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Liquid penetration of precompressed wood VI: Anatomical characterization of pit fractures*

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Abstract Pit fractures of refractory coniferous heartwoods caused by precompression in the radial direction were investigated and are discussed in terms of improved liquid penetration. Small cracks appeared at the boundary between the torus and margo, along the outer margin of the margo, and on the torus when specimens were compressed and deformation was fixed by drying. The remarkable cracks were generally observed for *Cryptomeria japonica* D. Don. *Pseudotsuga menziesii* Franco showed peculiar detachment of the torus from the pit border, and *Larix leptolepis* Gordon exhibited only small cracks on the torus. These fractures patterns were clearer when the precompressed specimens were recovered by water impregnation and then redried.

Keywords Pit · Refractory wood · Precompression treatment · Liquid penetration

Introduction

During the chemical treatment of wood it is necessary to impregnate chemicals into the wood uniformly and deeply. On the other hand, for wood drying the impartial removal of water from wood is important. The efficiency of these two processes generally depends on the smooth and easy movement of liquid in wood. There are two types of liquid movement in wood: diffusion through the cell walls and flow in the cell lumens. The latter should be more considerable during wood processing. The difficulty of liquid flow between cell lumens varies among wood species and wood portions. Especially the heartwood of some conifers, such as Douglas fir and larch, is regarded as the refractory wood portion for both the impregnation of liquid and removal of water.

One of the main reasons for obstruction of liquid flow in coniferous heartwood is believed to be closure of the bordered pits by pit aspiration and occlusion. Generally, almost all of the pit membranes are aspirated to the pit aperture under dry conditions; additionally, the surfaces of the pit membranes of heartwood are frequently covered with heartwood extractives. The pit closure due to these two conditions is considered responsible for the marked reduction in liquid flow in heartwood.

Several methods for opening closed pits have been introduced to accelerate liquid flow in heartwood.[1–3] Among them, precompression is assumed to be the simplest method and does not require special equipment. According to previous studies, precompression under appropriate moisture and heat conditions effectively increases the penetration of liquid into refractory wood samples of practical size without causing a significant reduction in strength.[4] Furthermore, compared to other methods, a uniform effectiveness might be expected in the longitudinal direction because the wood samples can be precompressed on the whole tangential surface.

The effect obtained by precompression has been mainly estimated in terms of increased liquid permeability. The structural change in closed pits by this treatment has not yet been investigated. Investigation of the relation between increasing liquid permeability and the structural change of the closed pits is required to improve this treatment system. In this report, fractures of closed pits induced by precompression were observed by scanning electron microscopy

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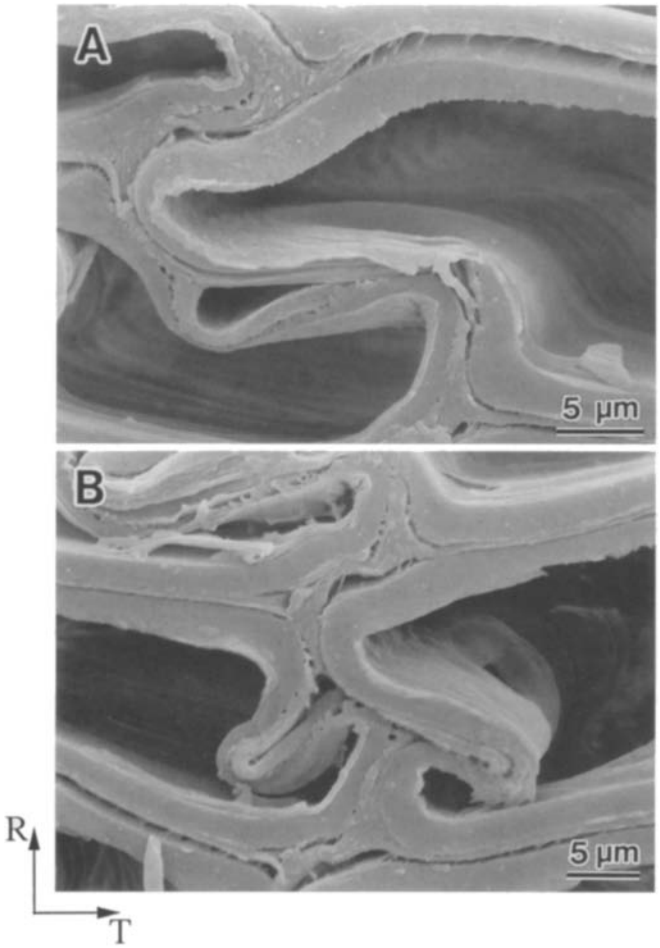

Fig. 1. Cell wall deformation around the pit region by compressive loading in the radial direction (*Cryptomeria japonica*). *R*, radial direction; *T*, tangential direction. The cell walls with the bordered pit were bent (**A**) or collapsed (**B**) in the radial direction

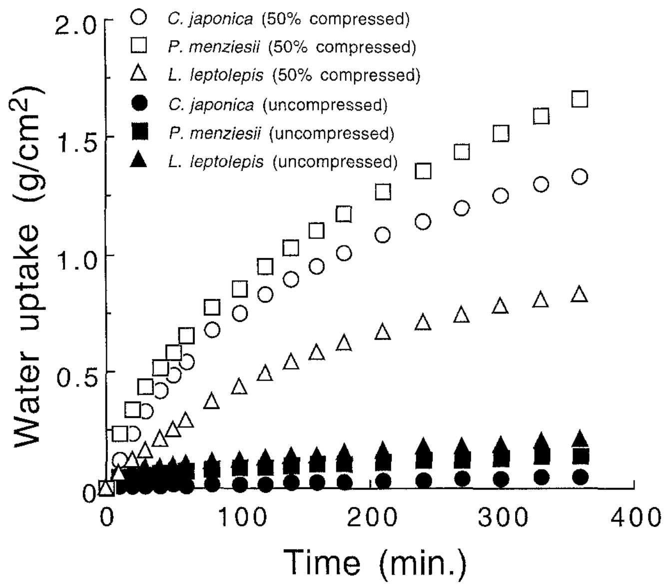

Fig. 2. Water uptake of 50%-compressed (*open symbols*) and uncompressed (*closed symbols*) specimens

(SEM), and their patterns are discussed in terms of improved liquid penetration.

Materials and methods

Three kinds of coniferous heartwood (*Cryptomeria japonica* D. Don, *Larix leptolepis* Gordon, *Pseudotsuga menziesii* Franco) were used in this experiment. The specimens subjected to precompression measured 10mm (radial) × 10mm (tangential) × 50mm (longitudinal).

Specimens swollen with water were compressed in the radial direction at 20°C, and the deformation was fixed in a jig. The compressive ratios were set to 15%, 30%, and 50% with respect to the original thickness. The compressed specimens were dried at room temperature for 5 days and then at 30°C for 5 days, fixing the deformation.

Radial surfaces of the 15%- and 30%-compressed specimens were prepared by cutting with fresh knives. They were then ion-sputter-coated, followed by SEM observations (JEOL JSM-35CF II).

For the 50%-compressed specimens, the compressive deformation was recovered by water impregnation under vacuum condition, and the recovered specimens were dried at room temperature for 5 days and at 30°C. After drying, the radial surfaces were observed. Water uptake of the 50%-compressed specimens was also measured by immersing one end of the specimens in water for 360min at room temperature. The result was expressed as retention per unit area of the end surface.

When observing the pit membranes, care must be taken in selecting the accelerating voltage of electron beam of SEM because the pit membranes with a thin primary wall[5] are so fragile they can be easily damaged by high-voltage beam irradiation. Our preliminary investigation clarified that the pit membranes were not damaged when observed with a voltage lower than 10kV. Therefore a voltage of 10kV was selected for SEM observation in this experiment.

Results and discussion

Pit fractures caused by precompression treatment

When wood was compressed in the radial direction, the uniform deformation of the cells was hardly detected on the transverse surface; it was mainly concentrated in the early wood zone. Even though the specimens were compressed up to 15%, 30%, and 50% of the deformation ratios, the typical characteristics of the pit fracture were commonly recognized in all of the specimens regardless of the deformation ratios.

Wood specimens swollen by water could be compressed viscoelastically without causing fracture of the cell wall which leads to a large decrease in mechanical properties. When the precompressed specimens were recovered by

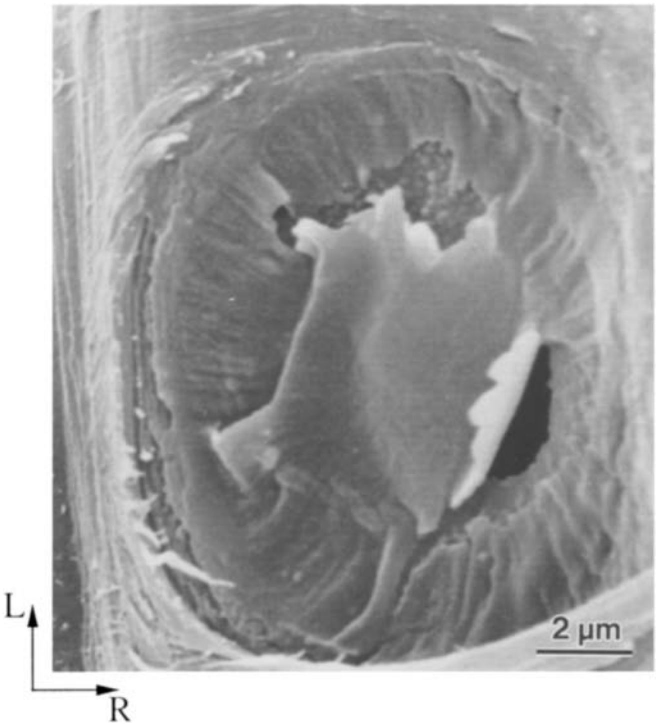

Fig. 3. Fracture of pit membrane caused by compression in the radial direction (*C. japonica*). *L*, longitudinal direction; *R*, radial direction

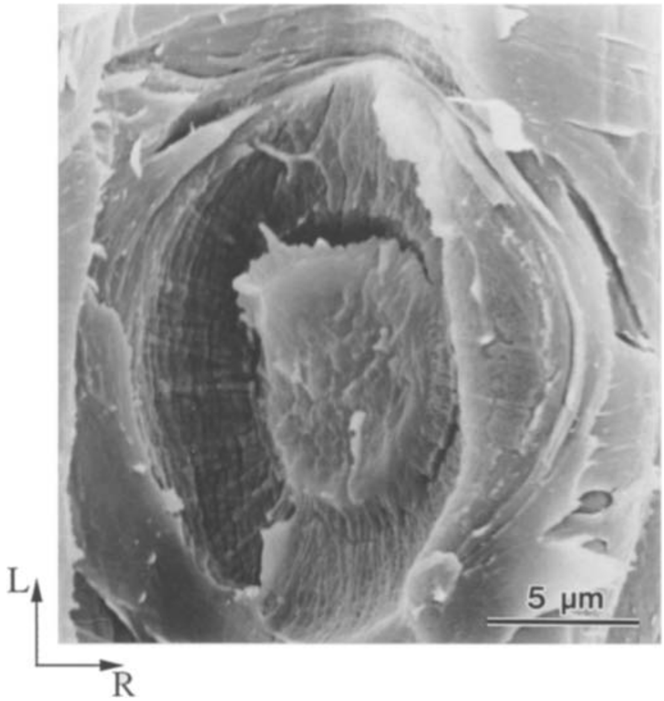

Fig. 4. Fracture of pit membrane caused by compression in the radial direction (*P. menziesii*). *L*, longitudinal direction; *R*, radial direction

water immersion, negligible compression deflects were observed along unpitted cell walls, though retaining only traces of corrugations.[6] Figure 1 shows cell deformation caused by compressive loading in the radial direction under swollen conditions. The radial cell wall was largely bent (Fig. 1A) and was collapsed around the pit region (Fig. 1B). These observations suggested that severe damage or changes occurred on the pit membranes or the pit borders.

Figure 2 shows the water uptake of the 50%-compressed specimens after the end surface of specimens was immersed in water. The values of precompressed wood were 7–25 times greater than those of the uncompressed controls. *C. japonica* showed the largest improvement in terms of water uptake, followed by *P. menziesii*. In contrast, *L. leptolepis* demonstrated only a small improvement.

Figure 3 shows a fractured pit membrane of *C. japonica* in which the torus is visibly separated from the outer surface of the pit border. This type of fracture of the pit membranes was commonly observed for *C. japonica*, and the precompression treatment was assumed to improve liquid penetration.

Figure 4 shows the fracture of the pit membrane of *P. menziesii* under an aspirated condition. Visible cracks clearly appeared at the boundary between the torus and margo, resulting in the peculiar detachment of the torus from the pit border. Such cracks were also frequently observed in other species compressed at deformation ratios of 15%, 30%, and 50%, but were rarely recognized in uncompressed specimens. Therefore it was believed that this type of crack typically appeared on the pit membranes of wood compressed in the radial direction, especially for *P. menziesii*, which had rigid but fragile pit membranes of the thickened torus and margo.

Figure 5 shows cracks on the pit membrane of *L. leptolepis*. Small cracks were observed at the boundary between the torus and margo, along the outer margin of the margo, and on the torus. The heartwood of *L. leptolepis* is said to contain about 30% heartwood extractives which mainly consist of arabinogalactan. The extractives are deposited not only on the cell lumen surfaces but also on the pit membranes, so it may obstruct the liquid flow between adjacent tracheids. Precompression could cause cracks or slits even on the thickened pit membranes covered with heartwood extractives, although these cracks were not large or deep enough to permit complete penetration of water or liquid through the membranes. When comparing the pit membranes of *L. leptolepis* with those of *P. menziesii*, the former is considered to be more flexible than the latter, which suggests the lesser appearance of the fractures between torus and margo and the separation between the pit membrane and the border. This evidence was proved by the fact that the combination of hot-water extraction and precompression improves liquid penetration in *L. leptolepis*.[7]

To discuss the appearance of cracks at the boundary between torus and margo and along the outer margin of margo, the main mechanism of pit fractures was considered as follows. The cell wall, torus, and margo are regarded to be aligned almost parallel in the radial direction, having different thicknesses. This disproportional structure may be deflected by a moment exerted by the externally compressive load in the radial direction. Because the deflection of

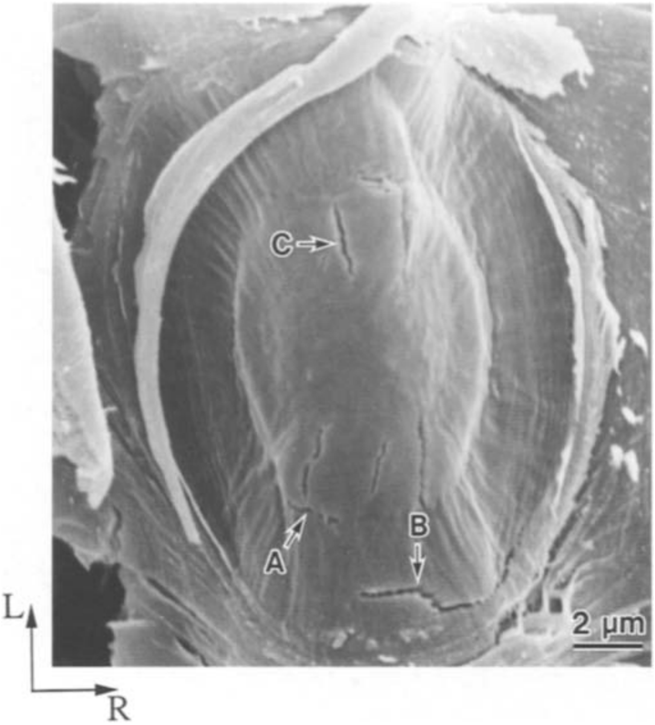

Fig. 5. Fracture of pit membrane caused by compression in the radial direction (*Larix leptolepis*). Note cracks between the torus and margo (*arrow A*), along the outer margin of the margo (*arrow B*), and on the torus (*arrow C*). *L*, longitudinal direction; *R*, radial direction

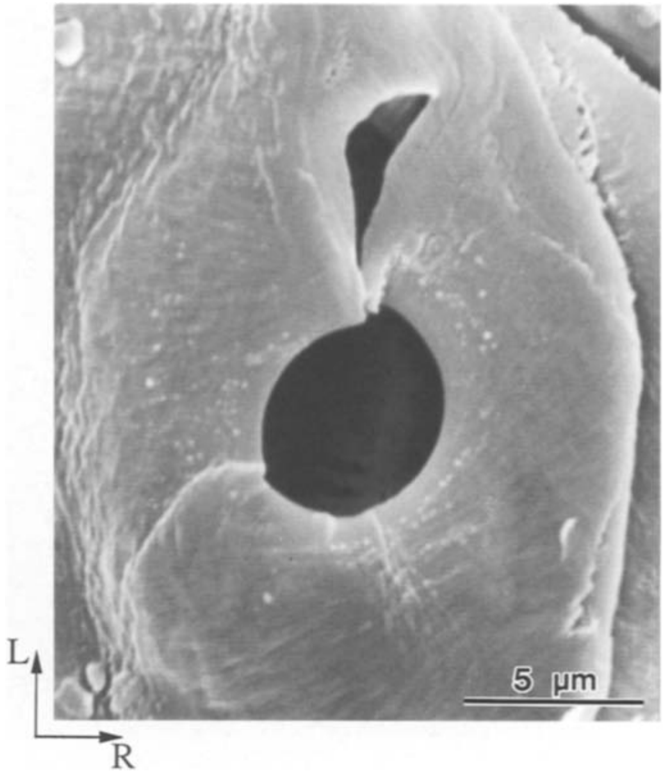

Fig. 6. Fracture of pit border caused by compression in the radial direction (*L. leptolepis*). *L*, longitudinal direction; *R*, radial direction

margo is larger than that of torus or the cell wall, the shear stresses are caused at the boundary between torus and margo and along the outer margin of margo if the cell wall and pit membrane are uniformly deformed. When the shear stress exceeds the shear strength, the cracks should occur at the boundary and margin. Once the cracks appear, they may advance easily because of the high concentration of stress at their tips. The cracks on the torus are believed to be formed by the concentration of stress around small defects when the torus is bent.

Tearing was also observed on a pit border (Fig. 6). The tears formed on the pit border would enlarge the pit aperture to enhance liquid permeability.

Pit fractures caused by water recovery and drying after precompression treatment

Compressive deformation of wood fixed by drying was almost completely recovered by water impregnation. When deformation-fixed wood of *C. japonica* was dipped in the liquid and the deformation was released, penetration increased markedly, showing more than 25 times the value for the untreated wood.[4] The structural changes in pits caused by the process of water recovery and drying were investigated.

Figure 7 shows the pit membrane of *P. menziesii* after 50% precompression and full recovery by water impregnation. Cracks that appeared when the compressive

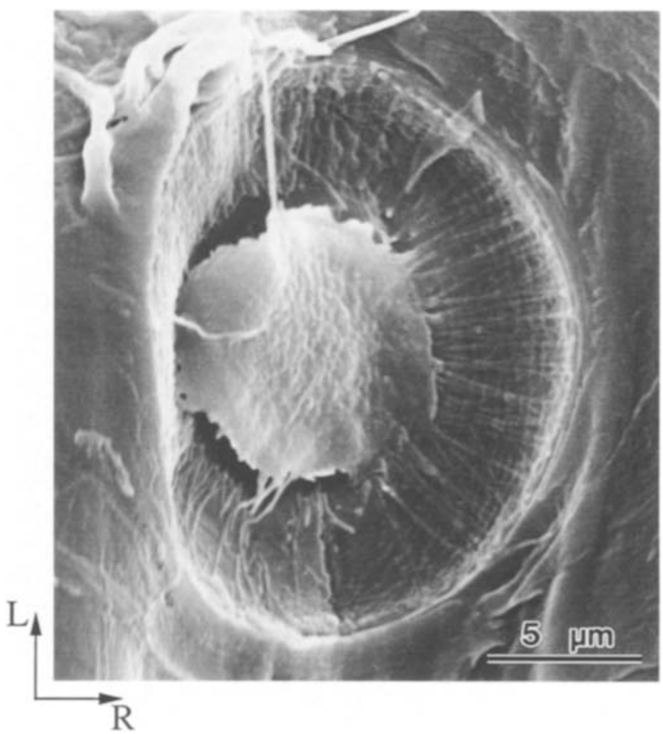

Fig. 7. Fracture of the pit membrane caused by water recovery after 50%-compressive deformation and redrying (*Pseudotsuga menziesii*). *L*, longitudinal direction; *R*, radial direction

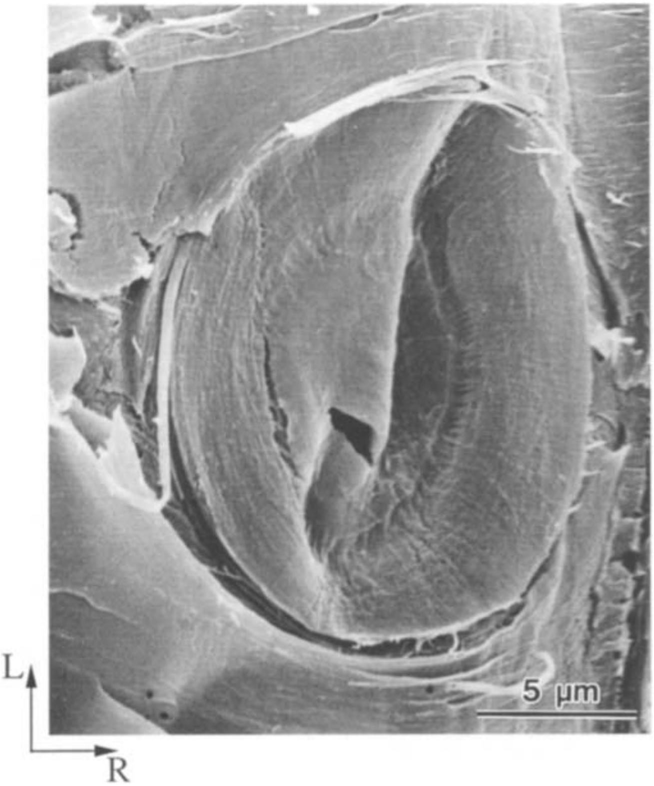

Fig. 8. Fracture of pit membrane caused by water recovery after 50%-compressive deformation and redrying (*L. leptolepis*). *L*, longitudinal direction; *R*, radial direction

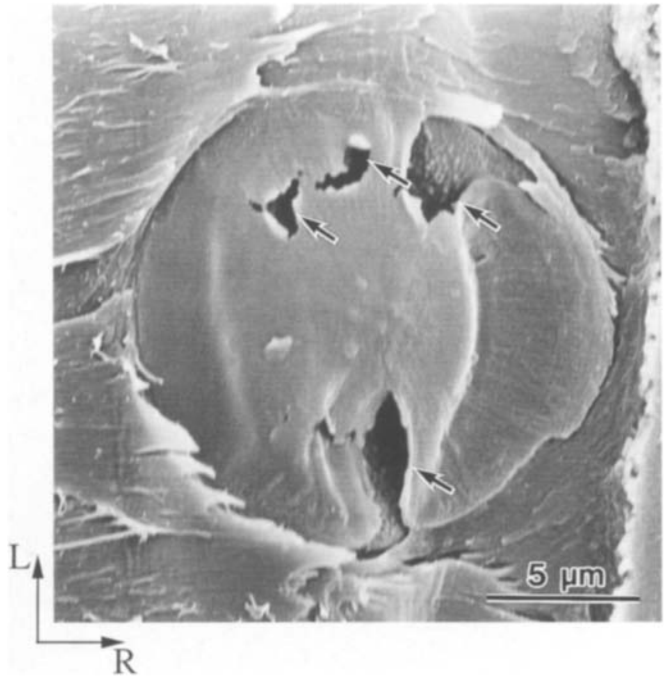

Fig. 9. Fracture of pit membrane caused by water recovery after 50%-compressive deformation and redrying (*C. japonica*). Large and small holes are clearly observed (*arrows*). *L*, longitudinal direction; *R*, radial direction

deformation had been fixed by drying were considered to advance during water recovery and redrying. On the pit membrane of *L. leptolepis* treated by the same process (Fig. 8), typical cracks were also detected on the torus and were assumed to advance and enhance the penetration of liquid through the pit membrane. Figure 9 shows the pit membranes of *C. japonica*, in which circular holes clearly penetrated the pit membranes. Holes in the pit membranes were rarely observed for whole wood specimens before precompression. Therefore they were believed to be formed only after the precompression-recovery treatment. It was assumed that cracks appearing when the compressive deformation had been fixed by drying would advance to make circular holes via the recovery process.

A series of pit fractures is believed to occur as follow: Small fractures were formed on the pit structures by the precompression treatment under water-swollen conditions and the dry-setting of the compressive deformation. The fractures advanced by stretching the pit membranes through water recovery of the deformation under vacuum. By redrying after water recovery, the fractures expanded even more caused by the drying stress that concentrated at the tips of the fractures, and they were more clearly visualized. This continuous process should enable us to produce the clearly visible cracks even on flexible and thickened pit membranes or thin structures of the membranes.

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