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A RETROSPECTIVE ON SOME INCOMPLETE ULTRASONIC RESEARCH

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Abstract
This paper reflects on personal incomplete and unpublished research, or research ideas that were not brought to practice. Included are six studies (or ideas) in the area of ultrasonic research, some of which may perhaps stimulate further research by others.

***Key words**: acoustic emission; acousto-ultrasonics; composites; machining; drying; draught stress; coatings.*

BACKGROUND

The two major technologies discussed in this paper are acoustic emission (AE) and acousto-ultrasonics (AU) (Beall 1987). AE is produced in materials under stress and is usually sensed with piezoelectric transducers coupled physically to the surface of the material. AU involves the analysis of transmitted signals through materials over a fixed path to evaluate characteristic or active changes in the material or by scans to locate defects. AE has been used with wood-based materials since the 1960s. AU, which was developed in the late 1970s, was applied to wood in the mid-1980s. AE gives indications of weaker (or weakened) material or structures by emissions at low stress levels, and increased numbers and/or rates of events at higher stress levels. AU evolved from AE technology, but uses an active pulser to inject repeatable stress waves that are typically received by conventional AE transducers, and the resulting waveform is analyzed to determine the change in signal characteristics over the path. AU also differs from conventional ultrasonic techniques in that more subtle flaws, such as poor quality adhesive bonding, can be detected. In most applications, the pulsing element is a conventional piezoelectric transducer that is energized with high-voltage pulses.

Ultrasonic Properties of Wood

For solid wood, typical ultrasonic velocities for extensional waves are l-2km/s across the grain and 5-6km/s along the grain. Most wood composite panels have similar velocities in all directions and attenuation similar to solid wood across the grain. Attenuation of waves is caused by three effects, geometry, material properties, and temperature which limits the detectable distance. In wood-based materials, material attenuation is about an order of magnitude greater than geological materials and two orders greater than metals. Since material attenuation increases exponentially with frequency, the usable upper frequency level for transducers on wood-based materials is about 100-200kHz. Wood is a dispersive material, meaning that the frequency content changes with movement of the wave through the material. The net effect is to lose the high frequency component of the signal, often causing an apparent delay in arrival time of the signal. Because of the variations in velocity and attenuation, the positioning of transducers is critical, particularly for solid wood where the grain direction is well defined.

Coupling of Transducers to Wood

Coupling presents the greatest source of variability and the major impediment to online implementation of AE or AU in industrial processing of wood-based materials. The factors that affect coupling are the acoustic impedance match of the transducer to the substrate, the quality of coupling between the transducer and the substrate, and the characteristics of the substrate.

The means of coupling the transducer to the substrate depends on the application, and includes grease, adhesive, dry coupling (elastomeric), and air coupling. For AE studies, coupling is generally effected using either a grease couplant or by adhesively bonding the transducer to the material. Bonding must be used cautiously since differential thermal expansion of the bonded interfaces can cause failure within the bond or generate stresses that might cause extraneous AE. For many AU applications, the surface must be scanned, which can be done through dry coupling using rigid or elastomeric materials, but coupling pressure must be high enough to "squeeze" out air gaps and maintain consistent local pressure on the material.

AE/AU Characteristics and Signal Processing

The most important AE parameters are "events," which connotes a single burst of energy from a transducer “hit” by a stress wave that can have one or more threshold crossings. In some AE research, determining the location of events is a primary concern, for example, to determine if there is a growing flaw that could become critical. Wood has both anisotropic and attenuation problems that greatly limit location such of flaws. In establishing the maximum sensitivity for AE studies, the threshold is set just above the continuous AE level. Note that the path to the transducer is unknown, as is the level of attenuation in that path (the attenuation could be variable and/or unknown).

In contrast with the passive reaction of the AE transducer to stress waves from active defects, AU uses a transmitting transducer. By stimulating the transmitter, we can repeatedly inject very consistent stress waves into the material. AU also has the capability of controlling the input frequency. There are a number of options in AU for transmitter/receiver combinations/configurations that depend on attenuation, dispersion, frequency sensitivities, and waveform processing needs.

Both AE and AU have used root-mean-square (RMS) to represent a quasi-energy measure. In the case of AE, this was a means of quantifying emissions from continuous processes, for example, that of machining. One of the most important differences between AE and AU is the order of magnitude in energy levels that are generated and/or detected. AE has been developed to push the limits of signal-to-noise in detection of events that may be as low in level as ion migration. AU, in contrast, swamps the system with energy to overcome attenuation and minimize signal losses.

RESEARCH PROJECTS

Measurement of tree drought stress using AE

The purpose of this exploratory study was to determine if it were possible to monitor trees in a plantation to determine when they go into drought stress, which can be relieved by selective harvesting. Acoustic emission occurs in plants that undergo water stress, causing embolism of the cells (loss of water), in which (for softwoods) the openings in pit membranes between adjacent cells aspirate. Most studies have been done on excised portions of plants, such as branches) under artificial rehydration. The major reaction of plants under stress is to close the leaf stomata to preserve water in the branches, stems, and roots.

Two 2-m potted lodgepole pine trees with contrasting forms (“good” and “poor”) were obtained, with the expectation that they would respond differently to water stress. The trees were placed in a greenhouse having temperature control for a 5-da period. They were monitored using two channels in an AET5000 system with 60 dB preamps (125-250kHz filters) and 30dB amplifiers, with a 1-V floating threshold. The outer bark (dead material) was removed from a small area on the stems about 300mm above soil level. A transducer (175kHz) was attached on each tree using an elastic band and grease couplant (Fig 1). The data were printed (not recorded) in 24-h plots. In order to fit the output onto a single 24-h display on the monitor, the interval for data collection was 4min, therefore the Y-axis units are AE per 5min.

Fig. 1.
Attachment of AE transducer to inner bark of potted ponderosa pine tree

The conditions were cloudy with some sun breaks and a little rain during which changes in AE occurred within minutes, decreasing with rain (presumably from the high RH) and increasing with sun exposure. The runs were started at 1400 and the good tree was watered the next day at 0900, with no subsequent watering; the poor tree was not watered. Fig. 2 and 3 show the AE from the good tree on Days 1 and 2. Days 3 and 4 had no changes after the end of Day 2; on Day 5, the greenhouse flooded from rain, and both trees were exposed to water, each recovering to the AE levels of Day 1. On Days 1 and 2, the shapes of the AE curves for the two trees were nearly identical, including very subtle changes from atmospheric disturbances. The major difference in the outputs is that the poor tree reached the baseline at the end of Day 2 and remained there until exposed to water on Day 5. The poor tree also displayed greater stress, having about 50% greater AE during the first two days.

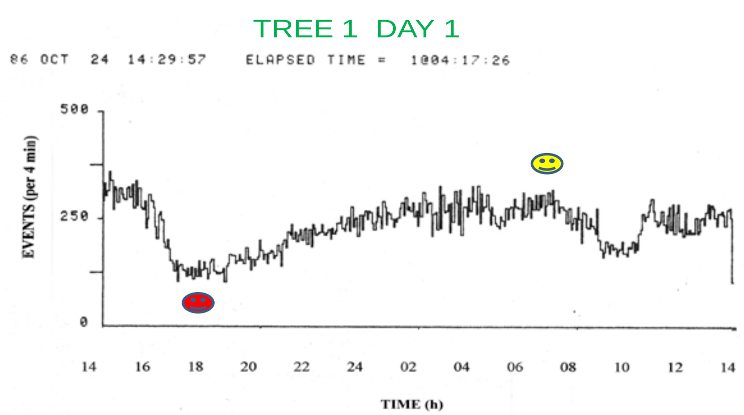

Fig. 2.
Printout of the display on the AET5000 monitor of AE events from the "good" tree during Day 1. Minimal AE occurred at sunset (about 1800h) and maximum near sunrise (about 0700h). The vertical scale (events/4 min) was established to display a 24-h period on the monitor

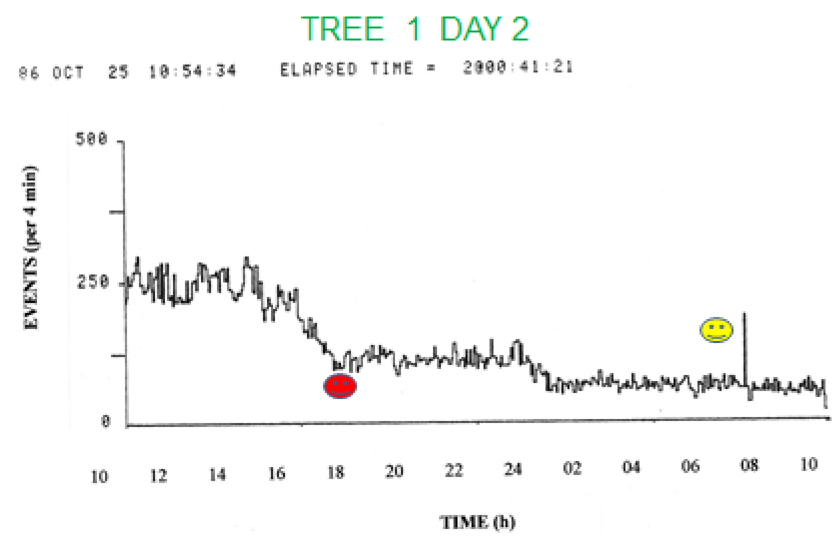

Fig. 3.
Continuation of the plot of the good tree for Day 2. Note that the same minimum at sunset occurs, but the period after sunset no longer increases to a maximum

In general, AE followed a diurnal cycle, with a decrease to minimum AE at sunset and then a steady rise to about sunrise. Apparently, the stomata begin closing a few hours before sunset, causing a reduction in moisture transport, and then the stem begins transporting moisture from the roots to the branches after sunset. Stem swelling also follows a diurnal cycle and this would presumably be in phase with the AE curve; unfortunately, stem measurement transducers were not used.

Composite Panel Machining

We were contacted by a researcher from Masonite Corporation to see if we could verify an observation that he had made in a mill in northern California. This mill produced hardboard door skins, and he noticed that as the panels exited the press, there was considerable variation in noise from saws that trimmed the edges. It was anticipated that the output from the trim saws could have provided information on the uniformity of formation of the edges of the hardboard mat and could be used to make upstream adjustments for better uniformity.

We had previously published research on using RMS from machining operations for process control, and had also verified an AE output relationship to density. We set up a system in the laboratory to mimic the mill system using the same blades, blade clearance, and feed speed. Masonite provided samples of door skin panels for the trials. Then we added a 30kHz resonant transducer to capture airborne noise at 150mm from the blade. The AE system included a 60dB preamp, 15-45kHz filter, and an AET204A with 30dB gain (Fig. 4). The output of the amplifier was fed to an A/D board in a computer.

The output signal from the AET204a was digitized at one sample/ms, with an averaging period of 30ms, which retained the signal content while removing AE fluctuations (Fig. 5). The variation of RMS that we measured most likely represented density variations within the door skins. Undoubtedly, if cuts were made closer to the outside untrimmed edge, this variation would be much greater. Unfortunately, the project was terminated before we had an opportunity to verify the RMS output by making density scans prior to the cut.

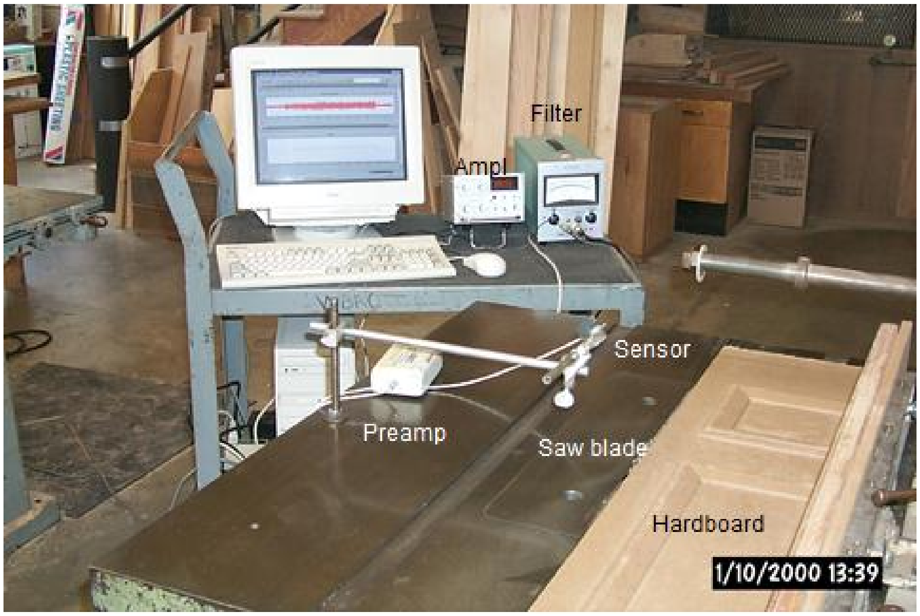

Fig. 4.
Laboratory experimental arrangement for sensing AE during sawing of a hardboard door skin

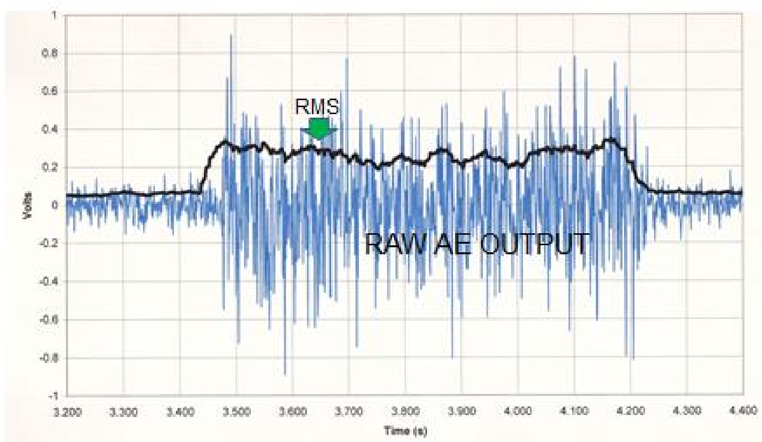

Fig. 5.
AE output from the 30 kHz transducer (raw AE output) and resulting RMS smoothed values

Coating Strength

There is an ASTM standard for coating "pull-off" (D4541) that has been used in a number of studies for monitoring AE during the tensile detachment of films from metallic surfaces. We decided to try this for coatings on wood substrates (Veeraraghavan 1995). The first need was a test fixture to bond to the coating and permit controlled detachment with a test machine. Fig. 6 shows the fixture having a 25-mm-dia rounded bolt head with a polished surface to bond to the coating.

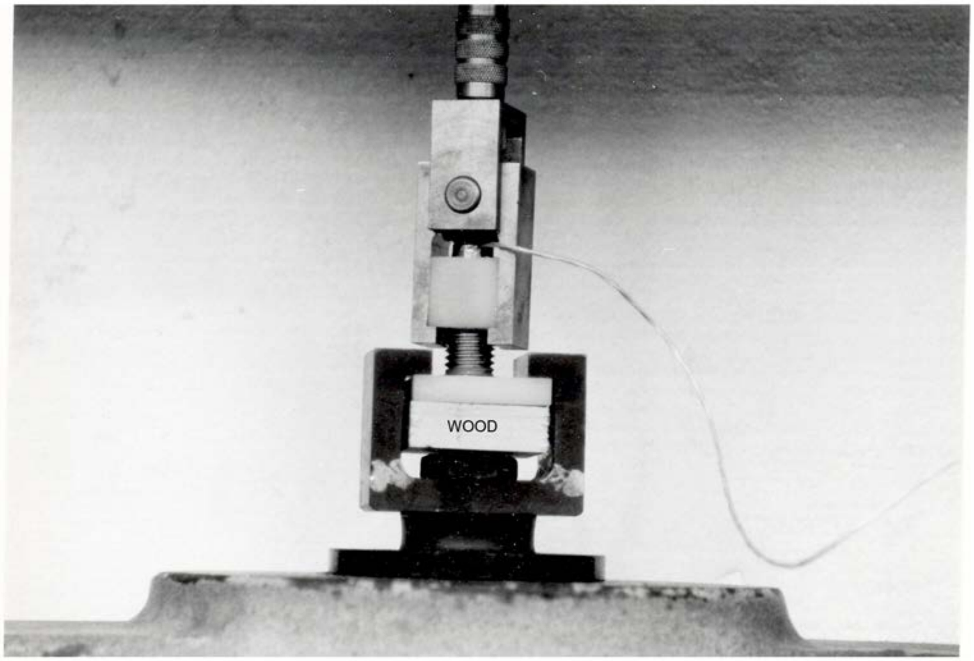

Fig. 6.
Apparatus for tension-normal testing of wood coatings

The upper end of the bolt was also polished for attachment of a miniature 175kHz transducer. The grip of the test machine held a plastic acoustic isolation block positioned on top of the wood sample that also served to position the bolt head. Another plastic block provided isolation for the upper clamp. A special cutter was used to sever the coating precisely at the margins of the bolt head. Three wood species (eastern white pine, southern pine, red alder) and three coatings (polyurethane, nitrocellulose, enamel) were studied. The bonding of the bolt head to the coating was with a cyanoacrylate contact adhesive. To control the location of failure, the tests were done at different points of curing and at different temperatures. The coatings were controlled at the same mass per unit area for each test and the tensile force was applied at 0.5mm/min, which required 10-25s for pull-off. The AE data was amplified with a 40dB preamp and 22dB amplifier, and captured with two systems, an AET5500 to process the typical AE parameters, and an 8-bit A/D Sonix unit. The Sonix unit provided the means to compute special time- and frequency-domain relationships. Image analysis equipment and a light microscope were used to determine the nature of the fractured surface (coating/interface of coating, and wood/wood). A major finding was that the force of pull off was unrelated to the coating and wood variables, meaning that the ASTM standard approach would be of little value. However, several of the AE parameters, AE events to failure and ratio of first moment to RMS provided insight to the location of failure, with the latter the more useful. The technique appeared to be promising to evaluate the full cure time, in which no failure occurs in the coating, and the interfacial and substrate role of coating attachment. For example, the three coatings had different penetrations into the wood substrate and the effectiveness of these penetrations could be assessed by the AE parameters.

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Composite Panel Properties

In some unpublished work, resin- and density-variable particleboard were scanned in a rudimentary setup using 375kHz transducers, which gave a high regression coefficient between AU through-transmission and internal bond (Fig. 7).

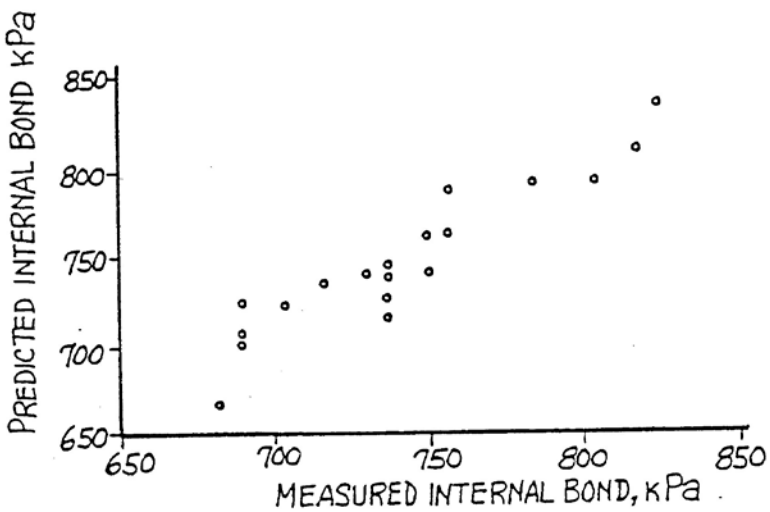

Fig. 7.
Relationship of predicted and experimental internal bond for 19 specimens of 16-mm-thick particleboard over a range of 40 – 105°C having an R^2 = 0.85

This showed promise as a potential on-line mill gauge and a series of studies were performed to acquire more data. This information was felt to be adequate to develop a prototype, and which was subsequently licensed for commercial development. That system consisted of wheeled transducers for direct through-transmission using 75kHz transducers, which resulted in two patents (Shearer et al. 1988, 1989) (Fig. 8).

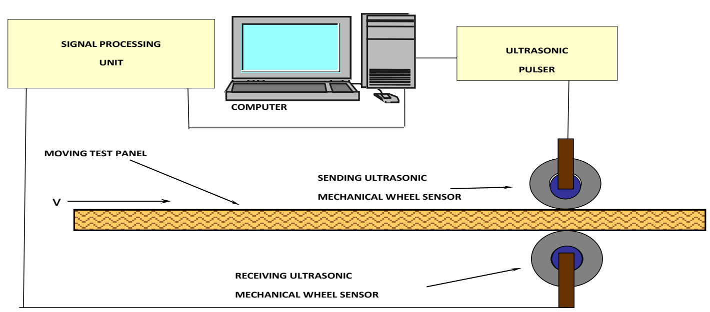

Fig. 8.
Schematic diagram of commercialized internal bond analyzer.

Recently, as a step toward air-coupling, which was claimed in the second patent, some testing was done with transducers coupled to the same side on laboratory-prepared non-oriented strandboards (McGovern 2015). Nine groups of 10-mm-thick, boards (710 x 710mm) were produced with three resin contents and three densities. Transducers were mounted on one surface with 110mm spacing (center to center). Three ultrasonic parameters were measured: phase velocity, frequency spectrum ratio, and power spectral density ratio. A square wave pulse with a center frequency of 100kHz was generated and amplified by a function generator and gated amplifier, and sent to the transmitter. The received signal was passed through a bandpass second order Butterworth filter (2kHz to 500kHz), amplified, and each signal was averaged 50 times to minimize noise. Ten independent measurements were taken for each panel at different locations to obtain average values (Fig. 12). Because resin content is associated with board strength, this relationship shows promise for interrogating the surface and/or core of boards for mechanical properties.

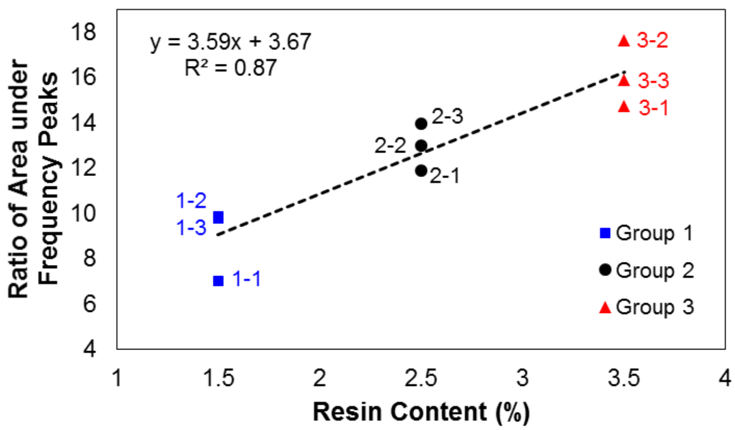

Fig. 9.
Single-sided test results on non-oriented standboard. Groups 1, 2, and 3 were 1.5, 2.5, and 3.5% resin content, respectively. The second number relates to density, where 1, 2, and 3 are 620, 580, and 660kg/m^3, respectively

Sawing Performance

Industrial round saws and bandsaws typically use saw guides that inject a lubricant between the saw blade and guide. The guides are especially important for thin blades. The lubricant serves to minimize friction that causes heat and wear. Fig. 10 illustrates a guide for a round saw showing lubricant injection points at the leading edge of the guide. Most guides have a recess (D in Fig. 10) to concentrate and reduce the volume of fluid. Typical fluid flow rate is about 0.5 – 0.8L/min. The fluid is predominantly water, but has a special oil added to adhere better to metal and that has good film strength. The incompressibility of the fluid prevents the blade from having direct contact with the guides.

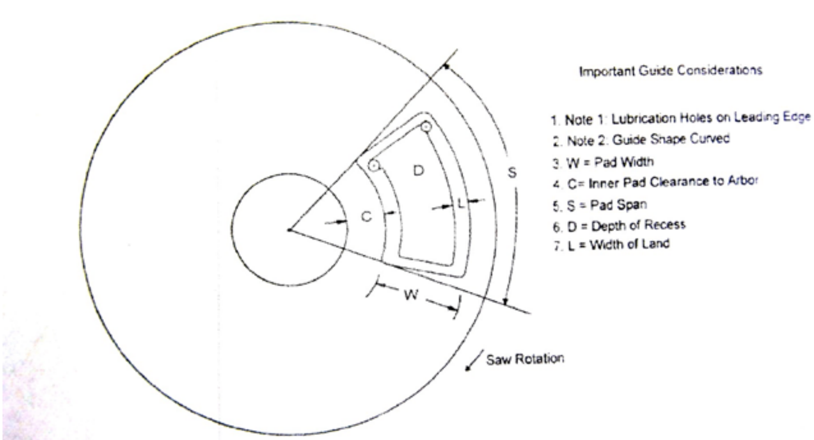

Fig. 10.
Saw guide configuration for commercail round saws

At the Weyerhaeuser Technology Center in Federal Way, Washington, we had an experimental setup for round saws similar to those used in production, but designed to control the operating variables. Our hypothesis was that we could use an acoustic emission transducer bonded to the saw guide to detect: (1) contact between blade and guide, (2) anomalies in the sawing process such as contact of the blade with an embedded object and/or loss of a blade tooth, (3) blocked or low flow rates, and (4) air bubbles that could permit compression of the fluid. The first objective was trivial, but the second required that the lubricant act as an acoustic couplant to transfer AE from the blade to the transducer. To test this, we clamped a 175kHz AE sensor to the guide (at D in Fig. 10) and used a relatively low amplification (60db). Initially, there was extraneous noise from air bubbles in the system, but after purging the air, there was no further interference. Pencil lead breaks were made on the stationary blade and again with the blade rotated by hand, with excellent results for each trial.

Endpoint Moisture Content Detection During Lumber Drying

A number of studies have been done to monitor AE during the drying process. My concentration in this area was to develop a method of collecting AE using a "special sticker," a metal substitution for a wooden sticker used to separate courses of lumber during drying (Beall 2001),(Fig. 11).

Fig. 11.
A solid aluminum "special sticker" is shown with aa attached cylindrical rod containing an AE transducer and preamplifier

A frequency of 40 kHz was found to provide the best sensitivity considering the attenuation of the wood. The sticker captures AE from the courses above and below from checks caused by shrinkage stresses during drying. By monitoring AE, the kiln conditions can be controlled to limit the effects of drying stresses. However, as lumber approaches the target endpoint moisture content, the AE rate diminishes greatly, reducing the value of the technology to control the drying endpoint (Fig. 12).

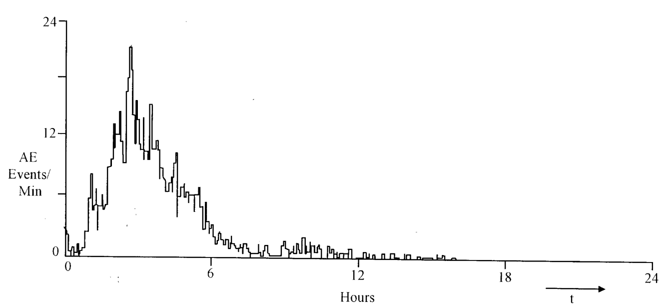

Fig. 12.
AE events produced by a softwood dried at 120ºC. Peak AE occurs at stress reversal, which is close to the fiber saturation point. At 18 h, the wood is essentially oven dry

In the patent, there is a claim for using AU to determine the endpoint moisture content. This is accomplished by adding a second special sticker directly above or below the existing one. The sensor/preamplifier assemblies would be modified by adding a swtich to permit periodic pulsing (say every 15min) to measure the change in the AU parameters as the moisture content approaches the endpoint. During the non-pulsing time, both stickers would be actively measuring AE output. The pulsing could be done at higher frequencies using tone-burst activation to overcome attenuation. In this measurement, grain orientation and density are invariant, which should make it possible to determine the moisture content. The major variable is the effect of temperature on attenuation, but in the later stages of kiln settings, the temperature is usually constant.

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