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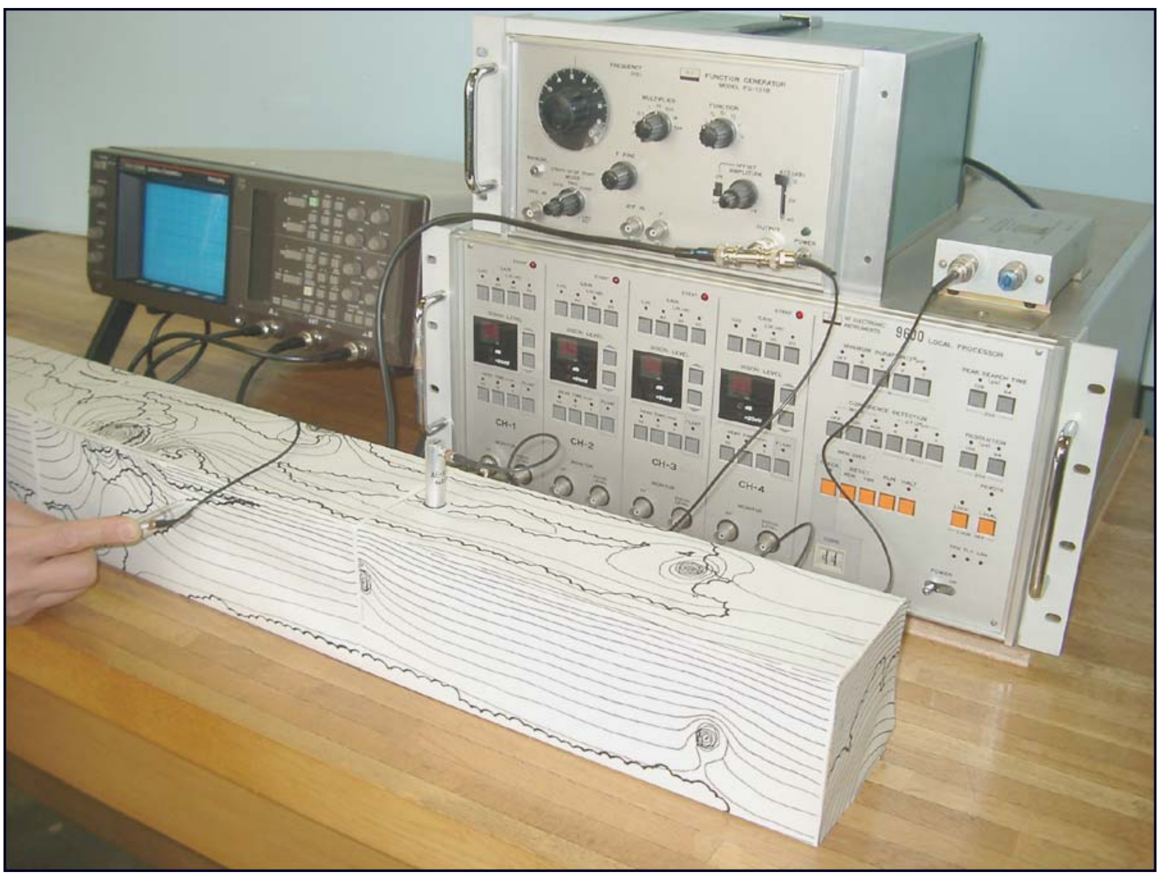
Acoustic Emission and Acousto-Ultrasonic Techniques for Wood and Wood-Based Composites

A Review

Sumire Kawamoto
R. Sam Williams



Abstract

This review focuses on the feasibility of acoustic emission (AE) and acousto-ultrasonic (AU) techniques for monitoring defects in wood, particularly during drying. The advantages and disadvantages of AE and AU techniques are described. Particular emphasis is placed on the propagation and attenuation of ultrasonic waves in wood and the associated measurement problems. The review is divided into two sections, acoustic emission techniques and acousto-ultrasonic techniques. It includes historical background on the techniques as well as applications for wood and wood products. Because much research on nondestructive tests for wood has been published only in Japanese, considerable attention is given to those publications.

Keywords: acoustic emission, acousto-ultrasonic, wood, wood composites, wood drying

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Acoustic Emission and Acousto-Ultrasonic Techniques for Wood and Wood-Based Composites—A Review

Sumire Kawamoto, Senior Researcher
Forestry and Forest Products Research Institute, Ibaraki, Japan[1]

R. Sam Williams, Supervisory Research Chemist
Forest Products Laboratory, Madison, Wisconsin

Introduction

Nondestructive testing (NDT) is defined as the technical method to examine materials or components in ways that do not impair future usefulness and serviceability. NDT can be used to detect, locate, measure, and evaluate flaws; to assess integrity, properties, and composition; and to measure geometric characteristics (ASTM E1316). Various NDT technologies, such as ultrasonic-based methods, radiographic methods, dynamic methods, acoustic emission (AE) techniques, and acousto-ultrasonic (AU) techniques have been studied. Each NDT technique has both advantages and disadvantages with regard to cost, speed, accuracy, and safety.

NDT research on wood and wood materials was spurred in the United States by a symposium in Pullman, Washington, in 1980 organized by Roy F. Pellerin (Washington State University) and Kent McDonald (USDA Forest Service, Forest Products Laboratory). NDT research includes measurements of physical and mechanical properties, grading of materials, and monitoring of defects in trees, logs, solid wood, sawn timber and lumber, engineered wood, and composite products.

This review focuses on the feasibility of the AE and AU techniques for monitoring defects in wood, particularly during drying. It also describes the advantages and disadvantages of these techniques. Compared with applications of conventional NDT methods, AE/AU applications for wood processing are relatively new and still being improved. This review places particular emphasis on the propagation and attenuation of ultrasonic waves in wood and associated measurement problems. Because much research on NDT for wood has been published only in Japanese, considerable attention is given to these publications. A Web site maintained by Frank Beall of the University of California includes recent AE and AU research and detailed reviews published in English (www.ucfpl.ucop.edu/WDNDE.htm).

The properties of wood, unlike those of other materials, vary with respect to species, growth rate, grain angle, and other factors. No other material shows as much anisotropy as does wood. As a consequence, individual specimens, even those cut from the same board, often have different properties. In addition, AE/AU responses are more variable in wood than in other materials and problems occur with signal processing. Accordingly, NDT applied to materials other than wood should not be directly transferred to wood.

Although some investigations describe AE/AU techniques as useful in detecting flaws in metals, polymers, and ceramics, these techniques have had only limited success in wood. More fundamental research is required to identify wood properties that affect wave propagation and attenuation, such as density, defects, and moisture content.

The review is divided into two sections, Acoustic Emission Techniques and Acousto-Ultrasonic Techniques. It includes historical background on these techniques as well as their application to wood and wood products. Primary emphasis is given to their application to wood drying. For NDT techniques other than AE/AU, such as dynamic stress wave techniques and radiographic methods, refer to Ross (1994).

Acoustic Emission Techniques

General Concepts

Acoustic emission is a phenomenon frequently encountered in everyday life. An example of acoustic emission is the sound of a pencil being broken or wood being split. Technically, acoustic emission (AE) is defined as the class of phenomena in which transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material (ASTM E1316). The term also applies to the transient elastic waves so generated.

[1] P.O. Box 16, Tsukuba Norin, Kenkyu Danchi–Nai, Ibaraki 305–8687

Acoustic emission occurs in a range of intensities with different phenomena. "Tin cry," which occurs when tin is under tension or bending, is a typical example of AE on a small scale (Miller 1936). An earthquake is an example of AE on a large scale (Katsuyama 1994). The mechanism of AE generation is the same, whether it is a microcrack in a material or an earthquake. It is a release of elastic energy into AE waves by the formation of a crack in a solid.

The amount of AE wave attenuation depends on the properties of the material. Attenuation is greater in porous materials (such as wood) and viscoelastic materials than in metallic materials.

Acoustic emission is used to nondestructively monitor structural integrity and characterize the behavior of materials when they undergo deformation, fracture, or both. Unlike ultrasonic or radiographic techniques, AE does not require external energy; acoustic emission is released from the test object itself. AE is the only NDT method that can be used to monitor defects during manufacturing. Other conventional NDT methods require that the line be interrupted to test the materials. Acoustic emission techniques have been used for monitoring components and systems during manufacturing, detecting and locating leaks, mechanical property testing, and testing pressurized vessels (ASTM, current edition).

Advantages and Disadvantages

The advantages of AE techniques are as follows:

1. The position of developing cracks can be determined. The AE source can be determined from the time differential of AE signals among several AE transducers.
2. The classification and direction of cracks can be calculated by AE waveform analysis using moment tensor components.
3. The dynamics of the materials can be observed in real time.

The disadvantages of this method are as follows:

1. It is difficult to discriminate real AE signals from background noise during measurement.
2. For some materials, the generation of AEs does not occur until the material is loaded close to the proportional limit of the deformation.
3. The output signal of the AE transducer is the combination of the AE source wave, propagation, and transducer response. For wood or wood-based materials, unlike metal materials, small AEs generated from wood cannot be detected as AE signals because of considerable attenuation of AE waves during propagation, unless appropriate transducers are used.
4. For wood, the wave velocities are 4 to 5 km/s for longitudinal, 1.5 to 2 km/s for radial, and 1 to 1.5 km/s for tangential directions. Consequently, conventional AE source location techniques, which assume isotropic velocity, cannot easily be used for wood. Thus, AE source location, the most identifiable and beneficial factor of the AE technique for homogenous materials, is difficult to use on wood.

Terminology

Terminology is based on that outlined in ASTM E1316 (ASTM, current edition).

AE—The class of phenomena whereby transient elastic waves are generated by rapid release of energy from localized sources within a material, or the transient waves so generated. Other terms used in AE literature include (1) stress wave emission, (2) microseismic activity, and (3) emission or AE with other qualifying modifiers.

AE amplitude—Peak amplitude of AE signal during signal duration.

AE count—Number of times AE signal exceeds preset threshold level during any selected portion of a test. Count is affected by dead time. Ringdown counting is used for continuous emission, and event counting is used for burst emission.

AE event—Local material change that gives rise to an acoustic emission.

AE rms—Rectified time-averaged AE signal, measured on linear scale and reported in volts (root mean square (RMS) voltage).

AE signal—Electrical signal obtained by detection of one or more acoustic emission events.

AE signal duration—Time between AE signal start and AE signal end. AE signal start is the beginning of an AE signal recognized by the system processor, and AE signal end is the last signal crossing the threshold above the threshold.

AE signal rise time—Time between AE signal start and peak amplitude of that AE signal.

Dead time—Any interval during data acquisition when the instrument or system is unable to accept new data for any reason.

Emission, burst—Individual emission event generated in brittle materials such as wood, concrete, and rock.

Emission, continuous—Repeated emission commonly observed in metal. If the duration of each event is too short to identify, the event is recognized as a continuous emission.

Event count—AE counting method that counts each event.

Ringdown count—Number of pulses that exceed threshold level within signal duration.

Source location—Includes zone location, computed location, and continuous location. Zone location determines the general region of an AE source. Computed location is based on algorithmic analysis of difference in arrival times among sensors. Continuous location is based on continuous AE signals, as opposed to hit or difference in arrival time location method. It is commonly used in leak location of pressurized materials because of the presence of continuous emissions.

Threshold, voltage—Voltage level on an electronic comparator such that signals with amplitudes larger than this level will be recognized. The voltage threshold may be user adjustable, fixed, or automatic floating (ASTM E750).

Measurement

AE Wave and Signal Wave

An AE wave is an elastic wave, having a wide frequency range (kHz to MHz), generated by the release of energy by the formation of a microcrack. An AE signal wave is the output signal of the AE equipment after the AE wave has been electrically processed. The term AE wave is sometimes used as an abbreviation for AE signal wave. The frequency spectrum of the AE signal wave is affected by the properties of the transducer, materials, and wave path. The AE signal waveform is usually the overlap of longitudinal, transverse, Rayleigh, and reflected waves. The AE signal waveform is affected by specimen dimension; when the specimen thickness is smaller than the wavelength, the maximum amplitude is determined by Lamb waves instead of surface waves.

AE Transducer

The most important factor of an AE measurement is the selection of the appropriate AE transducer, depending on the purpose of the measurement. The transducer must have proper compression. It is also important to use the appropriate couplant to minimize energy transfer loss from the surface of the material. Couplant is defined as a material used at the substrate-to-sensor interface to improve the transmission of acoustic energy across the interface during AE monitoring (ASTM E1316). When surface mounting is difficult, wave guides can be used. These are solid wires or rods that link the surface being measured to a transducer. Acoustic emission transducers are generally piezoelectric (PZT) devices that transform motion produced by an elastic wave into an electrical signal (ASTM E1316). The dimension of the PZT element affects the frequency response of the transducer. The sensitivity of an AE transducer having a resonant frequency is generally higher than that of a nonresonant type. X-cut PZTs, used for most AE measurements, have the highest sensitivity in the Y-axis of the transducer. Periodic sensitivity checks of transducers are required (ASTM E1106 and E 1781).

To select the proper AE transducer, the sensitivity and frequency response should be taken into consideration. For a material with high attenuation, low resonant AE transducers should be used. For AE wave analysis, flat nonresonant transducers should be used. The velocity of most longitudinal AE waves is more than 4 km/s. Since wavelength is determined from the velocity divided by frequency, a higher frequency transducer gives better results for thin, small specimens. However, in materials having high wave attenuation, it is important to use the appropriate low resonant transducer.

Signal Processing

Signal processing requires several AE electronic components, including transducers, preamplifiers, filters, amplifiers, cables, and threshold and counting instrumentation (ASTM E750). Wave guides may be used in high temperature environments to get the AE wave to the transducer; however, the preamplifier should be as close as possible to the transducer. The frequency spectrum of the AE signal is the most practical way to determine the filter and amplifier selection. The level and quality of background noise determine the available amplifier/threshold and the lower frequency limit. The upper frequency limit is governed by wave attenuation. It is desirable to confirm the limitations of instrumentation for detecting AE in advance.

Until recently, AE instruments were limited by data storage capability and processing speed. Recent developments in computer technology have greatly decreased these limitations.

Data Interpretation for Wood

The distance between the AE source and the transducers affects the results, particularly for materials like wood. Before AE parameters are interpreted, the effects of transducers, system sensitivity, background noise, and material properties should be taken into consideration. Even though special precautions for isolating AEs from background noise are taken, the distinction of AEs from noise limits the interpretation. Monitoring the waveform, in addition to counting the signals, helps to distinguish AE from noise.

In wood, attenuation and wave velocity are different for longitudinal, radial, and tangential directions. Radial and tangential attenuation is larger than longitudinal attenuation. Individual specimens have distinct values. As for AE source location in wood and wood-based materials, the area where one transducer can distinguish the signals from the background noise should be taken into the consideration. Location software programmed for homogeneous materials should not be directly applied to solid wood, unless problems associated with anisotropic attenuation and heterogeneity can be solved.

Research Review

Historical Overview

Drouillard (1990, 1996) reviewed the development of AE technology from the time AE waves were first detected in rock, wood, and metal in the 1930s. The reviews describe AE research applied to mine timbers and research by Kishinoue using wood (Kishinoue 1934, 1990). Drouillard suggests that Kishinoue was the first person to record AE signals. In a Japanese article in 1934, Kishinoue described an experimental method to detect elastic shocks (AEs) during bending of quartersawn boards of Japanese cedar, pine, and cypress. He transferred the vibrations (AEs) associated with the fracture of a board into an electric gramophone through a needle on the board. Signals were recorded on cinematographic film. The instrument was developed by Haeno (1930).

In contrast to Drouillard, Isono (1984) reported that Förster of Germany was the first person to detect and investigate AE. Förster detected a small sound during growth of plants using amplification and recording instrumentation (Reich and Förster 1932). In the mid-1930s, he developed the system that had theoretically the same processing method as the currently used AE system, then carried out the acoustic analysis of the formation of martensite needles (Föster 1936). Much of Förster's work, which was related to the martensitic transformation of Ni-Steel, was presented in Drouillard's overview (1996).

Large-scale AEs from fracture in mines have been identified as the rumbling sound that occurs before an actual cave-in. Katsuyama (1994) described the experience of a miner in Japan in 1927, who escaped from a mine disaster after hearing rumbling prior to the cave-in. The AE technique for monitoring the stability of rock masses in mines was initiated in the 1940s by Obert (1941, 1942) and Mason and others (1948). Obert performed investigations in mines to determine if rock bursts could be predicted. Using a microphone and amplification, he detected subaudible noises of stressed rock as microseismic signals for predicting the rock movement preceding failure. Mogi (1962) studied AE generation in rock in relation to earthquakes.

The best known example of AE techniques is the "Kaiser effect" for metal (Kaiser 1953). When materials are subjected to cyclic loads with increasing stress, AE is not detectable until the previously applied stress level is exceeded (ASTM E1316). For composite materials, there is a similar phenomenon, the Felicity ratio, that is used to estimate the degree of deterioration during loading (Fowler 1986). Deterioration is determined as the ratio of loads P/P_1 where P_1 is the load where AE generation started during the first cycle and P the load where AE generation started during the second cycle.

After Kaiser's work, AE research progressed in the United States. Schofield (1958) first used the term acoustic emission, instead of previously used terms like stress wave emission, microseismic activity, and noise. He established the basic mechanism of AE under applied stress. In the 1960s, Green pioneered pressure vessel testing; this AE technique was used for rocket inspection in the United States (Green 1985). This established AE as a promising nondestructive testing method. Dunegan and others (1964) used AE equipment to detect defects in metallic vessels.

In the 1980s, Ohtsu applied the theory of source identification for earthquakes to AE waveform analysis, using seismic theory to characterize crack source kinematics to concrete. He proposed AE waveform analysis based on moment tensor analysis to identify crack type and crack orientation in concrete (Ohtsu and Ono 1984, Ohtsu 1988a). Neural network, the application of fuzzy theory to computer technology, was used to identify the signal start of longitudinal waves (Inaba 1994, Tiitta and others 2001).

The Acoustic Emission Working Group (AEWG) organized in 1967 has contributed to the development and distribution of AE technology throughout the world by organizing international symposia and participating in standardization activities. A detailed description of AEWG activity is presented by Drouillard (1996). In addition to standards issued by the American Society for Testing and Materials (ASTM), AE standards are issued by the American Society for Nondestructive Testing (ASNT), American Society of Mechanical Engineers (ASME), European Working Group on Acoustic Emission (EWGAE), Japanese Society for Nondestructive Inspection (NDIS), and, recently, the International Organization for Standardization (ISO) committee.

Publications are available in Japan on the fundamentals of AE in fields other than wood (Katsuyama 1994, Ogami and others 1979, Ohtsu 1988b). Ohtsu described AE analysis for application to concrete materials, and Katsuyama edited a book on *in situ* application of AE in metal, rock, concrete, and on-line monitoring of materials processing. Beattie (1983) described principles and instrumentation of AE. Kishi (1980a,b) reviewed studies on the strength evaluation of materials. Characteristics of AE during water transport in trees or plants have been investigated (Haack and Blank 1990, Sato and others 1996).

Research on Wood

The AE investigations for wood products can be classified into five fields: monitoring and control during drying, prediction of deterioration, estimation of strength properties, fracture analysis, and machining control. This section focuses on drying; the other areas are briefly described. More complete reviews of the literature on the use of AE method for wood and wood-based materials have been published (Beall 1990; Bucur 1995; Drouillard and Beall 1990; Fujii 1997; Noguchi 1985, 1991).

Drying of Wood

The use of AE techniques to minimize defects during wood drying has been studied since the 1980s. In early studies, methods were investigated for controlling kiln conditions by monitoring the AE count rate. The AE parameters used in the majority of studies were time-domain AE counts. The potential for using AE methods for controlling kilns was investigated by Honeycutt and others (1985), Kagawa and others (1980), Noguchi and others (1980), and Skaar and others (1980). Noguchi and others (1987) devised a feed-back kiln controlling system for drying discs based on moni-toring the AE count rate. Ogino and others (1986) used the cumulative AE energy determined by peak amplitude to predict checking in square cross-sections. Breeze and others (1995) reported that AE and steaming treatments could decrease checking during kiln drying without prolonged kiln residence time. Niemz and others (1994) compared signals detected by AE transducers to other piezoelectric transducers and indicated that AE transducers could be used to control wood drying.

Since 1985, the mechanism of AE associated with checking has been studied by various methods. Noguchi and others (1985) classified AE waveforms and spectra into four pat-terns. They observed differences in AE behavior between hardwood and softwood lumber and showed that a change of wood surface moisture content caused a quick AE response. Sadanari and Kitayama (1989) also classified AE signals into four similar patterns and reported that low frequency and high amplitude AEs could be used as an indication of the formation of checks. Quarles (1992) analyzed wave patterns and reported that the active propagation of surface checks was consistently associated with the occurrence of an increased number of high-amplitude events and that a sur-face-mounted transducer did not detect AEs associated with internal checking. The pattern of AE waves was associated with the formation of checks at the ends of specimens; low frequency and high amplitude AE waves were useful for monitoring drying.

Wave pattern recognition analysis was used to characterize AE signals associated with wood fracture; the signals could be used as parameters for monitoring wood drying (Lee and others 1996, Schniewind and others 1996). These research-ers concluded that pattern recognition cluster analysis could be successfully used to classify AE signals from wood. However, Lee and others (1996) reported that pattern recog-nition analysis was limited in application for monitoring and controlling kilns. Čunderlik and others (1996) performed a comparative investigation in beech tension and opposite wood microstructure during the drying process. Based on observations using scanning electron microscopy (SEM), these researchers reported that opposite wood generated several times more AEs than did tension wood and that AE activity correlated to stress in opposite wood.

Acoustic emissions associated with early stress release dur-ing drying were investigated. Booker (1994a) measured AE associated with surface checking of eucalyptus boards and hypothesized that AE was generated by intermittent slip in the crystalline regions of cellulose microfibrils in the cell walls. He reported that AE activity increased when surface elastic strain approached the proportional limit. Furthermore, the AE phenomenon was related to complex interactions between surface instantaneous strain and humidity/temper-ature change (Booker 1994b). Booker investigated the rela-tionship between strain energy and cumulative ringdown count. He concluded that cumulative count was not a useful measure for showing the propensity for surface checking and that peak AE rate values were related to surface elastic strain (Booker and Doe 1995). Innes (1997) performed an analyti-cal and finite element stress analysis and suggested that part of the vessels lying along the surface of a eucalyptus board acts as a stress riser when the surface of the board undergoes tension as it dries.

Acoustic emission associated with drying includes both emission generated by checking and emission generated by water movement. Early reports did not distinguish between these two possible causes of AE generation, although Rice and Skaar (1990) performed an experiment to detect AE associated with water movement in wood. Wood drying was monitored by measuring AE patterns generated from sur-faces of wafers under transverse bending stress. AE behavior was compared in green and partially dried wafers; failure was observed in tension perpendicular to the grain. Partially dried wafers generated AE throughout the bending test, whereas green wafers did not generate AE until they reached the proportional limit. Rice (Rice and Kabir 1992, Rice and Peacock 1992) suggested that microfracture during swelling increased the void volume available for moisture penetra-tion. Dimensional stability treatment of wood could prevent moisture penetration into microvoid areas within the wood. The AE response was low for nonswelling solvents and high for water and super-swelling solvents. Moliňski and others (1991) measured AE generated in wood that was mechani-cally restrained in the radial and tangential directions during soaking in water and reported that the source of AE was primarily radial cracks.

In Japan, AE associated with water movement has been investigated since 1987. Okumura and others (1987, 1989, 1992) and Kuroiwa and others (1996) reported that AE activity was a combined process of water movement, which was not related to checking, and stress release, which was associated with checking. In investigating the relationship between drying stress and AE activity, Okumura and others (1986a) found that AE frequency analysis by a wide band transducer did not reveal the formation of large checks. The researchers attributed the AE rate and amplitude changes to drying stress. It was later confirmed that during drying, the AE source gradually moved from the surface into the interior of small specimens (Okumura and others 1986b). Okumura and others (1988) pointed out problems associated with amplitude attenuation before the signals reached the AE transducers, particularly when AE waves were propagated radially or tangentially. These findings suggest that only a few AE waves are generated by checks caused by shrinkage or restraining stresses and that AE waves are generated primarily from the bulk specimen, irrespective of surface checks.

Okumura and others (1987, 1989, 1992) and Kuroiwa and others (1996) identified the mechanism of AE generation associated with water movement by observing AE waves generated during cyclic wetting and drying of the same specimen. Since thin small samples were used in this series of four studies, the effect of AE wave attenuation was negligible.

In the first study, Okumura and others (1987) showed that AE activity was basically the same in each cycle. AE activity was not different between the specimens with and without slits at positions two-thirds the radial distance between the pith and the edge of the discs. In the second study, Okumura and others (1989) showed that AE activity was similar in restrained specimens. As drying was completed, AE waves generated in a tangentially restrained specimen were associated with checking, but they did not affect the total AE event count, count rate, or amplitude distribution. The authors concluded that only a few AE waves are generated in conjunction with checking; most waves are generated from the whole volume of the specimen during drying.

In the third study, Okumura and others (1992) showed that AE total event count corresponds proportionally to the rate of shrinkage at cross-sectional areas and is not affected by solvents used for chemical treatment. The authors also discussed the retardation of drying at the contact area with the transducer and dead time of the apparatus, both of which affect the AE count.

In the final study of this series, Kuroiwa and others (1996) described differences between heartwood and sapwood in AE behavior associated with wetting and drying. Similar AE waves were observed for charcoal specimens during wetting and drying. Throughout this series of studies, AE was dependent on the length of the specimen tracheids.

Kawamoto (1993, 1994a) reported that the range of AE associated with drying that could be monitored by a 150-kHz AE transducer consisted of a small area underneath or adjacent to the transducer. Even AE waves associated with large checks were attenuated below the threshold level, except for those detected by a transducer mounted close to a check. In those studies, an acousto-ultrasonic (AU) technique was proposed to solve the attenuation problem of AE waves, particularly in the tangential or radial direction. To minimize problems with AE amplitude attenuation, the transducers were mounted at positions where large checks were anticipated to occur as the disc dried.

Wood is weakest in tension across the grain in the tangential direction, particularly in the plane of the ray cells. Stress concentration at this weak region causes crack propagation when tensile stress exceeds ultimate strength. Surface checks frequently develop parallel to the grain, particularly in the plane of the rays, which are oriented perpendicular to the longitudinal cells (Fujita 1974). Kawamoto (1993, 1994b) used maximum AU amplitude to locate weak regions in wood discs. Lower AU amplitude corresponded to lower elastic properties and lower density. The results showed that AU amplitude for longitudinal propagation depends on the density and microfibril angle of the tracheids and that sound propagates farther through latewood that has small microfibril angles (Kawamoto 1994b). Lower AU amplitude corresponds to greater microfibril angle, low density, and low mechanical properties. If a greater microfibril angle and lower density indicate weaker tissue, then reduced AU amplitude indicates an area with a high potential for checking and cracking. Therefore, a large drying crack is more likely to occur at a position where the AU amplitude is lower than that of the surrounding area. Kawamoto reported two techniques for predicting the most probable location for large drying checks (pith to bark) to occur.

Some reports indicate that AE methods are useful for monitoring drying checks, whereas others note that AE is insufficient since most AE waves associated with drying are associated with moisture movement. This occurs because of the differences among AE transducers and specimen/transducer geometry. The AE signal depends on the combined effects of specimen dimension, specimen/transducer geometry, transducer location, and degree of attenuation, particularly in the tangential and radial directions. It is important to consider the transducer orientation in relation to propagation direction of the AE wave. Piezoelectric transducers are usually much more sensitive to vertical transducer vibration than to horizontal vibration. Transducer frequency is also important. Low frequency transducers monitor AE waves generated in a larger volume than do high frequency transducers.

Before discussing the relationship between checking and AE activity, two factors that result in larger AE amplitude should be considered.

1. Larger AE amplitude can be obtained if the transducers are mounted to detect AE waves that propagate perpendicular to the transducer face, as long as a suitable frequency is chosen. If the transducers are mounted to detect AE waves propagating parallel to the transducer face, the AE amplitude can be much lower. In such cases, the AE information is not useful because of high attenuation and unclear wave fronts (unclear time difference).

2. Larger AE amplitude is obtained when AE waves are propagated in the longitudinal direction, since the attenuation is not as great as that in the tangential or radial direction.

In summary, several investigators have studied the characteristics of AE and the development of defects during wood drying. The majority of these studies used time-domain AE counts. The application of AE methods for controlling kiln conditions by monitoring the AE count rate has also been investigated. Researchers have reported that most AE waves detected during wood drying are unrelated to the formation of large drying cracks. Problems associated with AE amplitude attenuation occur in green discs before the waves reach the AE transducers, particularly when AE waves are propagated transversely. Most AE waves detected by 150-kHz transducers during drying are associated with moisture movement, and it is difficult to distinguish AE caused by checking from AE associated with moisture movement. To solve attenuation problems in tangential and radial propagation, transducers have been mounted close to large cracks in green discs.

Wood Decay

Decayed wood generates AE at a lower stress level in bending than does sound wood (Beall and Wilcox 1987, Noguchi and others 1986). Noguchi and others (1992) used partial compression to monitor early stages of decay in field tests. Raczkowski and others (1999) also used AE measured in a compression test in the radial direction to detect early stages of decay.

Acoustic emission was used to detect termite damage using 150-kHz transducers in laboratory and field tests (Fujii and others 1990, Noguchi and others 1991). To solve attenuation problems, Yanase and others (1998) used polyvinylidene fluoride (PVDF) film transducers. Lemaster and others (1997) investigated the effects of different AE transducers on detecting termite activity.

Strength Properties

Porter (1964) used the AE approach to study wood fracture. Several early investigations were concerned with AE generated by bending tests of finger joint specimens (Porter and others 1972, Dedhia 1980). Morgner and others (1980) reported that AE was generated at a lower percentage of modulus of rupture for particleboard than for solid wood. Sato and others (1990) hypothesized that AE is generated from the weak region at a lower stress. AE variables below the proportional limit of a static bending test were reported to correlate with proportional limit, strength, and ultimate deflection (Groom and Polensek 1987). After measuring AE during bending tests, Nakagawa and others (1989) suggested that estimation of MOR could be improved by combining MOE and AE. Ayarkwa and others (2001) reported that AE generated from bending tests of finger joints could be useful for predicting modulus of rupture.

Beall (1985) used AE to measure internal bond strength of wood-based materials. He also showed the effect of resin content and density on AE from particleboard during internal bond testing (Beall 1986). Ohtsuka and others (1993) investigated AE behavior associated with the strength properties of adhesives in shear loading of plywood and analyzed the fracture mechanism by means of AE amplitude and source location. Sato and others (1983, 1984a,b) investigated the mechanism of AE generation under tension. The researchers developed a machine that uses a rolling sensor to detect adhesive failure in plywood. Hwang and others (1991, 1993) used the AE approach to study the durability of adhesives.

Fracture Analysis

Ansell (1982) related the AE strain characteristics from softwood tested in tension to mechanisms of deformation observed by scanning electron microscopy (SEM). The correlation of AE total count with fracture toughness was reported. The relationship between fracture toughness and AE parameters was investigated through the observation of cleavage planes by SEM (Ando and others 1991, 1992, 1995). Suzuki and Schniewind (1987) found a relationship between fracture toughness and AE during cleavage failure in adhesive joints. Nakao applied the moment tensor method proposed by Ohtsu to wood using large amplitude AE (Nakao 1990, Nakao and others 1986, Ohtsu and Ono 1984).

Acoustic emission events were used to assess duration of load behavior in oriented strandboard during creep testing (Beall 1996). Fujimoto and others (1999) performed a fracture toughness test during and after drying and found that characteristics of AE were related to the critical intensity factor (K_{IC}) and microfracture. Average AE amplitude during tensile pulsated load was found to increase in accordance with the stress term of internal friction (Kohara and others 1999). Ogawa and Sobue (1999) measured AE generated by tensile force perpendicular to the fiber direction and discussed the effect of loading speed on crack propagation with respect to AE behavior. Berg and Gradin (2000) used AE monitoring during compression of spruce to investigate fracture history. The effect of temperature, strain, moisture content, and loading direction were investigated.

Wood Machining Control

Drouillard (1993) included wood machining control in his bibliography of AE of bearings and rotating machinery. Lemaster and others (1982) discussed the possibility of automating slow-speed cutting of wood using AE count rate. AE was found to be sensitive to both blade geometry and tool wear (Lemaster 1990, Lemaster and others 1985). Murase and others (1995) reported the possibility of using AE to monitor wood sanding. Tanaka used AE for adaptive control optimization for feed speed of wood during cutting (Tanaka and others 1993, Cyra and Tanaka 1996). Lemaster and others (1988) reported that AE corresponded to density profiles of composite panels. AE was also used to measure surface roughness (Lemaster and Beall 1993).

Other Research

Beall (1987c) monitored AE generated during pyrolysis and combustion. Fuketa and others (1993) performed AE source location in paper. Research has also addressed the propagation properties of AE waves, propagation direction, and effect of moisture content (Bucur and Feeney 1992, Kawamoto 1994b, Lemaster and Quarles 1990, Quarles 1990, Okumura and others 1988). To estimate the moisture-excluding effectiveness of surface coatings, Rice and Phillips (2001) used AE counts generated from weathered specimens immersed in water.

Acousto-Ultrasonic Techniques

General Concepts

Acousto-ultrasonic (AU) is defined as a nondestructive method that uses stress waves to detect and evaluate diffuse defects, damage, and variations in mechanical properties of materials. Whereas conventional ultrasonic methods can be used to assess large voids or other discontinuities, AU techniques can be used to assess subtle flaws and associated strength variations in wood and wood-based composite materials, particularly at adhesive joints (ASTM E1495). The AU method combines aspects of acoustic emission (AE) signal analysis with ultrasonic characterization methods (ASTM E1316). A pair of ultrasonic piezoelectric probes in a send/receive configuration are used to send a stress wave through a specimen. The receiving signals result from multiple reflections and interactions with the material microstructure in a volume of material between the sending and receiving probes. The output signal from the receiving transducer is processed in the same way as an AE signal. Different places in the specimen can be scanned as the pair of send/receive transducers is moved.

Breaking the lead of a mechanical pencil at the surface of a wood specimen has been used in place of an AU transducer to generate an ultrasonic pulse (Groom 1991, Nakao 1990, Nakao and others 1986, Okumura and others 1988). The AU wave generated by the breaking lead is referred to as artificial AE.

The basic approach in the AU technique is to rate the material using a stress wave factor (SWF). The SWF is the relative energy loss (attenuation) or propagation efficiency of the stress wave traveling through a specimen. Several ways to calculate SWF were described by Vary (Vary 1979, 1998; Vary and Lark 1978) and in ASTM 1495. The simplest definition is based on AE peak voltage or the ringdown count method.

Ringdown SWF is defined as

$$\mathrm{SWF} = RTC \tag{1}$$

where R is the repetition rate of input waveforms, T is the predetermined time interval, and C is the number of oscillations in the received waveforms that exceed a preselected voltage threshold (ringdown count).

Peak voltage SWF is defined as

$$\mathrm{SWF} = \text{peak voltage} = V_{\max} \tag{2}$$

where $V_{\max}$ is the maximum (peak to peak) voltage oscillation.

RMS voltage SWF is defined as

$$\mathrm{SWF} = (V_{\mathrm{rms}})^2 = (1/T)\int_{t1}^{t2} V^2 dt \tag{3}$$

where SWF is based on root mean square (RMS) voltage, T is a time interval (t_1 to t_2), t is time, and V is time-varying voltage.

The hypothesis is that more efficient strain energy transfer and strain redistribution during loading corresponds to increased strength and fracture resistance in composites (Vary 1987, 1991; Vary and Lark 1978). The energy dissipation of the stress wave is caused by discontinuities in damaged areas. Higher attenuation will usually indicate lower strength and impact resistance for composites. The AU technique is used to examine the presence or change of microflaws in composite materials, whereas the measurement of ultrasonic velocity is conventionally used to estimate the elastic constants.

Much characterization of AU has been done using isotropic materials. Williams and others (1982) analyzed ultrasonic input–output characteristics with sending and receiving transducers coupled to the same face of an aluminum plate. The practical attenuation occurred in the longitudinal waves. There was good agreement between the theoretical and experimental results for the output voltage amplitudes because of multiple reflections of longitudinal waves. Studies of the effects of specimen resonance suggest that natural vibration modes and associated nodal lines affect output signals (Karagulle and others 1985, Williams and others 1983).

Methodology

To assure reproducibility of AU measurements, it is necessary to choose appropriate transducers and ensure proper coupling between the surface of the material and the transducer (ASTM E1495–97). Special attention is required when placing transducers to distinguish the AU results from other factors such as coupling pressure, surface roughness, and mixed background noise.

As with AE signals, AU signals are affected by the coupling conditions between the substrate and probes, such as couplant selection, amount of couplant, and probe alignment and pressure (ASTM E1495). When the couplant is applied, the technician needs to avoid trapping air bubbles between the sample and transducer. Trapped air as well as surface roughness will decrease the amplitude of AU signals.

Properties of transducers also affect AU results. It is important to select a sending transducer that has a wide frequency range (broadband transducer). If a resonant transducer is used, it is difficult to separate the resonant property of the sending transducer from the AU signals traveling through the materials. The AU signal, like the AE signal, depends on the character of the transducers. For many fiber-reinforced composites, broadband transducer pairs with center frequencies ranging from 0.5 to 5 MHz are appropriate (ASTM E1495). However, materials having high attenuation require more sensitive receiving transducers. Ultrasonic attenuation can be large in wood, particularly in the tangential and radial directions. Accordingly, the resonant frequency of the receiving transducer for wood is usually lower than the frequency employed for other materials (100 to 500 kHz range).

In composites having laminate thickness comparable to the ultrasonic wavelength, investigations have shown that disperse wave modes simultaneously arise from several waves with different speeds (Hemann and Baaklini 1986, Tang and Henneke 1988, 1989). Lamb waves, first discussed by Lamb (1917), propagate in the plane of a plate. Tang suggests that AU techniques for composite laminates generally belong to the symmetric and asymmetric Lamb modes. He concludes that Lamb waves would be the most useful method to evaluate in-plane properties of laminated composite materials.

The AU application was used with wood-based composites to predict swelling resistance of hardboard and adhesive bond strength of finger joints (Reis and McFarland 1986, Reis and others 1990). Acoustic emission techniques were investigated in conjunction with AE techniques (Kawamoto 1994b). AU techniques can also be used to predict the positions of large drying checks in discs (Kawamoto 1994a,b). Amplitude and frequency analysis of AU signals has demonstrated the feasibility of AU for predicting joint or bonding strength of adhesives in glulam beams (Anthony and Philips 1991, Beall and Biernaci 1991, Groom 1991).

Additional basic research is needed to clarify the effects of wood characteristics on attenuation of ultrasonic waves and on AU/AE parameters.

Research Review

Historically, Vary and Bowles (1979) advanced the AU approach for the nondestructive evaluation of mechanical properties and defect status of fiber-reinforced composite materials. Several methods were developed to calculate the SWF (Duke 1988, Vary and Bowles 1979, Vary and Lark 1979, Williams and Lampert 1980). Vary suggested that mapping SWF was an effective way to identify the weak regions of tensile strength in fiber composite (Vary 1987, Vary and Lark 1979, Vary and others 1983). He indicated that SWF correlates with ultimate tensile and shear strengths that accompany different fiber orientations and fiber–resin matrix bonds. Govada and others (1985) showed that local regions of low SWF corresponded to high local displacement in moire fringe patterns in composite laminates. SWF was showed to be an indicator of accumulated degradation in composite laminates subjected to impact damage (Williams and Lampert 1980). A correlation was shown between ultrasonic attenuation at 4 MHz and number of flexural fatigue cycles to failure in graphite epoxy composite laminates. Williams and Doll (1980) indicated that attenuation above 1.5 MHz could be a good indicator of relative fatigue life. Fahr (1989) used SWF to estimate shear strength of adhesive bonds to steel specimens. Results of other studies showed that energy integral SWF could be used to indicate interlaminer and adhesive strength with filament-wound composites (Kautz 1985, 1986; ASTM E1736–95).

In the late 1980s, AU technology that was developed mainly to investigate the mechanical properties of fiber-reinforced composites was extended to wood composites. Beall (1987b, 1989b) summarized the AU technique for wood-based materials in conjunction with AE. In combination with an AE investigation of swelling of hardboard, Reis and McFarland (1986) found that SWF decreases with increased soaking cycles and higher SWF corresponds to lower thickness swelling. Green (1989) found a high correlation between internal bond strength of particleboard and AU voltage.

Reis (Reis and others 1986, Reis and Krautz 1986) extended the AU application for assessing adhesive bond strength between rubber and other materials to AU evaluation of adhesive strength in laminated wood beams. High shear strength values were shown to correspond to high SWF values. In other studies, a high correlation was shown between the adhesive bond strength of a finger joint and several SWFs (Reis 1989, Reis and others 1990). Beall (Beall 1987a, 1989, 1990; Beall and Biernacki 1991) demonstrated that curing of an epoxy glue line could be monitored by AU transmissions. In subsequent studies, Biernacki and Beall (1993, 1996) pointed out the effects of growth ring angle on AU wave propagation. Chen and Beall (2000) used root mean square voltage (RMS) as an AU parameter to monitor bond strength development in particleboard during pressing. Using narrow-band excitation to the transmitter, Anthony and Phillips (1991, 1993) demonstrated that AU-predicted tensile strength correlated with reduced finger-joint strength over time. Groom (1991) reported the feasibility of using AU for determining truss plate joint mechanical properties. A correlation was found between AU energy and truss-plate joint mechanical properties. The author suggested that frequency analysis would be useful for finding weakened joints.

Patton–Mallory and others (1987, 1989) used low frequency AU transducers to evaluate brown-rot decayed wood. The authors suggested that AU amplitude and frequency analysis would work well. RMS voltage and frequency analysis were found to be useful for evaluating biodeterioration of poles (Beall and others 1994), and several AU parameters were shown to correlate with the degree of decay (Tiitta and others 1998, 2001). Tiitta and others concluded that multiple signal feature analysis could be used to distinguish decay from certain types of natural wood characteristics, such as growth ring angle and knots.

Lemaster and Dornfeld (1987) investigated the feasibility of using AU methods to detect defects such as decay, knots, voids, and cross grain in lumber. AU was found to be sensitive to the presence of knots and grain angle, but insensitive to early decay. Lemaster and Quarles (1990) found that wave propagation was more affected by wood structural properties and surface characteristics than by physical properties.

Okumura and others (1988) used artificial AE (sudden break of mechanical pencil lead on wood surface) to observe AU waveforms with different wood species, grain orientation, and moisture content. The effect of wood anisotropy and species on AE/AU wave propagation was shown. Kawamoto (1994b) investigated the effects of microfibril angle and density on longitudinal AU wave propagation. A contour map was developed on the basis of AU waves propagated along the grain; wave propagation was found to be dominated by the existence of latewood. As was discussed previously, AE associated with drying attenuate waves to lower than the threshold level. To solve this problem, AU methods were developed to predict the position of large checks in wet wood discs during drying (Kawamoto 1994a).

Most previous AU studies using wood were concerned with one-dimensional wave propagation where the defects were located in the path of the ultrasonic wave. The anisotropic and inhomogeneous characteristics of wood that affect attenuation of ultrasonic waves were investigated by Shinbo and others (1953), Kamioka and Kataoka (1982), Okumura and others (1986b, 1988), Lemaster and Quarles (1990), Bucur and Feeney (1992), Beall and others (1994), and Kawamoto (1994b). As with AE, AU and artificial AE waves attenuate more in the transverse direction than in the longitudinal direction. Growth rings, natural defects, and moisture content of wood cause the AE/AU response to be more variable. These waves also attenuate more in specimens with high moisture content than in air-dried specimens. Recent AU studies by Beall's group are based on RMS voltage as the AU parameter (Chen and Beall 2000). Several wave classification methods have been investigated (Titta and others 2001). Hamstad (1997) suggests using newly developed transducers to solve problems associated with wood properties.

Concluding Remarks

Propagation properties of ultrasonic waves generated as acoustic emission (AE) and acoustico-ultrasonic (AU) waves in wood depend on grain angle, natural defects, and moisture content. To interpret AE/AU results, it is important to consider transducer properties. Studies of AE monitoring during wood drying indicate that one problem of AE/AU techniques is the attenuation of ultrasonic waves. This problem can be mitigated by proper selection and mounting of transducers. It is hoped that the information in this review will help identify areas for future research so that AE/AU techniques can find wider application for monitoring and controlling wood processing.

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