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Microcrack propagation in transverse surface from heartwood to sapwood during drying

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Abstract

Microcracks, which are difficult to be observed with naked eyes, occur on the transverse surface during the first stage of wood drying. The precise investigation of their appearance is critical for understanding the mechanism of crack occurrence and propagation, which influence the properties of wood. In this study, the location and time difference of microcrack occurrence on the transverse surfaces of outer heartwood to sapwood via the intermediate wood of *Cryptomeria japonica* were investigated. Using the developed confocal laser scanning microscope system and a digital microscope, the microcrack propagation was captured dynamically with the wide range of high-quality images; microcracks appeared initially in the heartwood region, immediately after drying. On the other hand, in sapwood, microcrack generation occurred only after microcracks appeared in intermediate wood, and the ones in heartwood started to close or were closed. Finally, most of the microcracks almost closed and some completely disappeared towards the end of the drying process. From this result, it can be established that appropriate drying conditions should be prepared during the early stage of drying to produce high-quality wooden products because microcracks can appear in heartwood, even though the moisture content of the specimen is high.

Keywords: Microcrack, Drying, Sapwood, Heartwood, Confocal laser scanning microscope (CLSM)

Introduction

Wood is of two types: sapwood, which is the outer part of the tree stem, including the outside bundle of growth rings adjacent to the bark of the wood disc, and heartwood, which is the inner part of the growth rings and does not exist in younger trees. In many trees, these two types can be commonly distinguished based on their different colours caused by heartwood substances, which are identified with expensive methods [1]. The types and quantities of the chemical components in the heartwood substance differ extensively among the wood species. These heartwood substances affect not only the colour but also the treatability of wood.

The water permeability in heartwood is reported to be lower than in sapwood [2–4]. One of the prominent effects is the low liquid/gas permeability caused by aspirated or encrusted pits [5, 6]; bordered pits, which control the movement of free water, are aspirated or embedded with heartwood substances after heartwood formation. This phenomenon causes fatal disadvantages in wood drying.

Wood must be dried before use as a material with dimensional stability because moist wood shrinks during usage. However, inappropriate wood drying might deteriorate the wood quality by causing cracks, which degrade the appearance, strength, durability, etc. Hence, it is crucial to prevent the occurrence of cracks during drying. Appropriate wood drying and the mechanism of cracking have been extensively researched [7, 8]. Attention was focused on cracking in the final stage of drying, which is influenced by the drying condition of the initial stage, where microcracks that cannot be observed by the naked eye exist [9]. However, microcracks occur on the transverse surface during the first stage of wood drying [10], and it is crucial to investigate their appearance precisely because of the possibility of propagation to large cracks, which can influence the wood properties.

In order to observe the details of the morphological changes of microcracks, we devised a confocal laser scanning microscope (CLSM) system [11], which includes a

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temperature and relative-humidity controllable environmental chamber to enable the observation of the in situ changes of tissues and cells during drying. With this system, we could visualize the microcrack appearance and transformation of the softwood of *Cryptomeria japonica* [12–14], ring-porous hardwood of *Melia azedarach,* and the diffuse-porous hardwood of the acacia hybrid [15]. From these results, it was found that the morphology of the microcrack distribution was strongly influenced by the wood structure, particularly the presence of latewood. Additionally, it was determined that the time of microcrack occurrence differed considerably between heartwood and sapwood, as well as between black heartwood with higher moisture content (MC) and red heartwood with lower MC [14]. The emergence of microcracks in heartwood was obviously faster than in sapwood. Moreover, it was found that the MC of heartwood specimens when first microcracks were occurred [14], which was measured based on the oven-dried weight, was above the fibre saturation point (FSP) though that of sapwood was around or below the FSP [12, 13]. To confirm these tendencies in the cross-surface of a tree, the sizes of the specimens and the harvested trees should be the same, i.e. the observation of the continuous surfaces of specimens in the same drying condition, where heartwood and sapwood are not divided, is indispensable. However, with the previous CLSM system, it is difficult to observe the microcracks occurring in both heartwood and sapwood, simultaneously, over a large area with high magnification.

In this study, I develop the new CLSM system equipped with an automatic stage to capture large areas, and focus on the location and time difference of microcrack occurrence in radially long fresh specimens of *Cryptomeria japonica*, which include both lower MC heartwood and higher MC sapwood, and discuss the relationship between the MC and microcrack appearance.

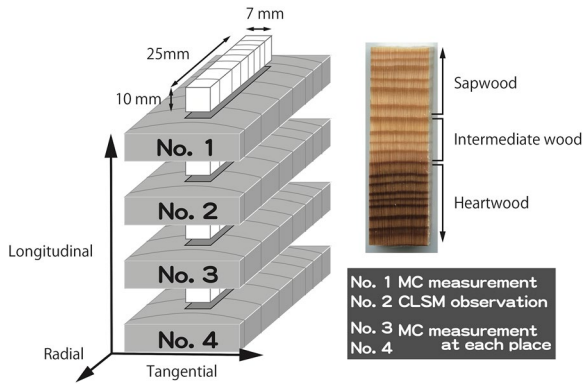

Fig. 1 Sample preparation: Four specimens were derived from an end-matched stick specimen. No. 2 was used for observation, No. 1 for measuring the MC, and Nos. 3 and 4 were used for measuring the MC at two appropriate instances during drying

Materials and methods

Materials

The green softwood, sugi (*Cryptomeria japonica* D. Don), harvested in the Kasuya research forest in Kyushu University, was utilized in this study. A long stick specimen, including both heartwood and sapwood, was derived from the log, and maintained in a frozen condition until use. After thawing at room temperature without drying, four successive 7 mm (tangential) × 25 mm (radial) × 10 mm (longitudinal) specimens were cut (Fig. 1). The longitudinal length was approximately equal to the specimens used in our previous study [12–14]. The growth-ring boundary was positioned either parallel or perpendicular to the surface. Every specimen was prepared in the same condition, and contained heartwood, intermediate wood which is distinguished by the white colour in the green condition in this research, and sapwood. One among the four specimens (No. 2) was used for CLSM observation, whereas the others were used for MC measurement (Nos. 1, 3, and 4). One among these three was used for measuring the MC in the entire specimen (No. 1), whereas the other two (Nos. 3 and 4) were used to obtain the MC of the divided heartwood, intermediate wood, and sapwood at two appropriate instances during drying. The transverse surface was smoothed with a sliding microtome. The green MCs of heartwood, intermediate wood, and sapwood were 58.7, 65.4, and 168.8%, respectively. The formed specimens were stored in a desiccator, which was maintained humid with saturated water, until the commencement of the experiment. The experiments were repeated nine times with other prepared specimens. All the specimens were carefully prepared without mechanical damage. Damages due to processing and freezing were not identified with the following CLSM observations.

Visualization method

To visualize the microcrack occurrence and propagation, a previously established CLSM system [11–15] was further developed and used (Fig. 2). It included a controlled-environment chamber on an inverted CLSM automatic stage (Leica TCS SP8) in which the temperature and relative humidity were controlled suitably with a thermofan and a humidity generator supplying dry air under barometric pressure. The advantage of this new system is that the bottom surface of larger specimens can be observed without being limited by the specimen thickness.

In this chamber, specimens were dried at a temperature of approximately 50 °C controlled by a sensor, at a relative humidity below 5%. Images of the bottom surfaces of specimens, including heartwood, intermediate wood, and sapwood, were continuously obtained by

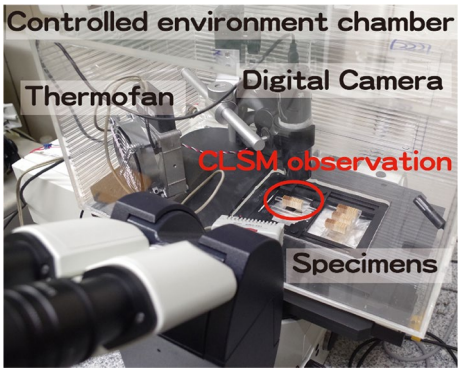

Fig. 2 Visualization method with the CLSM system. The temperature and relative humidity were maintained at approximately 50 °C and below 5% with a thermofan and humidity generator, respectively. The top and bottom surfaces of the specimen were observed using a digital camera and CLSM, respectively. The specimens for MC measurement were placed near the specimen for observation

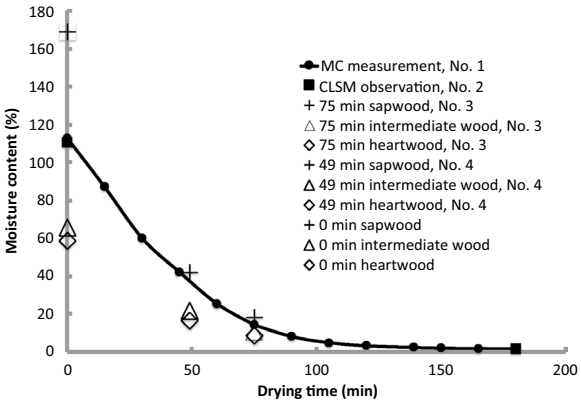

Fig. 3 The MC of the representative specimen. The specimens included heartwood, intermediate wood, and sapwood, for the MC measurement and CLSM observation. The MCs at 49 min and 75 min were measured from the divided specimens

the CLSM immediately after the four specimens were placed together on the microscope stage. The images were bundled using image software. High-quality images were recorded by a blue solid-state laser with an excitation wavelength of 488 nm. A bundle of surface images of specimens, including heartwood, intermediate wood, and sapwood, were successively captured every 2 min until the equilibrium MC in the chamber. The top surface of the specimen was also captured by a digital microscope (3R WM401WIFI) every minute to observe the distribution of microcracks in wide view. The first CLSM image was captured approximately 5 min after the specimens were placed within the chamber. Initially, no microcracks were confirmed by both methods.

The weights of the entire specimen (No. 1) were measured every 15 min, to determine the MC. To investigate the MC at two instances during drying, the weights of two specimens (Nos. 3 and 4), divided into three parts, heartwood, intermediate wood, and sapwood, were measured. The weights of the entire specimen were measured at the end of the drying process, when the changes in weight were stable. The MCs of the specimens were measured from the weight of the oven-dried condition.

Results

Change of moisture content

Four specimens were dried in a controlled-environment chamber, where the temperature and relative humidity were maintained at approximately 50 °C and below 5%, respectively. The decreasing MC of a representative specimen (No. 1 in Fig. 1) for MC measurement is depicted in Fig. 3. The MC of the initial green condition was 110.5% (No. 2 in Fig. 1) for the CLSM observation and 112.8% (No. 1 in Fig. 1) for the MC measurement. The MCs determined in the nine repeated experiments ranged from 105.1 to 128.8%.

The specimens were rapidly dried, after placement on the CLSM stage in the chamber. The drying time for the MC to fall below the FSP was between 45 and 60 min. It was assumed that some microcracks had appeared during this moisture condition. Further, two specimens were divided into three parts, heartwood, intermediate wood, and sapwood, at 49 and 75 min, respectively. The MCs of three parts at 49 min were 16.3, 21.9, and 41.7%, respectively, whereas those of the three parts at 75 min were 8.7, 10.5, and 18.0%, respectively. At the final drying condition, the MCs were 1.4% in both the CLSM (No. 2 in Fig. 1) and MC measurement (No. 1 in Fig. 1). The same drying tendency was exhibited by all the specimens.

Microcrack distribution on the top surface in the heartwood area.

The images of the top surfaces of specimens captured by a digital microscope in the heartwood area during drying are shown in Fig. 4. These images were captured every minute, when the specimens were dried. No microcracks could be distinguished on the specimen surface immediately after drying commenced (Fig. 4a). A microcrack first appeared in the latewood region adjacent to the ray parenchyma, after 12 min (Fig. 4b: white arrow) although the MC of the specimen for MC measurement (No. 2 in Fig. 1) was above 86.9% at 15 min, which is not only the MC of heartwood but that of the entire specimen including heartwood, intermediate wood, and sapwood. Further, several microcracks appeared and become wider and longer during the drying process (Fig. 4c: black arrows). The microcracks widened to a maximum

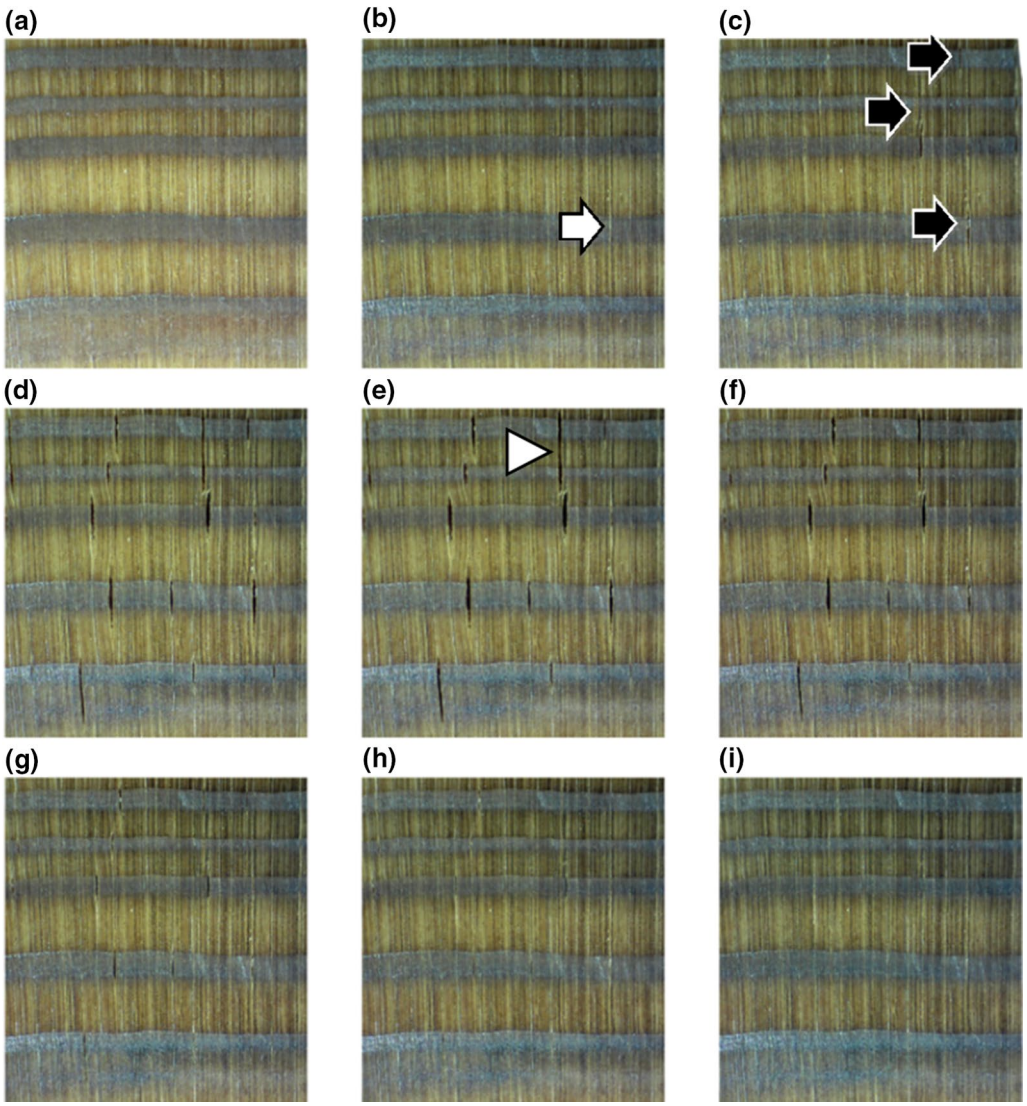

Fig. 4 Microcrack distributions on the surface of the heartwood area in the specimen. The images were captured with digital camera at **a** 3, **b** 12, **c** 20, **d** 33, **e** 40, **f** 49, **g** 60, **h** 75, and **i** 180 min. The white arrows indicate the initial microcrack occurrence, whereas the black ones indicate the wider and longer cracks and arrow heads indicate the cracks across the growth rings

between 33 (Fig. 4d) and 40 (Fig. 4e) min. Some microcracks developed to a maximum at 33 min (Fig. 4d), while the others were the largest at 40 min (Fig. 4e). The distribution and morphology of the microcracks indicate that they interact with the neighbouring ones. The MC of heartwood, in the presence of several microcracks (Fig. 4d), was assumed to be around the FSP, based on the MC of split heartwood at 49 min (Fig. 3); therefore, the MC of heartwood, when the first microcrack appeared, must have been above the FSP. This does not indicate the MC of the surface. The same tendency was observed in our previous research [14]. Microcracks appeared in the heartwood immediately after the specimen started to dry, even though the MC was above the FSP.

Figure 4e shows an interesting phenomenon, wherein microcracks emerged in the neighbouring growth rings connected by the same ray parenchyma (Fig. 4e: white arrow head). This phenomenon may have been observed because a larger specimen was used than those in previous studies [12–15], but it is also possible that this type of microcrack might develop into a harmful large crack, which is observable by the naked eye, although such cracks closed towards the end of the drying process, in this study.

Most microcracks closed after 75 min, when the MC in heartwood was below 10% (Fig. 4h), and the remaining microcracks also continued to close towards the end of the drying process (Fig. 4i). No microcracks were observable with the digital microscope.

CLSM observation of the microcrack occurrence from heartwood to sapwood

Compared to a digital microscope, the CLSM, which is equipped with an automatic stage, can acquire the sequential images from heartwood to sapwood. Using this, microcrack propagation on the bottom surface of the specimen was observed at high quality in a large region. It is also possible to control the image capture interval.

Figure 5 shows the CLSM images depicting microcrack appearances on the bottom surface of the same specimen shown in Figs. 3 and 4. The images were bundled using the continuous images from heartwood to sapwood, with image software. No microcracks were confirmed on the surfaces of all the specimens immediately after drying commenced, although these images could not be captured. When the first images were captured after 10 min, microcracks had already emerged in the heartwood region (Fig. 5a: square). However, there were no microcracks in the other regions. This microcrack occurrence tendency during the first stage of drying in heartwood as well as the results on the top surface of the specimen was the same as those in our previous study [14]. After this microcrack expanded with time, a second microcrack started to appear around intermediate wood after 31 min of drying (Fig. 5b: square). On the other hand, the first microcrack in sapwood appeared after 45 min of drying (Fig. 5c: square).

The time, when microcracks appeared in sapwood, is also similar to that in our previous research [12, 13]. However, the MC of sapwood, when the microcracks appeared, was considerably different. The MC at microcrack emergence in sapwood can be assumed to be above 41.7%, based on the results of the MC at 49 min of the split specimen (Fig. 3), compared to that around the FSP in our previous study. The reason could be that the area, where the microcrack occurred, adjacent to the intermediate wood in which the MC was low in the fresh condition, was more desiccated than the other areas of sapwood. The microcrack appearance time in the third growth ring in the middle of sapwood was 57 min (Fig. 5d square). It was assumed that the MC of this specimen was around the FSP, based on the results of 41.7% at 49 min and 18.0% at 75 min in Fig. 3. After 71 min, although the microcrack at the third growth ring (Fig. 5d: square) reached a maximum, the microcracks in heartwood and intermediate wood were closing or completely closed. All the microcracks continued to close; some closed completely, while the others remained at the end of the drying process (Fig. 5g).

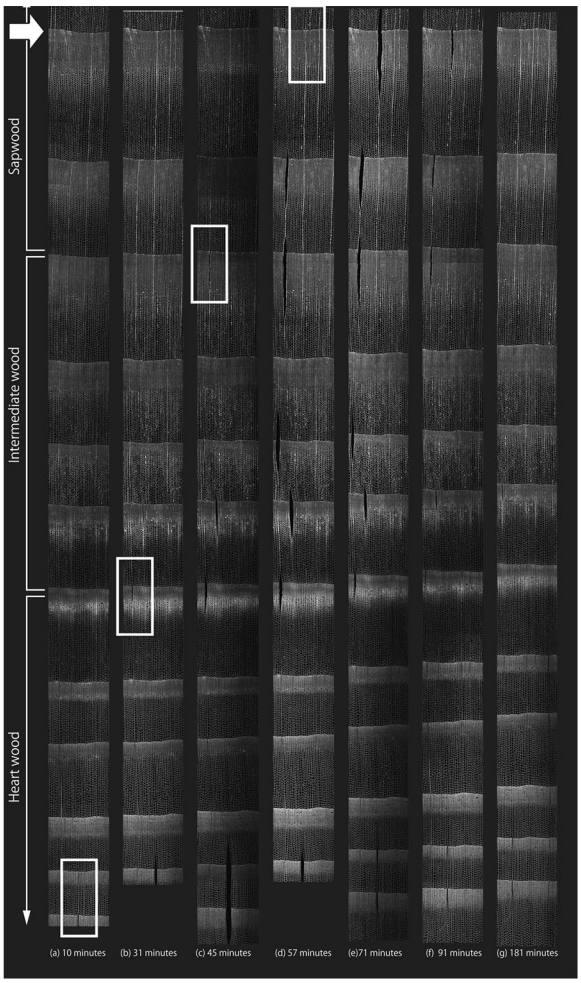

Fig. 5 CLSM images of the microcracks, from heartwood to sapwood, on the bottom surface of the specimen

Discussions

In our previous study, the occurrence of microcracks of *Cryptomeria japonica* heartwood, namely red heartwood, was investigated [14]. 15 mm (Tangential) × 15 mm (Radial) × 8 mm (Longitudinal) specimens were formed from heartwood. The results indicated that microcracks appeared in red heartwood with a low green MC between 35.2 and 70.2%, after 15 min of drying. In the same-sized sapwood, whose green MC ranged from 158.6 to 219.5%, microcracks appeared after 90 min [13]. On the other hand, the MCs of the heartwood and sapwood in this study, which included both heartwood and sapwood, were 58.7% and 168.8%, respectively. The moisture conditions as well as the time of microcrack occurrence were similar to those in our previous study.

Generally, the time difference in microcrack occurrence is related to the location on the surface of the specimen. If the MC on the outside of the specimen decreased prior to that inside, regardless of the type of wood (sapwood or heartwood), microcracks began to appear on the pith side as well as on the bark side in the radially long specimen, in this study. However, microcracks emerged faster in heartwood than in sapwood. The appearance of microcracks in sapwood (Fig. 5d: square) was considerably delayed than in heartwood (Fig. 5a: square), although both microcracks were almost the same distance from the pith and bark sides of the specimen (Fig. 6: white and black arrow heads). Similar time differences were derived not only from the results of other specimens with the CLSM, but also from the results of other specimens with the digital camera, although only the heartwood region was observed in this specimen. Therefore, it is unquestionable that microcracks generate in heartwood ahead. The influence of the location on the drying condition in a specimen appeared less compared to that of MC in heartwood and sapwood, in this study.

MC of the heartwood specimens when microcracks were appeared found to be above the FSP [14], which were measured from the weight of the oven-dried condition, although in sapwood specimens, microcracks generally appeared around the FSP [12, 13]. In this study, the same tendencies were confirmed from the estimated MC of the split heartwood specimens at green and 49 min (Fig. 3) measured based on the oven-dried weight though the MC at the point of the first microcrack occurrence (10 min) could not be measured. The emergence of microcracks in heartwood immediately after drying can be attributed to the lower water permeability because the MC of the surface appears to be below the FSP without water supply, even if it is above the FSP inside. On the other hand, the reason why microcracks in intermediate wood appeared between the time of occurrence in heartwood and sapwood is unclear with only discussion in comparison with heartwood and sapwood because we have never focused on intermediate wood.

Generally, intermediate wood located between heartwood and sapwood of *Cryptomeria japonica* is distinguished as white colour due to the difference of MC. The green MC of intermediate wood is lower than that of sapwood [16, 17], although that of heartwood is variable. The green MC of intermediate wood was 65.4%, in this specimen; however, microcrack appearance was delayed here (31–45 min), despite the early appearance at 10 min in heartwood with similar MC (58.7%). This phenomenon was assumed to occur due to liquid permeability as mentioned in introduction. The time difference in microcrack occurrence between heartwood and sapwood may be influenced by not only MC but also the water supply,

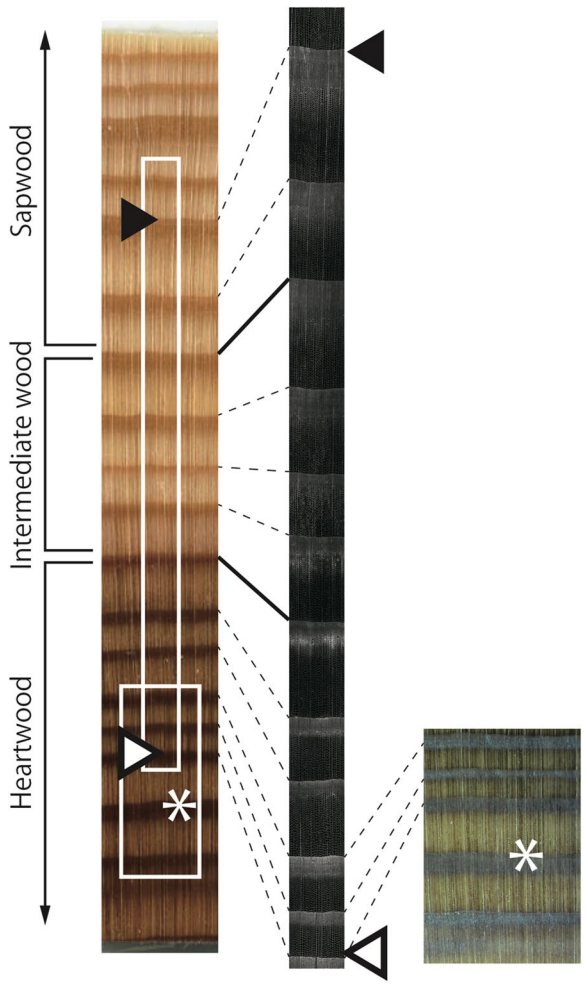

Fig. 6 Comparison of the locations, where microcracks appeared, using the CLSM and digital microscope. The image on the left shows the entire area of the specimen. The images in the middle and right are acquired from the bottom (CLSM) and top views (digital microscope) of the same specimen. The white and black arrow heads indicate the microcrack locations in heartwood and sapwood. The asterisk indicates their first appearance in heartwood

which appears to be the case in intermediate wood. If the water permeability in intermediate wood is higher than that in heartwood, microcracks would occur in intermediate wood after occurring in heartwood because water is supplied from within the specimen. According to the research on air permeability in intermediate wood of *Cryptomeria japonica*, remarkably higher results were derived [17], and there was a result that the air permeability in intermediate wood was higher than that in heartwood, though lower than that in sapwood [5]. On the other hand, the higher MC in sapwood can contribute to delayed microcrack occurrence, if the permeability of intermediate wood is the same as that of sapwood.

In this study, microcracks appeared in the order of location, from heartwood to sapwood through intermediate

wood. Moreover, significant information on the properties of wood for final use can be determined in the early stage of drying because microcracks appeared in heartwood, even though the MC was high. This indicates that the difference in MC was considerable within the wood, i.e. between the surface and interior in heartwood or between heartwood and sapwood. Therefore, the drying stress appears to concentrate on these microcracks, inducing large expanding cracks. The results of this study highlight the importance of basic research on the cracking mechanism during drying, considering both water permeability and MC for the respective wood.

Conclusion

In this study, the area on the specimen and the time difference in microcrack occurrence were focused upon, using radially long fresh specimens of *Cryptomeria japonica* containing both heartwood with low MC and sapwood with high MC, with a digital camera and the developed CLSM system. The results showed that microcracks appeared in the heartwood region, immediately after the commencement of drying. On the other hand, in the sapwood region, microcrack generation occurred only after microcracks appeared in intermediate wood, and the ones in heartwood started to close or were closed. Finally, most microcracks almost closed and some completely disappeared, towards the end of the drying process.

This result indicates that important information on the properties of wood for final use can be determined in the early stage of drying because microcracks appeared in heartwood, even though the MC was high. In addition, the results highlight the importance of basic research on the cracking mechanism during drying, considering both water permeability and MC for the respective wood.

Abbreviations

CLSM: confocal laser scanning microscope; FSP: fibre saturation point; MC: moisture content.

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Availability of data and materials

All data in this study are available from the corresponding author on reasonable request.

Competing interests

The author declares that I have no competing interests.

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