WAVEFORM FEATURES OF ACOUSTIC EMISSION PROVIDE INFORMATION ABOUT REVERSIBLE AND IRREVERSIBLE PROCESSES DURING SPRUCE SAPWOOD DRYING

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Acoustic emission (AE) and radial dimensional changes during dehydration under ambient conditions were compared between fully saturated fresh Norway spruce (*Picea abies* (L.) Karst.) sapwood and sapwood exposed to one or two rewetting-dehydration cycles. The aim of the study was to find out whether AE detected by wideband transducers (100 to 1000 kHz) gives useful information about the mechanical stresses generated during dehydration of small sapwood specimens. AE activity and peak amplitudes became lower after each dehydration-rewetting run. During the first dehydration run the highest peak amplitudes were detected at moderate moisture loss, whereas rewetted wood peaked towards the end of dehydration. AE of fresh, never-dried sapwood was also characterized by a higher count rate of low frequency AE (<175 kHz). Differences in amplitude and frequency clusters between small earlywood and latewood specimens suggest that earlywood is much more sensitive to irreversible processes upon drying than latewood, which might be related to pit functioning and shrinkage anisotropy. At moderate moisture loss, fresh, never-dried sapwood showed higher radial dimensional changes compared to re-wetted sapwood. If it is assumed that fresh, never-dried sapwood is more prone to dehydration stresses than pre-dried sapwood, critical stages during drying can be characterized by high mean peak amplitudes and by a higher count rate of low frequency AE.

Keywords: Acoustic emission testing; Average frequency; Peak amplitude; Norway spruce; Wood drying; Wood shrinkage

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INTRODUCTION

Acoustic emission (AE) testing on dehydrating wood has been used to control checking processes during lumber drying (Kawamoto and Williams 2002; Kowalski et al. 2004; Kowalski and Smoczkiewicz 2004; Beall et al. 2005; Jakiela et al. 2008), to learn more about wood shrinkage (Rosner et al. 2009, 2010), and to estimate a tree's susceptibility to drought stress (Rosner et al. 2006; Mayr and Rosner 2011). The recommended upper frequency level for AE testing on wood is 100 to 200 kHz, because material attenuation increases exponentially with frequency (Beall 2002). Therefore, resonant AE transducers within this frequency range are commonly used to monitor lumber checking induced by dehydration. Wideband transducers offer the opportunity to analyze the frequency characteristics of the acoustic signals emitted (Ogino et al. 1986;

Jakiela et al. 2008; Rosner and Kawamoto 2010). In this study, the information potential of AE detected by wideband transducers (100 to 1000 kHz) for monitoring mechanical stresses generated during dehydration was investigated in small sapwood specimens, where attenuation effects are negligible (Kawamoto and Williams 2002).

Drying checks develop because fiber saturation is reached far earlier in the shell than in the core of a specimen, and because wood is an anisotropic material with respect to cell wall shrinkage (Skaar 1988; Moon et al. 2010; Derome et al. 2011). Small fractures result in AE output that can serve as an early warning signal for larger fractures that would be considered as drying effects (Honeycutt et al. 1985). It is supposed that internal checking can be induced as well by the negative pressure of free water because it occurs long before most cells reach fiber saturation (Booker 1994b; Ball et al. 2005). Crack formation is indicated by high AE count rates (AE signals/time) and by AE with high amplitudes or energies (Quarles 1992; Niemz et al. 1994; Čunderlik et al. 1996; Beall et al. 2005). The bulk of AE during lumber drying, however, is induced by the breakage of the water columns inside the conduits due to high negative hydrostatic pressures (Kawamoto and Williams 2002; Tyree and Zimmermann 2002).

Recently, it was also shown that wood anatomy and pit aspiration influence AE feature characteristics of dehydrating spruce sapwood. AE cumulative counts increase linearly with the number of tracheids at a given wood volume (Rosner et al. 2006) and the mean AE energy, a waveform feature that is dependent on amplitude and signal duration, is positively correlated with the mean tracheid lumen area (Mayr and Rosner 2011). High AE count rates are measured at the onset of wood drying when a high percentage of free water is still present and at moisture contents around fiber saturation (Quarles 1992; Booker 1994b; Niemz et al. 1994; Čunderlik et al. 1996; Ball et al. 2005; Rosner et al. 2010). Fresh, never-dried conifer sapwood has a different shrinkage behavior and produces not only more AE, but also stronger AE than pre-dried sapwood, and therefore it should be more prone to dehydration stress (Rosner et al. 2010). There is, however, little knowledge about the changes in the frequency composition of the AE generated during a whole dehydration run because the use of resonant transducers is more common than the use of wideband transducers (Beall 2002).

The aim of this study was to investigate differences in radial dimensional changes and variations in the frequency composition of AE between fresh, never-dried, once pre-dried, and twice pre-dried Norway spruce sapwood beams. In a second step, AE characteristics of fresh and pre-dried specimen with defined wood anatomy (earlywood and latewood) were analyzed to get information about the dehydration stresses generated within annual rings.

EXPERIMENTAL

Specimen Preparation

Norway spruce (*Picea abies* (L.) Karst.) bole segments, 20 cm in length, were taken immediately after felling at 4 m height from ground and transported to the lab in plastic bags containing fresh water. Sapwood specimens with a transverse surface of 10 x 10 mm were isolated by splitting the wood along the grain. Tangential and radial faces of the beams were planed on a sliding microtome. The final shape of the small standard beams was 6 mm tangential, 6 mm radial, and 100 mm longitudinal, and contained 3 to 4 annual rings. During all preparation steps the specimens were kept wet. Specimens were then soaked in distilled water under partial vacuum for 24 h to refill empty conduits with free water and afterwards stored at 4°C in water containing 0.01 vol.% Micropur (Katadyn Products Inc., Switzerland) to prevent microbial growth. Wood splits (4.5 mm tangential, 0.7 mm radial, and 18 mm longitudinal) were produced from fresh earlywood and latewood (Fig. 1) and soaked as described above. Specimens were split along the grain and not cut, in order to avoid transverse severing of the tracheids.

Acoustic Emission Testing of Dehydrating Sapwood

Dehydration was achieved at ambient climatic conditions (25-27°C, 30% r.h.) to equilibrium moisture content of 8.5%. Each run took 24 h. AE was monitored with the AMSY-5 High-Speed AE system (Vallen Systeme GMbH, Munich, Germany). A preamplifier (40 dB) was used in combination with a WD wideband acoustic transducer operating in the frequency range between 100 and 1000 kHz (Physical Acoustics Corporation Princeton Jct, PA, USA). The WD transducer is a multi-resonant wideband transducer with three frequency peaks at 100 kHz, 275 kHz, and 550 kHz. Although it does not provide exactly the real frequency distribution of a given process, it allows a raw frequency clustering, as tested in experiments with defined driving pulse frequencies (Eaton et al. 2007). High-fidelity broad-band sensors with a flat response (i.e. McLaskey et al. 2007) may reproduce the original frequency distribution of a given process more accurately. However, the lower sensitivity is a serious limiting disadvantage for the given application in practice. AE was recorded with a detection threshold of 35 dB. The AE features assessed were the peak amplitude (dB) and the average frequency (kHz). One single AE signal is termed as an “AE count” within this study.

Transducers were positioned on the tangential wood surface of fully saturated, standard beams using the acrylic resin clamp assembly described in Rosner et al. (2010). Silicone paste (Wacker, Burghausen, Germany) was used as a coupling agent. The specimen was positioned on a sample holder fixed upon a compression spring, which minimized the decrease in contact pressure during dehydration (Rosner et al. 2009). Contact pressure was monitored by a load cell (DMS, Type 8416-5500, range 0 to 500 N; Burster, Gernsbach, Germany) positioned between the AE transducer and the screw of the acrylic resin clamp. The wet specimen was wrapped in Parafilm (American National Can, Greenwich, USA). A window of 2 cm length on one tangential cut face covered with silicone paste was left open in order to mount the AE transducer directly on the wood surface. Contact pressure between the transducer and specimen was set to 30 N (Beall 2002), and the clamp assembly was put on a balance (resolution 10^{-3} g, Sartorius, Göttingen, Germany). Recording of AE and coupling pressure was started after quickly removing the Parafilm cover and superficial water. Wood splits were mounted to the transducer without coupling media because the use of any coupling media would have influenced the re-saturation process of the small wood splits. After the first dehydration run, all specimens were re-soaked at 4°C in distilled water containing 0.01 vol. % Micropur under partial vacuum until they reached their former saturated weight, which was achieved after about 96 h. Thereafter, the second AE testing run took place. Before the third testing run was started, wood specimens were again re-soaked until their former saturated weight was reached. The dry weight was obtained by drying wood beams after the third AE testing run at 103°C to constant weight in order to calculate moisture content (MC) variations.

Analysis of contact pressure and AE data filtering was achieved with Vallen VisualAE™ software (Vallen Systeme GMbH, Munich, Germany). A cluster point set at 175 kHz led to the best results for visualizing the average frequency differences between fresh and pre-died sapwood or between earlywood and latewood. In order to compare AE results of wood beams and wood splits, data were analyzed in steps of 10% AE cumulative counts (CAE). For each treatment, mean values were calculated from four sapwood beams, earlywood, and latewood split specimen, respectively. Statistical analysis was carried out with SPSS® 15.0. Values are given as mean ± standard error (SE). Differences between mean values were accepted as significant if P was < 0.05.

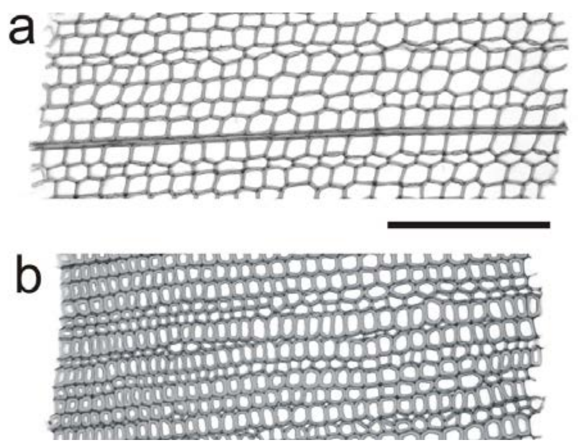

Fig. 1. Transverse sections (25 µm) of an earlywood split specimen (a) and of a latewood split specimen (b). Methodological details can be found in Mayr and Rosner (2011). The reference bar represents 250 µm.

RESULTS AND DISCUSSION

Fresh, never-dried spruce sapwood beams were more prone to dehydration stress than once or twice pre-dried sapwood beams; they showed higher dimensional changes at moderate moisture loss (Fig. 2a), a higher total number of AE (Fig. 2b) with a distinct AE count rate peak at 140% MC (Fig. 2c), and significantly higher amplitudes at 20 to 150% MC (Fig. 2d). AE count rate of pre-dried wood was very low until 60% MC, and a peak at moderate moisture loss was missing (Fig. 2c). Highest amplitudes in fresh wood beams were found when only 20% of total AE was produced (Fig. 3a). Once pre-dried wood beams reached highest amplitudes at 80% CAE, whereas twice pre-dried at 90% CAE. A remarkable change was observed in the frequency composition; the AE count rate <175kHz of fresh sapwood beams was much higher than that of once or twice pre-dried sapwood, whereas the AE count rate >175 kHz was not much influenced by pre-drying

(Figs. 3a-c). Below 40% MC, twice pre-dried sapwood showed even a higher rate of AE >175 kHz than of AE <175 kHz (Fig. 4c).

Crack formation due to dehydration is indicated by AE bursts with high count rates (Quarles 1992; Niemz et al. 1994; Čunderlik et al. 1996; Lee et al. 1996; Beall et al. 2005), which are measured at the beginning of drying, in the warming phase induced by tension at the surface due to earlier onset of shrinkage, and below fiber saturation (Niemz et al. 1994). High amplitude (Quarles 1992, Beall 2002; Kawamoto and Williams 2002; Beall et al. 2005), low duration (Beall 2002; Jakiela et al. 2008), and low frequency AE (Ogino et al. 1986; Kawamoto and Williams 2002) have been used as an indication of fiber fracture and matrix cracking. During the constant drying rate period of Japanese larch heartwood, most of the frequency spectra of AE events contain high frequency components >300kHz, while the AE events with low frequency components occur frequently near the critical moisture content. High frequency components are attributed to non-destructive capillary action of free water, whereas low frequency components have been identified with crack formation (Ogino et al. 1986).

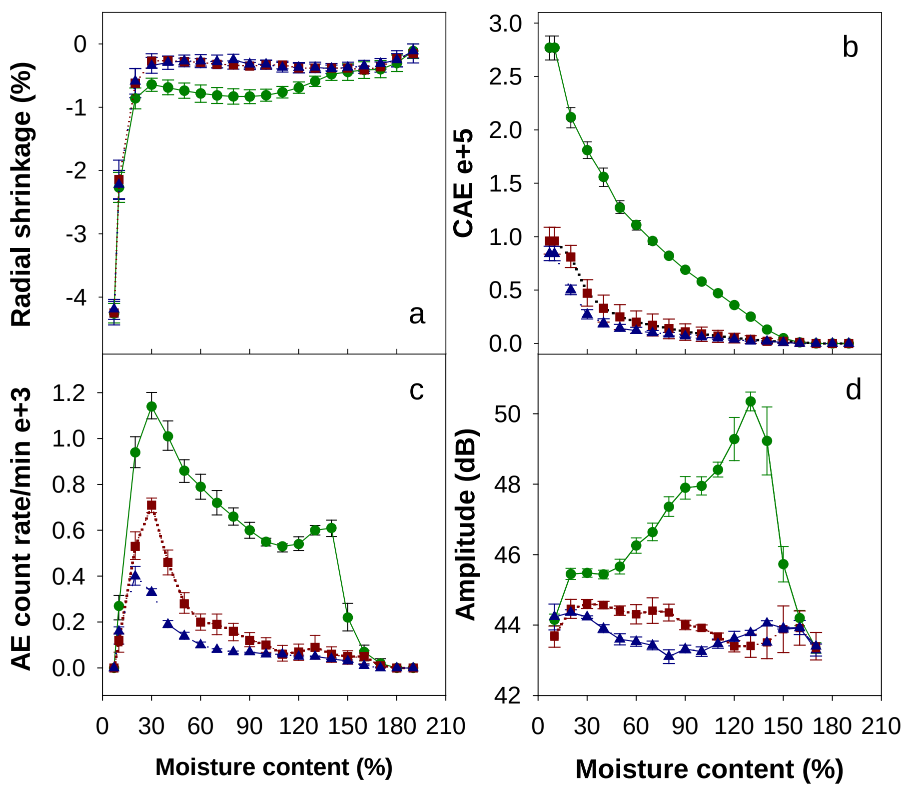

Fig. 2. Radial shrinkage (a), AE cumulative counts (b), AE count rate/min (c), and peak amplitude (d) at different moisture content steps from full saturation till the equilibrium moisture content. Circles and lines represent fresh sapwood specimen, squares and dotted lines once pre-dried specimens and triangles and dashed lines twice pre-dried specimen.

AE associated with drying includes both emission generated by checking and water movement, where the bulk of AE is induced by capillary action (Kawamoto and Williams 2002; Tyree and Zimmermann 2002). In tracheids still containing free water, negative pressures develop that act perpendicular to the cell walls and try to draw the walls inwards (Tyree and Zimmermann 2002). This phenomenon can be observed in stems of living trees as reversible diurnal diameter changes (i.e. Neher 1993; Offenthaler et al. 2001), and such effects are observed in sapwood only (Irvine and Grace 1997).

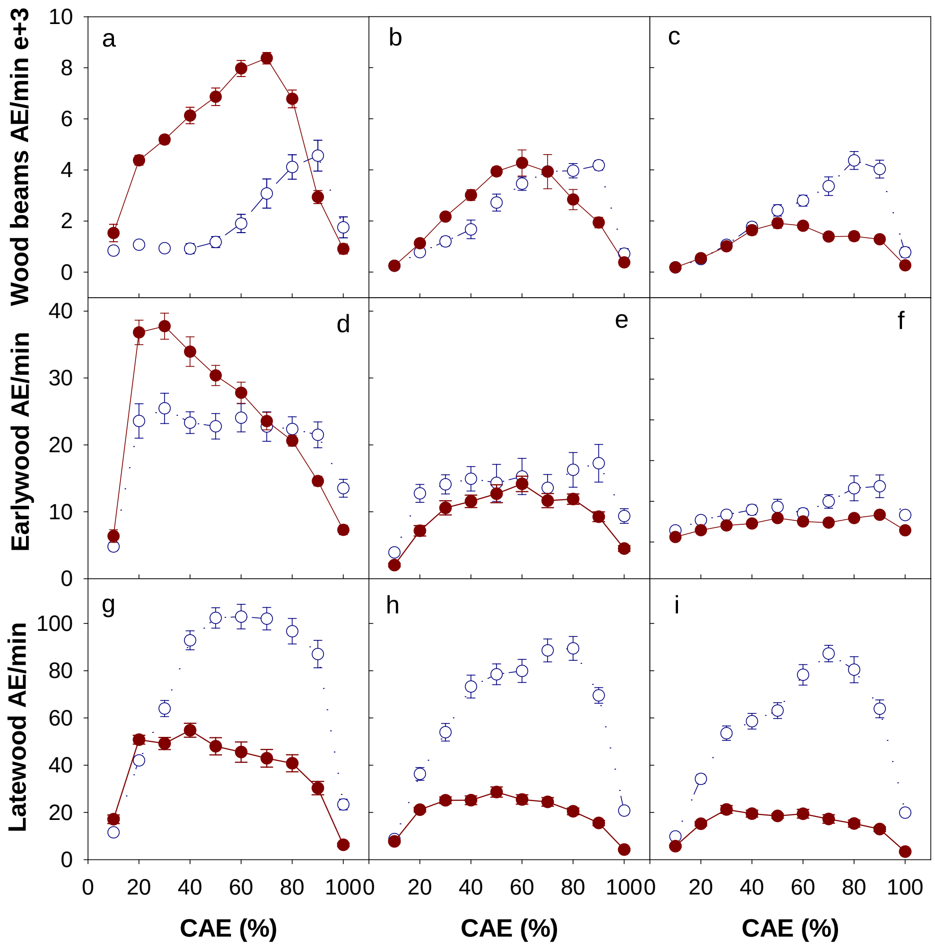

Fig. 3. AE count rates of fresh (a), once pre-dried (b), and twice pre-dried (c) sapwood beams; of fresh (d), once pre-dried (e), and twice pre-dried (f) earlywood splits; and of fresh (g), once pre-dried (h), and twice pre-dried (i) latewood splits at different steps of AE cumulative counts (CAE). Filled symbols represent AE <175 kHz, empty symbols AE >175 kHz.

When the negative pressure becomes too high, the water column will break, leading to a sudden stress release, which causes the bulk of AE during lumber drying (Kawamoto and Williams 2002; Tyree and Zimmermann 2002). Capillary action of free water can even lead to cell wall collapse during lumber drying (i.e. Booker 1994a; Booker 1994b; Innes 1995; Putoczki et al. 2007; Blakemore and Langrish 2008). The most likely reason for the differences in the shrinkage behavior of fresh and pre-dried wood (Fig. 1a) is the capillary action of free water associated with pit functioning (Rosner et al. 2010). AE count rate, amplitude distribution, and frequency composition of fresh wood beams suggest that a critical stage of drying is not only around 30% but also at 130 to 140% moisture content (Figs. 2c-d, Figs. 4a-c). Moisture contents above 130%

are reached by wet storage of wood (i.e. after wind-blow events) and might cause severe problems during the kiln drying process. Pre-dried wood was less prone to dehydration stress; there was not much difference in AE counts between the second and the third dehydration run (Kuroiwa et al. 1996), even when the cell lumens were filled with free water at the beginning (Fig. 2b). Why did dehydration stress become lower after the first dehydration run and what was the role of earlywood and latewood?

AE counts (n e+3) of fresh earlywood splits (2.7 ± 0.1) were significantly higher than of once (1.6 ± 0.3) and twice (0.8 ± 0.1) pre-dried earlywood splits. AE counts (n e+3) of fresh (11.0 ± 1.1), once pre-dried (8.5 ± 1.7) and twice pre-dried (8.0 ± 1.5) latewood splits showed, however, no significant differences. Structural characteristics influencing the behavior under drought stress are wood density, pit frequency, and anatomy of the bordered pits. Latewood emitted much more AE at a given volume, because the tracheid number is higher than in earlywood. The count rate of signals <175 kHz became lower after each drying-rewetting cycle in earlywood (Fig. 3d-f), as well as in latewood (Fig. 3g-i), but it was more pronounced in earlywood. In fresh and pre-dried latewood, the AE count rate >175 kHz was generally higher and, except at the onset of dehydration, frequency rate clusters showed a quite similar behavior.

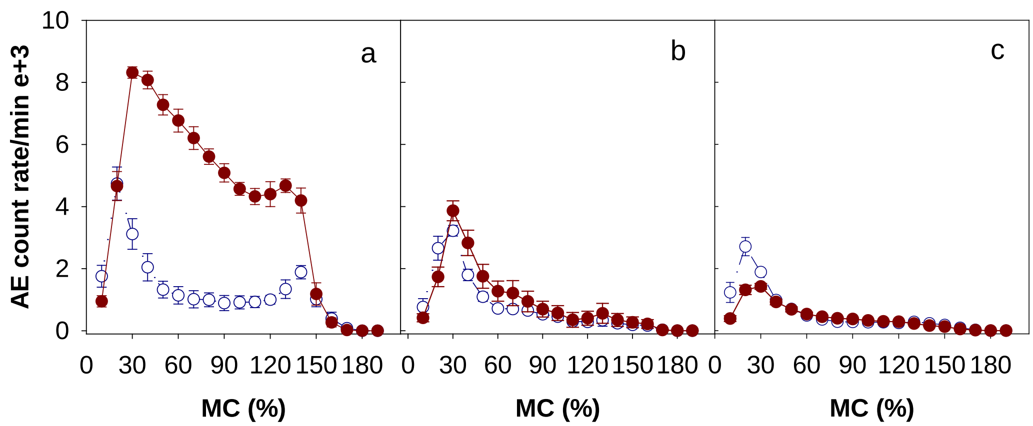

Fig. 4. AE count rate of signals <175 kHz (filled symbols) and of signals >175 kHz (open symbols) from fresh never-dried (a), once pre-dried (b) and twice pre-dried (c) sapwood beams at different moisture content (MC) steps

These results suggest that latewood was less prone to dehydration stress than earlywood. At moderate moisture loss (well above fiber saturation), pit functioning may explain the differences in stress response of earlywood and latewood. Pit frequency is much higher in Norway spruce earlywood (Rosner et al. 2007), and differences exist in the pit functioning (Domec and Gartner 2002; Rosner et al. 2010). The pit membrane of latewood pits is too rigid to result in aspiration upon dehydration. Latewood pits thus merely remain open after a dehydration cycle. Bordered pits of fresh earlywood become aspirated under the influence of the species-specific negative pressure in order to prevent the water columns from breakage. When the stresses become too high, the pit membranes can be ruptured (Domec at al. 2006), which may be an AE source in fresh wood but not in pre-dried earlywood. Repeated influence of drought stress also weakens the pit membranes (Hacke et al. 2001); consequently, the water columns inside the tracheids break earlier (at less negative pressures) in re-filled than in fresh earlywood (Rosner et al. 2010). Small air bubbles might also be trapped in the conduits after re-hydration that could induce the breakage of the water columns at lower dehydration stress (Hacke et al. 2001). In a pre-dried specimen, deformation induced by capillary action will thus not reach the value that is possible in fresh wood with intact pit membranes; therefore, dehydration stress becomes lower after the first dehydration run (Rosner et al. 2010).

Below fiber saturation, AE peak amplitude and frequency characteristics reflected differences in cell wall shrinkage of earlywood and latewood. Due to its higher density (Fig. 1), conifer latewood is more prone to cell wall shrinkage than earlywood (Stamm 1971; Skaar 1988; Pang and Herritsch 2005; Perrè and Huber 2007; Derome et al. 2011). However, conifer latewood shows minimal shrinkage anisotropy in the tangential-radial plane, whereas in conifer earlywood tangential shrinkage is more than twice the average radial shrinkage (Moon et al. 2010). During the first dehydration run, shrinkage anisotropy may lead to more microfractures in earlywood than in latewood, which might explain the enormous differences in total AE between the first and the following dehydration experiments in sapwood beams (Fig. 2a) and earlywood splits. Total AE counts of latewood did not decrease significantly after the first dehydration run as in earlywood, which suggests that irreversible processes, such as microcracking, occurred during the first run in earlywood. AE is hypothesized to be generated by intermittent slips in the crystalline regions of the cellulose microfibrils comprising the tracheid cell walls (Booker 1994a). However, AE ceased when only half of the total shrinkage was reached (Fig. 2), suggesting that neither the longitudinal shrinkage of the noncrystalline region of the cellulose microfibrils, nor the lateral expansion and longitudinal shrinkage of the cellu-lose microfibrils upon drying (Abe and Yamamoto 2005; Zabler et al. 2010), caused any AE during the last stages of drying. Nevertheless, changes in molecular packing of the cellulose crystallites, which are only partly reversible (Hill et al. 2010), might have influenced the attenuation properties of the sapwood.

CONCLUSIONS

1. AE count rates clustered by average frequencies could be successfully used to discriminate between reversible and irreversible processes occurring during lumber drying. The results obtained by means of WD sensors (PAC) suggest that irreversible processes are characterized by a higher count rate of AE <175 kHz.
2. Maximum AE count rate and high amplitude AE detected by resonant transducers with the upper frequency range of 100 to 200 kHz have been promising candidates to detect stress levels prior to lumber checking (Lee et al. 1996; Beall 2002; Beall et al. 2005). The multi-resonant wideband WD sensor (frequency range 100-1000 kHz) is less sensitive to background noise compared to resonant transducers operating in the upper ultrasonic frequency range and allows as well a frequency clustering of the AE count rate.
3. Similar experiments followed by localization of drying checks should be performed on larger wood specimen in order to test the reliability of the AE frequency clustering method to predict critical stages during lumber drying processes.

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