 °C for 120 min and their HTR strains were determined. The specimens were then swollen using DMSO solvent, and then completely dried after the solvent exchange with water at room temperature. Their HTR strains were then compared with their DMSO swelling and drying shrinkage strains. The volumetric HTR strains in the CW were about twice as large as those in the NW. A clear commonality between the HTR behavior and both DMSO swelling and drying shrinkage behavior was identified, which indicates that HTR of softwood is caused by volumetric changes in the matrix substances.

The HTR has been defined as a phenomenon due to the release of locked-in growth stress when a wood specimen is hygrothermally treated. To determine whether DMSO treatment has a similar effect as hygrothermal treatment, both hygrothermally-untreated and hygrothermally-treated specimens were swollen using DMSO, and their dimensional changes during and after DMSO treatment were compared. The results showed that DMSO treatment is a possible alternative for releasing locked-in growth stress.

In chapter 3, the author conducted vibrational properties measurement to discuss the mechanism of HTR for softwood. The changes in vibrational properties of CW and NW of softwood (hinoki and sugi) in longitudinal (L)-direction were measured after hygrothermal treatment at 60, 80, and 100 °C. The relationship between those changes and HTR strains were discussed. The hygrothermal treatment induced an increase in mechanical loss tangent ($\tan\delta$) and a decrease in specific dynamic Young's modulus (E'/ρ). It seems that the changes in vibrational properties due to hygrothermal treatment had a time–temperature dependency: longer treatment durations and higher treatment temperatures induce larger increases in $\tan\delta$ and larger decreases in E'/ρ. In contrast to the quenching effect, $\tan\delta$ and E'/ρ did not recover to their original state even after long-term conditioning of hygrothermally treated wood in water at 20 °C.

For CW with a large microfibril angle (MFA), there was a clear relationship between the changes in vibrational properties and HTR strains. The $\tan\delta$ increased and E'/ρ decreased with hygrothermal treatment, corresponding to dimensional changes in the L-direction. The most likely mechanism of HTR for softwood is that the hygrothermal treatment softens the lignin to release locked-in growth stress. Subsequently, irreversible structural changes in lignin induce both the changes in vibrational properties and HTR. For NW, because of a small MFA, HTR strains due to irreversible structural changes in lignin in the L-direction are possibly restricted by rigid crystalline cellulose. As a result, the relationship between the changes in vibrational properties and HTR is uncertain.

In chapter 4, the research subject changed from HTR of softwood to HTR of hardwood. The changes in vibrational properties of konara tension wood (TW) and NW in L-direction were measured after hygrothermal treatment at 60, 80, and 100 °C. The relationship between those changes and HTR strains were discussed. The hygrothermal treatment induced an increase in tanδ and a decrease in E'/ρ. An extremely large decrease in E'/ρ of TW was found after hygrothermal treatment. The changes in vibrational properties due to hygrothermal treatment exhibited a time-temperature dependency: longer treatment durations and higher treatment temperatures induce larger increases in tanδ and larger decreases in E'/ρ. Almost no quenching effect was found even after the long-term conditioning of hygrothermally treated wood in water at 20 °C.

For TW with extremely small MFA, there was a clear relationship between the changes in vibrational properties and HTR strains. The tanδ increased and E'/ρ decreased with hygrothermal treatment, corresponding to dimensional changes in the L-direction. The most likely mechanism of HTR for TW is that the hygrothermal treatment induces the qualitative changes of cellulose crystalline in gelatinous (G)-layer to release the locked-in growth stress, which results in both changes in vibrational properties and HTR. The mechanism of HTR for normal hardwood is similar to that of softwood. Because of a small MFA, HTR strains due to irreversible structural changes in lignin in the L-direction are possibly restricted by rigid crystalline cellulose. As a result, the relationship between the changes in vibrational properties and HTR is uncertain.

In chapter 5, the author summarized the observed results in this study. Those findings provide important information for developing a novel method to control and utilize the HTR for the wood industry.