Effect of High-Temperature Heat Treatment on the Acoustic-Vibration Performance of *Picea jezoensis*

Lingjing Zhu,[a,b] Yixing Liu,[a] and Zhenbo Liu[a,]*

The crystallinity and acoustic-vibration parameters of *Picea jezoensis*, including specific Young's modulus (*E/ρ*),coefficient of sound-radiation resistance (*R*), sound resistance (*ω*), and the ratio of Young's modulus to the dynamic stiffness modulus (*E*/G), before and after heat treatment were measured and characterized. Conditions for the heat treatment included N_2 as the protection gas and temperatures of 170 °C, 190 °C, and 210 °C with holding times of 2 h, 3 h, and 4 h. The results showed that specific Young's modulus, the coefficient of sound-radiation resistance, and the ratio of Young's modulus to the dynamic stiffness modulus increased, whereas sound resistance decreased, thereby improving the acoustic performance of the wood. The maximum increments were 5.7% for specific Young's modulus (210 °C, 3 h), 8.8% for the coefficient of sound-radiation resistance (210 °C, 3 h), and 13.8% for the ratio of Young's modulus to the dynamic stiffness modulus (210 °C, 4 h). Conversely, the maximum decrease in sound resistance was 5.6% (170 °C, 2 h). The crystallinity of heat-treated samples universally increased, and the maximum reached 60.67% (210 °C, 4 h), which was 9.9% higher than that of the control group. Moreover, the sound resistance decreased within increasing crystallinity growth, indicating that these two parameters were negatively correlated. Overall, the acoustic-vibration performance of *P. jezoensis* was improved through heat treatment, with the best vibration performance obtained at 210 °C with a holding time of 4 h.

Keywords: Wood; Heat treatment; Vibration performance; Crystallinity

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INTRODUCTION

Woods with good vibration characteristics are usually selected for the soundboard of musical instruments. One example is *Picea jezoensis* wood. However, strict requirements for soundboards include no defects (cracks, knots, or wormholes), qualified density, annual ring width, number of annual rings, and microscopic features (Liu 2007), which hinder the use of *P. jezoensis* for musical instruments. The universal shortage of wood resources has led to fewer suitable wood types being available for the production of soundboards. Consequently, methods to modify and improve the acoustic performance of *P. jezoensis*, which otherwise has poor acoustic vibration performance, could effectively alleviate the shortage of wood resources needed for musical instruments.

At present, in addition to physical methods such as heat treatment and fungal decay treatment, chemical impregnation is a common chemical method for improving the vibration performance of wood. The density, moisture content, moisture absorption, and extract content of wood are modified by chemical impregnation, which remarkably improves the vibration performance of wood (Yano and Minato 1992; Akitsu *et al*. 1993; Sakai *et al*. 1999; Chang *et al*. 2000; Liu and Liu 2012). Schwarze *et al*. (2008) used *Xylaria longipes* soft-rot fungi and the blood red-colored *Physisporinus vitreus* white-rot fungus to improve the acoustic performance of Norway spruce and American sycamore, which can be compared with cold-temperate woods that are used in soundboard production (Schwarze et al. 2008). However, some harmful substances may remain on the wood surface during chemical impregnation, and there appears to be some difficulty in controlling the degree of decay from the fungal decay treatment. Moreover, the processing cycle of fungal decay treatment is also longer. Thus, heat treatment may be a better option because it requires no chemicals and has the advantages of a short cycle, recyclable waste, relative safety, and environmental friendliness.

Heat treatment degrades hemicelluloses in wood, reducing the hydroxide radicals in the cell wall and weakening the moisture adsorption of wood while improving the dimensional stability and enhancing the resistance to bio-destruction under hypoxic conditions at temperatures at or above 200 °C (Markku 2004). Domestic and foreign studies have focused on the influence of heat treatment on the mechanical properties, dimensional stability, and color of wood (Stamm and Hansen 1937; Kollman and Schneider 1963; Bourgois *et al.* 1991; Kubojima *et al*. 2000; Sun and Li 2010), but there have been fewer studies assessing acoustic performance. Kubojima *et al*. (1998) studied how heat treatment at 120 to 200 °C for 0.5 to 16.0 h using N_2 or air affects the vibration performance of Sitka spruce. They found that the density of wood decreased with increasing temperature and holding time. In addition, Young's modulus, shear modulus, crystallinity, and crystal grain width initially increased and remained stable at 120 to 160 °C, and then decreased with increasing temperature. The longitudinal-direction loss tangent value for all temperature treatments increased, whereas the radial-direction loss tangent value increased at 120 °C and then decreased at 160 °C and 200 °C. During the early stages of the heat treatment process, the crystallinity first increased and then decreased over time (Kubojima *et al*. 1998). Inspired by the ancient musical instrument, "Qin Jiao Wei,"Jia (2010) studied the influence of heat treatment on the acoustic properties of China fir at 120 °C, 140 °C, 160 °C, 180 °C, 200 °C, and 220 °C with a holding time of 2 h. The researchers determined that the density, Young's modulus, sound resistance, and attenuation coefficient decreased with increasing temperature, whereas the specific Young's modulus and the coefficient of sound-radiation resistance increased. The acoustic property of fir, heat-treated at 220 °C, was superior to that of ancient fir (Jia 2010). In the high-temperature heat treatment of *Metasequoia* at 120 to 220 °C with a holding time of 0.5 h, Sha (2015) showed that the heat treatment improved the vibration performance of wood. Specific Young's modulus and cellulose crystallinity notably increased, whereas the attenuation coefficient decreased. Moreover, crystallinity greatly influenced the specific Young's modulus, *i.e.*, the latter increased with increasing cellulose crystallinity (Sha 2015). The hemicellulose of heat-treated wood releases acetic acid through depolymerization and deacetylation, which produce low-molecular-weight compounds, and the extract content of wood changes because of high-temperature evaporation (Esteves *et al*. 2010). In addition, high temperature crystallizes cellulose by rearranging the molecules present in the quasi-crystalline region of cellulose. Xylan and mannan, which are contained in hemicellulose, also possess crystallization capacity because of the removal of acetyl functions, resulting in improved crystallinity (Ding 2012). The improvement in crystallinity and changes in extract content improve the acoustic properties of wood (Ma 2005). Obviously, determining how to improve the vibration performance of heat-treated wood is important.

In the present paper, *P. jezoensis* was treated under N_2 protection by an ultra-high-temperature heat treatment (Sun and Li 2010) for various temperatures (greater than 150 °C) and holding times. The effect of the high-temperature treatment on the vibration performance and crystallinity of *P. jezoensis* was also considered, with the aim of providing theoretical references for the functional modification of the acoustic performance of wood for its use for the soundboard of traditional musical instruments.

EXPERIMENTAL

Materials

Picea jezoensis without any obvious defects was cut into 300 (longitudinal) × 30 (radial) × 10 (tangential) mm samples with polished surfaces. Before the experiment, the samples were placed in a 20 °C environment at 65% relative air humidity and adjusted to the equilibrium moisture content. Nine different treatment conditions were run according to different temperatures and holding times (170 °C, 190 °C, and 210 °C for 2, 3, and 4 h), with five samples for each treatment. The parameters of each group of samples were compared before and after heat treatment.

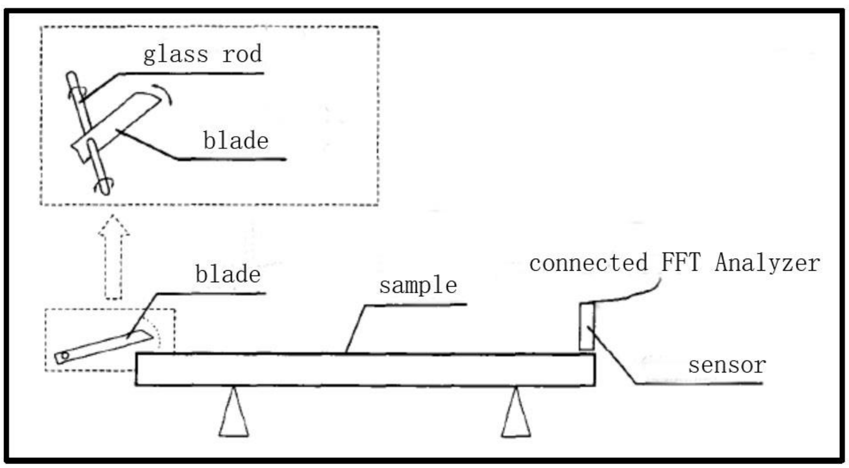

Fig. 1. Diagram of resonance frequency measurements

Methods

Measurement of the acoustic performance of wood

Based on the beam theory of the free boundary conditions at both ends (Akitsu *et al.* 1991), the acoustic properties of wood were measured using a two-path, multi-purpose FFT analyzer (CF-5220Z, ONO SOKKI, Yokohama, Japan) by bending vibration and under the critical condition of free ends. A diagram of the experimental set-up is presented in Fig. 1. The sample was supported by an elastic tripod at the nodal point with a supporting point (0.224 times the total length of the sample) away from one end of the sample. Consequently, the same end or the center of the sample was struck with a blade, so that the sensor at the opposing end would receive the vibration signal. The vibration spectrum was determined using the FFT analyzer and processed with a special software (Visual Basic, Microsoft, Richmond, USA) compiled by Professor Liu Yixing of Northeast Forestry

University to examine the vibration performance parameters, including specific Young's modulus, sound resistance, and the coefficient of sound-radiation resistance (Huang 2013).

High-temperature treatment technique

Heat treatment was divided into three stages, as discussed below. The treatment time refers to a constant-temperature holding time. First, during the drying stage, wood samples were preheated in a device under different experimental conditions, and the temperature was raised to 80 °C over 1 h. Nitrogen was injected into the device, and the temperature was rapidly increased to 103 °C to dry the samples to a moisture content of approximately 0%. According to the exploratory experimental results related to the heating of *P. jezoensis*, the temperature holding time lasted approximately 8 h. During the holding-time stage, the temperature was raised to the final treatment temperature and holding time combination of 170 °C, 190 °C, and 210 °C for 2 h, 3 h, and 4 h. Finally, during the cooling and adjusting stage, samples were cooled to below 100 °C after the heat treatment, and the N_2 inlet was discontinued. The general power was shut off when the samples cooled to below 80 °C, and then the samples were collected and placed in a constant temperature humidity chamber to obtain equilibrium moisture content.

Crystallinity measurement

An X-ray diffractometer (D/MAX-3B, Japanese Rigaku Co., Tokyo, Japan) was used to measure the crystallinity of the samples, using the following conditions: Ni optical filter for removing the CuKb radiation, pipe flow of 32 mA, pipe pressure of 40 kV, X-ray tube made of Cu, and scanning speed of 5°/min within the range of 5° to 40° (2θ). The nine treatment groups were subjected to high-temperature treatment, and one additional group served as the blank control. All samples were adjusted to the dimensions of 80-mesh wood flour, which was dried and divided into the treatment groups. The samples in each group were examined in triplicate to obtain a mean value. The Segal experience equation (Segal *et al.* 1959) was used to calculate relative crystallinity (*CrI*; Eq. 1),

$$CrI(\%) = (I_{002} - I_{am}) / I_{002} \times 100 \qquad (1)$$

Where I_{002} is the maximum strength of (002) the lattice diffraction angle (arbitrary unit), and I_{am} is the diffraction intensity of amorphous background when 2θ close to 18°.The units of I_{am} and I_{002} are the same.

RESULTSAND DISCUSSION

Woods for the soundboard of musical instruments should possess adequate acoustic-vibration performance, acoustic-radiation performance, transmission, consumption of vibration energy, and crystallinity (Liu *et al.* 2006). The following indicators of vibration performance in *P. jezoensis* were analyzed: specific Young's modulus (E/ρ), coefficient of sound-radiation resistance (R), sound resistance (ω), the ratio of Young's modulus to the dynamic stiffness modulus (E/G), and crystallinity.

Effect of High-Temperature Treatment on the Acoustic Vibration

Specific Young's modulus

The effects of the heat treatment conditions on the specific Young's modulus are presented in Fig. 2.

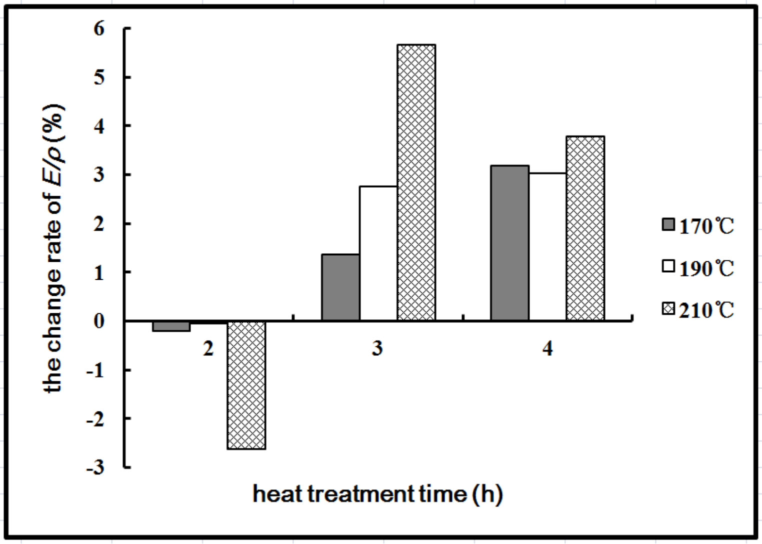

Fig. 2. Effect of heat treatment conditions on the specific Young's modulus, *E/ρ*

The specific Young's modulus, *E/ρ*, is an important physical quantity for evaluating the acoustic vibration performance of wood. A larger *E/ρ* represents a higher vibration efficiency of wood and a greater suitability for soundboard (Liu 1998). After the heat treatments, *E/ρ* either increased or decreased, and its maximum rate of change (5.6%) was about 3-fold greater than the minimum rate of change (-2.6%). At the final temperatures of 170 °C, 190 °C, and 210 °C for 2 h, the *E/ρ* decreased by 0.2% to 2.6%. When the treatment time was held at 3 h, the *E/ρ* increased by 1.4% to 5.7%, and further increased with increasing temperature. When the holding time was 4 h, the *E/ρ* increased by 3.0% to 3.8%.

These findings indicate that a higher heat treatment over a longer holding time (greater than 2 h) increased *E/ρ*. After heat treatments of 170 °C and 190 °C with different holding times (2, 3, and 4 h), *E/ρ* continued to increase over time, indicating that at lower heat treatment temperature (170 °C and 190 °C), and longer holding time (4 h) increased *E/ρ.* At a higher temperature (210 °C) after 2, 3, and 4 h, the rate of change in *E/ρ* was -2.6%, 5.7%, and 3.8%, respectively. These values were all presented as extreme values, showing that higher-temperature heat treatment (210 °C) significantly affected *E/ρ*. When the holding time was longer (4 h) or shorter (2 h), it was not conducive to increase the value of *E/ρ*, so it is very important to choose proper holding time (3 h) to get the most ideal value of *E/ρ*.

The *E/ρ* is affected by Young's modulus and density. After high-temperature heat treatment, the orderly structure of cellulose molecules in the amorphous area was crystallized, and some components of hemicelluloses, such as xylan and mannan, were crystallized by the deacetyl reaction. Consequently, the stronger crystallinity improved the Young's modulus (Chen *et al*. 2007). However, during heat treatment, the volatilization of some organics and the degradation of cellulose and hemicellulose reduced the density of *P. jezoensis*, leading to an increased *E/ρ.* However, higher temperature and longer holding time destroyed the crystalline structure, resulting in an amorphous structure, such that the mechanical properties (such as Young's modulus) of wood were greatly damaged. Thus, setting the appropriate temperature and time is important. In this experiment, the rate of change in *E/ρ* reached a maximum of 5.7% at 210 °C with a holding time of 3 h, implying that this condition produced a relatively ideal treatment.

Coefficient of sound-radiation resistance

The effect of heat treatment conditions on the coefficient of sound-radiation resistance, *R*, is shown in Fig. 3. According to the theory of vibration, a larger *R* results in more efficient vibrations (Watanabe 1987). With a larger *R*, the vibration energy can radiate acoustic energy farther, resulting in a higher-volume sound that lasts a longer time. Of the three different holding times, increased treatment temperature increased *R*, and the maximum rate of change (8.8%) was approximately 18-fold larger than the minimum rate of change (0.5%). For shorter holding times (2 h and 3 h), a higher temperature increased *R*, whereas for longer holding times (4 h), temperature exhibited less of an influence on *R*. At lower treatment temperatures (170 °C and 190 °C), longer treatment times resulted in a larger *R*. At higher treatment temperatures (210 °C), the appropriate holding time (3 h) can greatly increase *R*; whereas, with holding times beyond 3 h, the growth of *R* decreased. These results indicated that a higher temperature, with an appropriate holding time, was necessary to obtain an ideal *R*. Furthermore, the heat treatment temperature of 210 °C with a holding time of 3 h achieved the greatest improvement in *R* (8.8%).

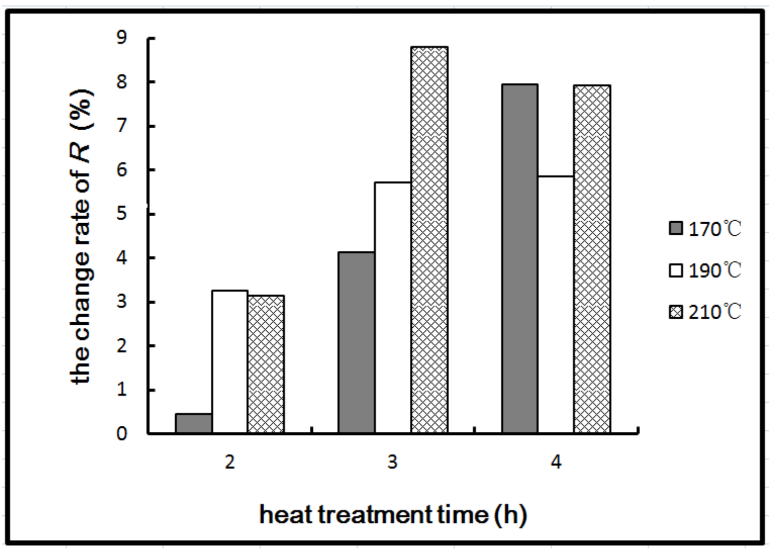

Fig. 3. Effect of heat treatment conditions on the sound-radiation resistance, *R*

Sound resistance

The effect of heat treatment conditions on the sound resistance, ω, is shown in Fig. 4. The sound resistance, ω, also known as the characteristic resistance, is mainly related to the time response characteristics of vibration. Compared with other solid materials, wood has a smaller ω and larger *R*, making it a high-quality material for acoustic radiation (Liu and Shen 2009). Figure 4 shows that the high-temperature heat treatment remarkably reduced ω and that the maximum rate of change (-5.6%) was approximately 8.0-fold the minimum rate of change (-0.7%). For a shorter holding time (2 h), higher-temperature treatment resulted in a greater reduction in ω (0.7% to 5.6%). In contrast, a longer holding time (3 h and 4 h) exhibited less of an influence on ω. Additionally, a lower treatment temperature (170 °C) decreased ω with prolonged holding time (0.7% to 4.5%). Consequently, at higher treatment temperatures (190 °C and 210 °C), the effect of holding time on ω was not very apparent. Given that wood with good acoustic performance exhibits a smaller ω, the heat treatment at 210 °C with a holding time of 2 h was ideal, resulting in a maximal reduction in ω of 5.6%.

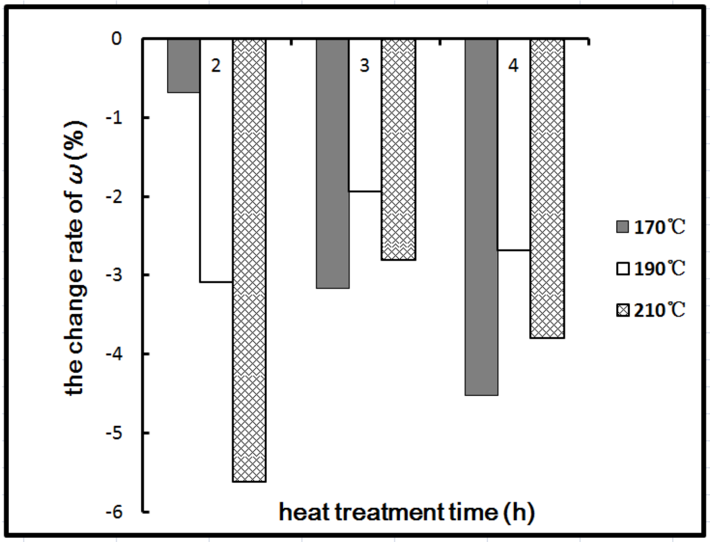

Fig. 4. Effect of heat treatment conditions on the sound resistance, *ω*

The ratio of Young's modulus to the dynamic stiffness modulus

The effect of the heat treatment conditions on the ratio of Young's modulus to the dynamic stiffness modulus, *E/G,* is shown in Fig. 5. *E/G* describes the deformation mode of a material under the action of an external force. Previous studies have shown that *E/G* is positively correlated with the absolute value of the slope of the "envelope line" on the frequency spectrum curve (Liu 2004); therefore, adopting *E/G* can conveniently and significantly describe the features of this curve, as well as evaluate the vibration efficiency and tone of soundboard wood.

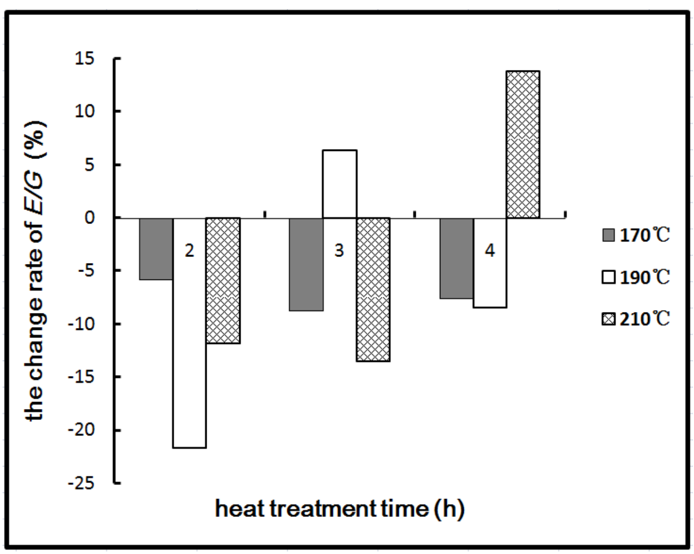

Fig. 5. Effect of the heat treatment conditions on the ratio of Young's modulus to the dynamic stiffness modulus, *E/G*

This evaluation involves the determination of the amplitude distribution law of fundamental frequency and the high-order harmonic on the frequency axis of the material, as well as the continuous frequency spectrum within the operating frequency range. A large

E/G means that the response of improving the low-frequency region and suppressing the high-frequency region may be possible throughout the entire frequency area; thus, the “equal-loudness−level contour” auditory feature of humans can be compensated to improve acoustic quality (Norimoto 1982). Figure 5 shows that the influence of the heat treatment conditions on *E/G* followed no obvious trend, and that the maximum rate of change (-21.7%) was approximately 4-fold the minimum rate of change (-5.8%). Most treatment conditions reduced *E/G*, except for the heat treatment at 190 °C and 210 °C, with a holding time of 3 h and 4 h, respectively. The *E/G* decreased when the holding time was shortened (2 h), and the reduction initially increased before decreasing with increasing temperature. During longer holding times (3 and 4 h), *E/G* fluctuated. Figure 5 also shows that at a lower temperature (170 °C), *E/G* was lower, and with prolonged holding time, the reduction increased before decreasing thereafter. Likewise, at higher temperatures (190 °C and 210 °C), *E/G* fluctuated. Considering that wood with good acoustic performance has a larger *E/G*, the heat treatment at 210 °C, with a holding time of 4 h, was preferred and improved *E/G* by 13.8%.

Table. 1. Degree of Crystallinity of *P. jezoensis* at High Temperatures

No.	Temperature (°C)	Holding Time (h)	Angle of 002 Crystal Face (°)	Average Relative Crystallinity (%)
1	170	2	22.28	58.33
2	170	3	22.46	60.03
3	170	4	22.40	58.86
4	190	2	22.34	58.92
5	190	3	22.22	52.85
6	190	4	22.29	55.25
7	210	2	22.30	60.10
8	210	3	22.44	58.58
9	210	4	22.26	60.67
10	Control group	-	22.51	55.23

Effects of High Temperature on Crystallinity

The relative crystallinity of wood quantifies the amount of crystalline cellulose. During the heat treatment, the structure of cellulose can change, which inevitably influences its crystallinity. A reasonable increase in wood crystallinity benefits vibration efficiency and tone (Liu and Shen 2009); thus, a certain degree of crystallinity is necessary to optimize the acoustic performance of wood.

The relative crystallinity of *P. jezoensis* after the heat treatments is displayed in Table 1. Under different treatment conditions, the 002 diffraction peak of the crystal face was located near 22° (from 22.22° to 22.51°).

The effect of the heat treatment temperature and holding time on the relative crystallinity of wood is presented in Fig. 6. Sun *et al.* (2010) studied the changes in crystallinity of larch wood treated at 180 to 240 °C for 4 h. They showed that for the same heat treatment time, after different ultra-high-temperature treatments, the crystallinity initially increased, then decreased, and then increased again, until reaching its maximum of 65%. These findings were similar to those of Akgül *et al.* (2007) and Long *et al.* (2008). Previous studies have focused on the same time period to discuss the influences of temperature variation on wood crystallinity, whereas the influences of different temperatures and holding times on the crystallinity of *P. jezoensis* are novel findings.

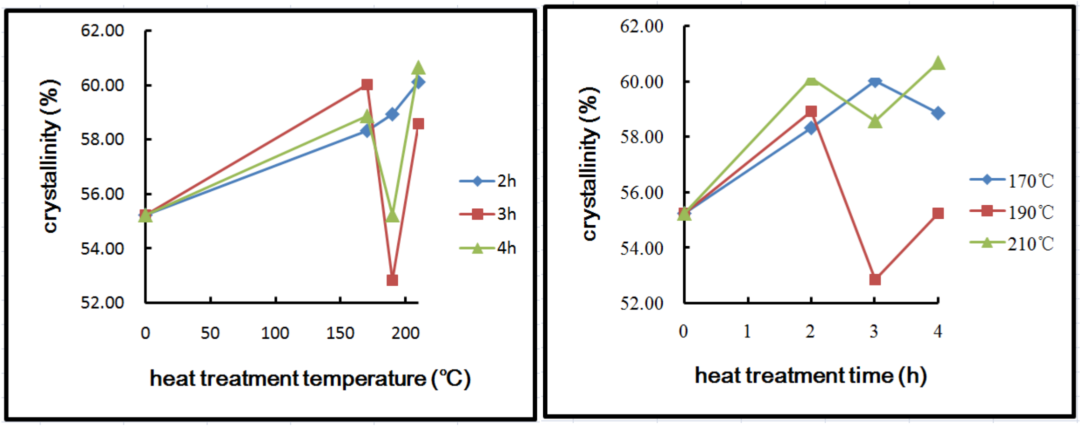

Fig. 6. Effect of the heat treatment a) temperature and b) holding time on the crystallinity of *P. jezoensis*

Table 1 and Fig. 6a show that for the same heat treatment duration, increased temperature led to increased relative crystallinity within a shorter holding time (2 h) (60.10% at 210 °C for 2 h); whereas, relative crystallinity over a longer holding time (3 h and 4 h) increased and then decreased, before finally increasing again to the maximum of 60.67% (210 °C 4 h). Table 1 and Fig. 6b show that at the same heat treatment temperature, a longer duration of treatment initially resulted in a rise and then a drop in crystallinity at a lower treatment temperature (170 °C), resulting in a maximum crystallinity of 60.03% (170 °C, 3 h). At higher treatment temperatures (190 °C and 210 °C), crystallinity initially increased and then decreased, before finally increasing again, reaching a maximum of 60.67% (210 °C, 4 h).

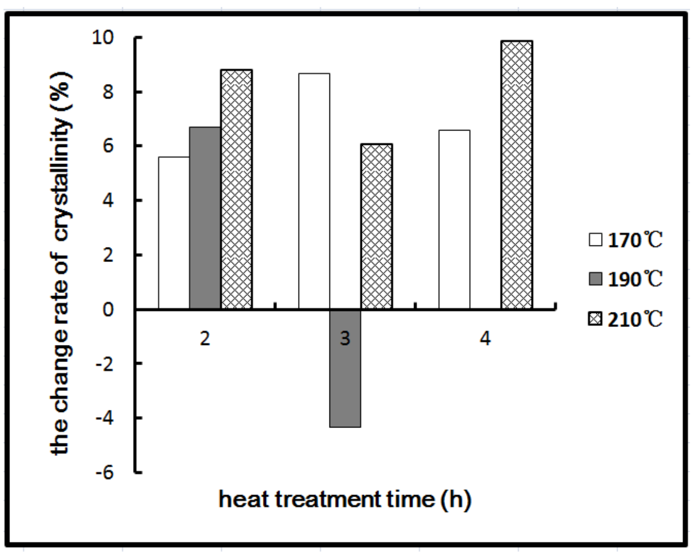

Fig. 7. Effect of heat treatment conditions on the rate of change in relative crystallinity

Next, the rate of change in relative crystallinity under different treatment conditions was examined. The effect of the heat treatment temperature and holding time on the change in crystallinity is presented in Fig. 7. Untreated wood with 55.23% relative crystallinity was used as the control, and the relative crystallinity in the other groups after heat treatment universally improved, with the maximum of 60.67% (210 °C, 4 h), which was 9.9% higher than that of the control group. The relative crystallinity dropped only once to 52.85% (190 °C, 3 h), which was 4.3% less than that of the control group. These findings indicated that most of the high-temperature treatments improved the relative crystallinity of *P. jezoensis*.

The crystallinity of *P. jezoensis* cellulose increased with increasing temperature, which can be because the high temperature resulted in moisture loss in the amorphous region, such that hydroxyls on the macromolecular chain of cellulose mutually bonded to form an -O- structure by removing a water molecule. This phenomenon decreased the space among fibrils in the amorphous region and increased the intermolecular forces, leading to increased compactness of fibril arrangement. The formation of a new chemical bond enabled the fibrils of the amorphous region to become orderly and arrange toward the crystalline region. Consequently, some of these fibrils went to the crystalline region, leading to an increase in crystallinity. Moreover, this increase in crystallinity of cellulose was attributed to the hydrogen-bond association between free-hydroxyl and hydroxyl groups, which decreased the intermolecular spaces and increased the intermolecular forces. However, with increasing temperature, the sudden decrease in crystallinity may result from the formation of acetic acid on the hemicellulose, which destroys the structure of cellulose through acidolysis; thus, the polymerization of cellulose weakened, leading to weaker crystallinity. The later rise in crystallinity may result from the recrystallization of some schizolytic microfibrils on the destructive cellulose molecular chain and inside the amorphous region with increased temperature (Sun e*t al.* 2010).

Relationship between crystallinity and sound resistance

Wood with good vibration performance has a larger specific Young's modulus and smaller sound resistance, and crystallinity can affect the vibration performance of wood (Shen 2001).

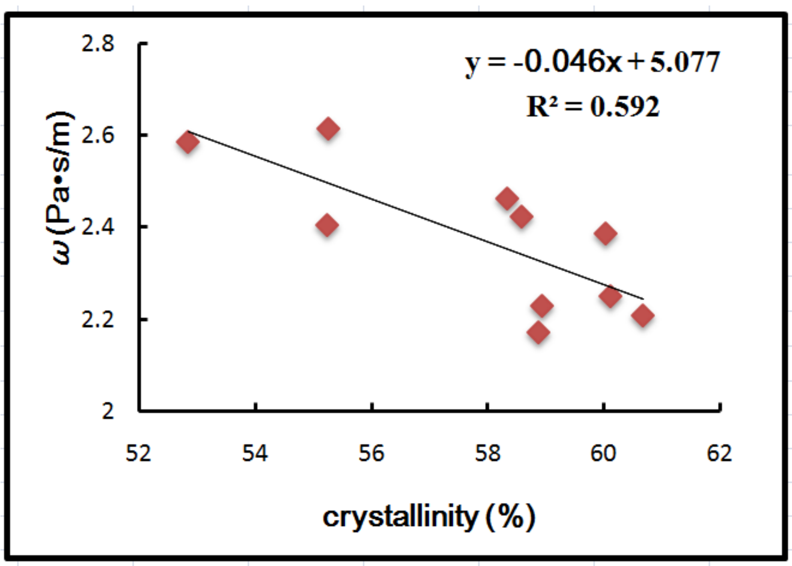

Fig. 8. Relationship between sound resistance, *ω*, and relative crystallinity

The specific Young's modulus of *Fraxinus mandshurica* and spruce wood increases with the increase of their cellulose crystallinity (Ma 2005). When the crystallinity of Sitka spruce, *Picea likiangensis*, and *P. jezoensis*, reached their peaks, the specific

Young's moduli also reached their maximums, resulting in an optimal vibration quality (Shen and Liu 2001). This positive correlation has been demonstrated in many studies; however, research on the relationship between crystallinity and sound resistance of wood remains limited. Accordingly, this relationship was explored in the present work (Fig. 8). The figure shows that the sound resistance of heat-treated *P. jezoensis* decreased with increasing crystallinity, *i.e.*, when the latter was 58.86%, the former decreased to the minimum value of approximately 2.17 Pa•s/m. The coefficient of determination, R^2, was 0.592, indicating that the regression equation explained about 59% of the variance. The sound resistance with crystallinity were negatively correlated. Therefore, the heat treatment improved the crystallinity of wood to reduce the sound resistance and thus improve the vibration performance of wood.

CONCLUSIONS

1. After heat treatment under the appropriate conditions, the specific Young's modulus (E/ρ), the coefficient of sound-radiation resistance (R), and the ratio of Young's modulus to the dynamic stiffness modulus (E/G) of *P. jezoensis* improved by varying degrees, while the sound resistance (ω) weakened. As a result, the acoustic-vibration performance of *P. jezoensis* improved. The maximum E/ρ of 5.7% (210 °C, 3 h), R of 8.8% (210 °C, 3 h), and E/G of 13.8% (210 °C, 4 h) were obtained. Conversely, the maximum reduction of ω was 5.6% (170 °C, 2 h).

2. After super-high-temperature heat treatment, the crystallinity of *P. jezoensis* increased, *i.e.*, the relative crystallinity peaked at 60.67% (210 °C, 4 h), which was 9.9% higher than that of the control group. At the holding time of 2 h, the relative crystallinity of the samples increased with increasing temperature. For holding times of 3 h and 4 h, the crystallinity initially increased, then decreased before increasing again. Maintaining the same treatment temperature (170 °C) initially increased the relative crystallinity and then decreased it with increasing holding time. Maintaining higher treatment temperatures (190 °C and 210 °C) initially increased the relative crystallinity and then decreased it before finally increasing it again.

3. The sound resistance of heat-treated *P. jezoensis* decreased with increasing crystallinity; therefore, the two were negatively correlated ($R^2 = 0.592$). This result implies that the vibration performance can be improved by increasing the crystallinity, which in turn reduces the sound resistance.

4. In summary, the 210 °C temperature and 4 h holding time were the best heat treatment conditions for *P. jezoensis*, in which the vibration performance was optimum. In these conditions, E/ρ, R, E/G, and crystallinity increased by 3.8%, 7.9%, 13.8%, and 9.9%, respectively, whereas the maximum sound resistance reduction was 3.8%.

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