ACOUSTIC EMISSION ASSOCIATED WITH OAK DURING DRYING

Stephen L. Quarles

Assistant Professor of Forestry
University of California
Forest Products Laboratory
1301 S. 46th St.
Richmond, CA 94804

(Received June 1990)

ABSTRACT

Time-domain acoustic emission (AE) parameters were monitored during the drying of 25- and 50-mm-thick California black oak (*Quercus kelloggii*). Consistent drying conditions (82 C dry bulb temperature/43 C wet bulb temperature) were used throughout the experiment, and an AET 5500 acoustic emission monitoring system was used to monitor AE activity. AE event rates for both thicknesses were similar, with approximately 90% of all activity occurring during the initial 15 to 20 hours of drying, when the average moisture content was still above 50% (oven-dry basis). Active propagation of surface checks was consistently associated with the occurrence of an increasing number of high amplitude events (i.e., those between 60 and 79 dB), although nonvisible micro-failures could have been associated with the large number of lower amplitude events. The high amplitude events typically comprised less than 1% of all events occurring during a given run. Surface-mounted transducers did not detect AE associated with the internal checking that occurred in all test samples.

Keywords: Acoustic emission, drying, drying defects, surface checking.

INTRODUCTION

As early as 1964, researchers began reporting on the possibility of using acoustic emission (AE) to monitor stress development during drying (Skaar et al. 1980). It was not until 1980, however, that research in the drying area began in earnest, and since that time there have been many publications related to this topic. The central objective of research in AE has been the development of a reactive kiln control system, similar in nature to that described by Skaar et al. (1980) and Honeycutt et al. (1985), and by Noguchi et al. (1987). Honeycutt et al. (1985) reported that the drying rate of oak specimens was controlled by adjusting kiln conditions to maintain a ring-down count rate of approximately 1,000 per minute. Noguchi et al. (1987) reported on a control system in which 1-inch-thick circular disks were dried based on a preset value for the ring-down counts per 10 second interval (designated as p) and on the rate of increase of p over 10 minute intervals.

Several studies have confirmed that AE resulted from strains and fractures that occurred during drying (Kagawa et al. 1980; Wassipaul et al. 1986; Ogino et al. 1986; Noguchi et al. 1987). Others have reported that the level of AE is affected by specimen size, species (e.g., hardwoods versus softwoods), and drying conditions (Becker 1982; Noguchi et al. 1980, 1983, 1985). These studies have investigated the drying of boards or disks (i.e., cross sections). The majority of studies to date have used AE time-domain parameters in their analysis; however, recent publications have also reported on frequency-domain analysis to monitor drying (Sadanari and Kitayama 1989; Ogino et al. 1986).

Several AE publications related to drying defects have concentrated on detecting and quantifying checking. Techniques that have been used to detect checking have included monitoring an electrical current in conductive paint (Noguchi et al. 1987), and periodically photographing the drying specimen (Ogino et al. 1986). Two other publications have reported on methods to quantify the size or

Wood and Fiber Science, 24(1), 1992, pp. 2–12

amount of checking. Michalski (1983) used the stress wave factor (a measure used in acousto-ultrasonic testing and is based on a function of the pulser replication rate, the reset time, and the number of threshold crossings) to monitor the amount of internal checking that occurred during drying, and Quarles and Zhou (1987) reported that image analysis could be used to quantify surface checking during drying.

The research discussed here expands on the current knowledge related to the characterization of AE associated with check development during drying. The primary objective of this study was to characterize the AE activity associated with surface check initiation and propagation. Specific objectives included 1) determining whether the AE time-domain parameters of event rate and peak amplitude distribution could provide additional information, relative to the already investigated ring-down count rate, regarding the state of surface check development and propagation, and 2) determining whether surface mounted transducers could detect the occurrence of internal checking.

MATERIALS AND METHODS

Flat-sawn California black oak (*Quercus kelloggii*), a red oak type, was used for all drying runs. Experimental material consisted of nominal 25-mm and 50-mm-thick boards with dimensions of either 100 mm (width) by 140 mm (length) or 150 by 140 mm. The 100- by 140-mm samples were designated S, and the 150- by 140-mm samples were designated L. All edges were sealed with silicon caulk and aluminum foil prior to drying. Constant drying conditions of 82 C dry-bulb and 43 C wet-bulb temperature were used for all drying runs. The severe conditions were used to help ensure surface checking. The 25-mm samples were dried for approximately 48 hours, and the 50-mm samples were dried for approximately 72 hours. The drying rate of each sample was monitored by mounting the sample on a weighing platform that was connected to a load cell. The load cell was mounted on the under side of the kiln, and therefore was not subjected to the kiln conditions.

The door to an experimental micro-kiln had three glass windows installed in order to enable the drying process to be videotaped. Lights were mounted in front of two of the windows and a video camera was mounted in front of the third window. The drying sample was mounted vertically on the load cell, making the videotaping of surface check development possible. The back side of each sample could not be viewed, but was inspected at the conclusion of each run. The first 12 hours of each drying run were taped. The videotapes were played back in an image analysis system (an Olympus Corporation C-2 Image Analyzer) and the length of each surface check was measured as a function of drying time.

An AET (Acoustic Emission Technology) 5500[1] general purpose acoustic emission (AE) monitoring system, in conjunction with a 286-type microcomputer, was used to monitor and record AE activity. A 1.0 V floating threshold, with a total system gain of 80 dB (60 dB preamp), and a 125–250 kHz filter were used in all runs. With these settings, the minimum and maximum peak amplitudes for a given event were 40 and 79 dB, respectively. Two 175 kHz resonant piezoelectric transducers were attached to the surface of each sample using a high temperature hot-melt adhesive. The hot-melt adhesive served a dual purpose as a couplant, and as an adhesive to hold each transducer stationary. A small angle brace and constant force spring were also used to secure each transducer to the wood sample (Fig. 1). Each transducer was 22 mm in diameter. Since physical properties and anatomical characteristics of wood affect propagation, two transducers were used on each sample in order to minimize attenuation effects. The transducers were located 40 mm from each end of the samples, and 60 mm apart. Sample material was obtained from oak logs processed at the Uni-

---

[1] Manufactured by Hartford Steam Boiler Inspection Technologies, Sacramento, California.

versity of California Forest Products Laboratory, and was not surfaced prior to drying. However, a 25-mm diameter end mill was used to prepare a relatively smooth surface where the transducers were positioned.

A post processing program was written to allow for the measured AE time-domain parameters to be averaged over a user selected time interval. This program also incorporated a histogram feature which allowed the distribution of AE events based on peak amplitude or other event parameters, and user selected ranges and time intervals, to be determined.

RESULTS AND DISCUSSION

Information presented in this paper will be limited to AE event rate and peak amplitude data. Other time-domain data were initially analyzed (ring down counts, rise time, event duration, and a measure of energy, defined by a function that includes peak amplitude and the logarithm of event duration), and the trends were very similar to those observed in the event rate and peak amplitude data (Quarles 1990).

The average initial and final moisture contents for the 25- and 50-mm samples were 97.6% and 94.3%, and 11.9%, and 13.4%, respectively. The total events and the number of events per peak amplitude group for each sample are given in Table 1. The absolute number of events was quite variable between specimens, and even between transducers mounted on the same specimen (differences between transducers can be expected because of differences in the calibration curves of given transducers). Note that the total events bore little relation to whether surface checking actually occurred. In fact, the total events between specimens, and even between thicknesses, were not significantly different (p-values = 0.92 and 0.32, respectively). These results indicated that cumulative events alone were not indicative of the propensity to check and therefore would not be an appropriate controlling parameter. This observation is in agreement with the results of Noguchi et al. (1987). These results also showed that as long as the samples were properly end-coated to prevent excessive end drying, AE activity was not a function of specimen size. Therefore, even though specimen size, designated by either S or L, will be indicated, no distinction will be made between the two sizes when discussing results.

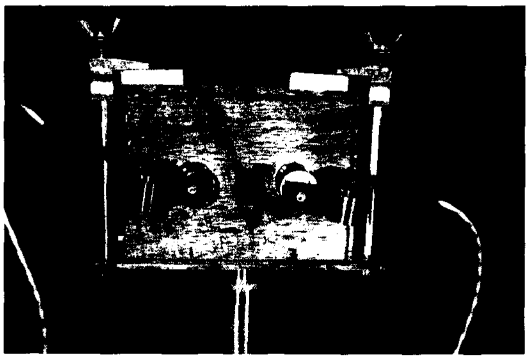


FIG. 1. Photograph of the experimental setup showing weighing platform and the transducer locations on the sample, and the technique used to attach the transducer to the wood.

With the experimental drying conditions (82 C dry bulb temperature/43 C wet bulb temperature), the 12 hours of videotaping were sufficient to observe check development and propagation to maximum length, and usually sufficient to observe check closure in the 25-mm material. In some cases, however, check closure was observable only because of dramatic decreases in check width, even though the check length remained unchanged. For the 50-mm material, 12 hours was sufficient to monitor check development and propagation. With these samples, check closure occurred approximately 25 hours into the drying run.

General trends in AE activity

Two event versus time curves for 25-mm specimens are shown in Fig. 2. In these plots, the number of events per 10-minute interval is shown. The moisture content determined from load cell data is also shown. Note that checking was not observed in sample S13144. For all 25-mm specimens, there was a consistent global or local maximum in the event rate data at approximately 0.5 hours (labeled A),

TABLE 1. *Total number of events accumulated during drying for each sample, segregated by transducer and event peak amplitude group. Percent of total events is given in parentheses.*

		Transducer 0					Transducer 1				
Sample	Checking	Σ Events	40–49 dB	50–59 dB	60–69 dB	70–79 dB	Σ Events	40–49 dB	50–59 dB	60–69 dB	70–79 dB
25 mm											
S12144	Yes	64,116	53,794 (83.9%)	10,071 (15.7%)	217 (0.3%)	34 (0.1%)	278,656	232,183 (83.3%)	45,596 (16.4%)	706 (0.2%)	171 (0.1%)
S13144	No	96,117	66,909 (69.6%)	27,979 (29.1%)	1,050 (1.1%)	179 (0.2%)	108,422	87,636 (80.0%)	20,467 (18.9%)	1,025 (0.9%)	194 (0.2%)
S12344	Yes	94,653	82,666 (86.4%)	12,725 (13.3%)	222 (0.2%)	40 (0.1%)	179,381	157,149 (87.6%)	21,762 (12.1%)	380 (0.2%)	90 (0.1%)
L12444	Yes	61,461	52,940 (86.1%)	8,160 (13.3%)	295 (0.5%)	66 (0.1%)	194,181	164,926 (84.9%)	28,425 (14.7%)	626 (0.3%)	204 (0.1%)
50 mm											
S02184	No	222,459	212,303 (95.4%)	9,872 (4.5%)	240 (0.1%)	44 (0.0%)	106,651	92,923 (98.1%)	13,426 (12.6%)	246 (0.2%)	56 (0.1%)
S03184	Yes	151,940	138,705 (91.3%)	12,959 (8.5%)	227 (0.2%)	44 (0.0%)	145,714	123,289 (84.6%)	21,871 (15.0%)	469 (0.3%)	85 (0.1%)
L03284	Yes	118,862	100,991 (85.0%)	17,389 (14.6%)	384 (0.3%)	98 (0.1%)	244,248	205,735 (84.2%)	37,601 (15.4%)	769 (0.3%)	143 (0.1%)
L02284	Yes	79,600	69,173 (86.1%)	10,054 (12.6%)	283 (0.4%)	90 (0.1%)	173,433	150,778 (86.9%)	22,012 (12.7%)	500 (0.3%)	143 (0.1%)

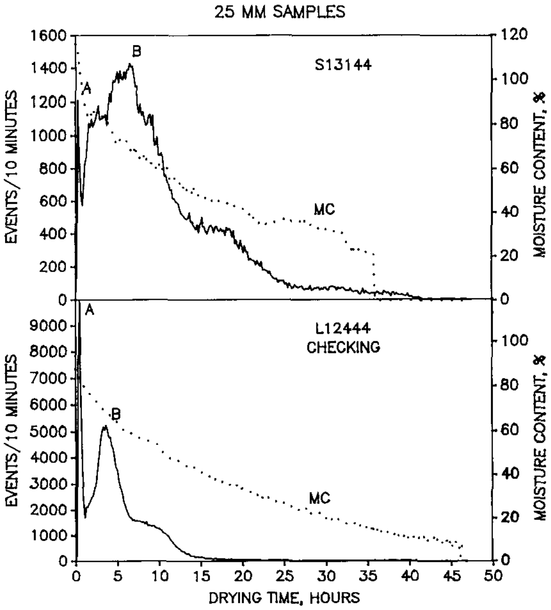


FIG. 2. Events per 10-minute interval and moisture content curves for the 25-mm samples S13144 and L12444. Checking was observed in sample L12444, but not in sample S13144.

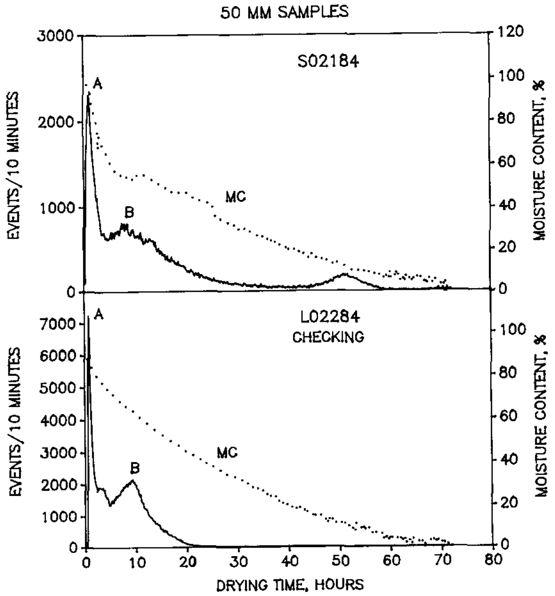


FIG. 3. Events per 10 minute interval and moisture content curves for the 50-mm samples S02184 and L02284. Checking was observed in sample L02284, but not in sample S02184.

with subsequent peaks occurring later in the run. This trend was observed whether or not surface checking occurred. The same trend was observed in the 50-mm samples (Fig. 3), with the initial maximum occurring at approximately 1 hour (labeled A). These trends are in qualitative agreement with the results of Noguchi et al. (1985), and may have been caused by events associated with cavitation of water in the lumens (Milburn 1973; Tyree and Dixon 1983) and/or micro-failures that were not visible to the naked eye. A second peak occurred after the initial maximum at 0.5–1.0 hours. These maxima have been labeled B. In the 25-mm samples and the 50 mm-sample in which checking was observed, the secondary maxima occurred when the average moisture content of the samples was approximately 70%. In sample S02184 (checking not observed), the average moisture content at point B was approximately 55%.

The majority of AE event activity occurred during the initial 15 to 20 hours, regardless of thickness. After 20 hours of drying, the average moisture contents for the 25- and 50-mm samples were approximately 40% and 50%, respectively. The event curves for all samples were generally similar. The maximum event rate per 10-minute interval was greater in the case where checking occurred, as was the change in event rate as a function of time in the vicinity of the second maximum (labeled B in Figs. 2 and 3).

In order to determine whether drying temperature had an unusual effect on the initial maximum in AE activity (occurring from 0.5 to 1 hour), additional 25-mm samples were dried at both 65 C and 50 C, each time using a 43 C wet-bulb temperature. Results from these tests showed that the maxima were still present early in the run. These samples were not videotaped during drying. Finally, a test was run using a previously dried specimen that had been cooled to room temperature and then reinstalled in the kiln, and re-exposed to the 82/43 C conditions. No event peak was ob-

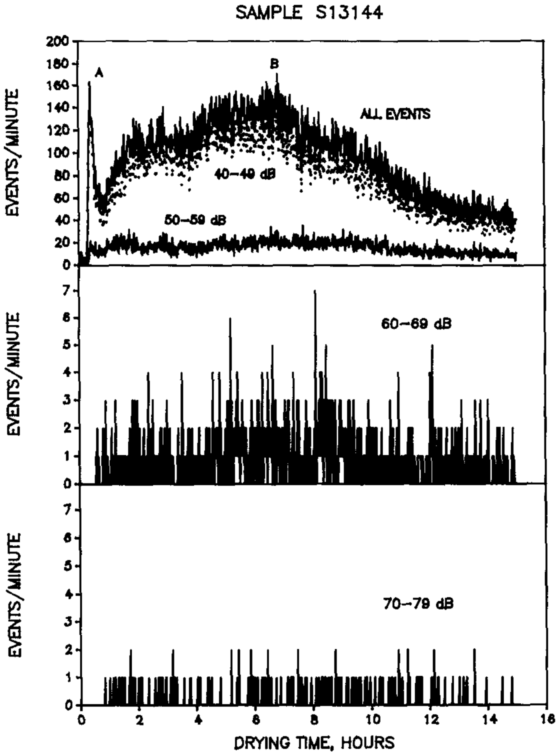


FIG. 4. Events per minute, segregated by peak amplitude group, for the 25-mm sample S13144 (surface checking not observed).

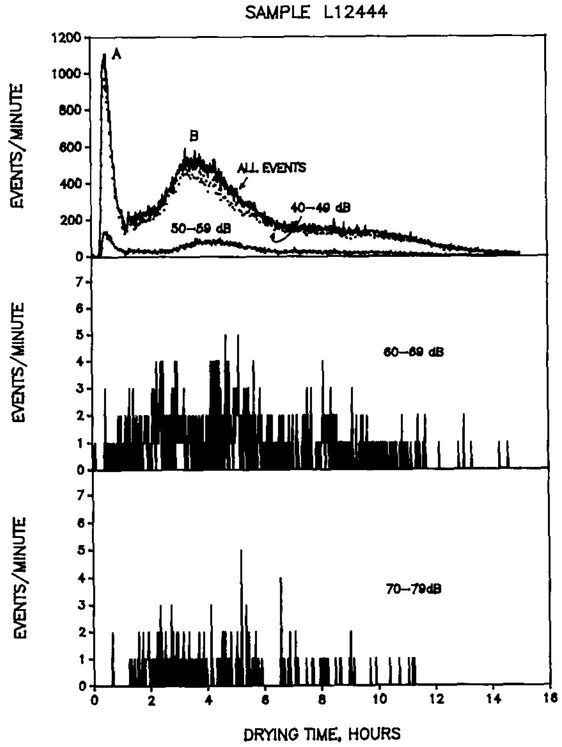


FIG. 5. Events per minute, segregated by peak amplitude group, for the 25-mm sample L12444 (surface checking observed).

served during this test, indicating that the initial rapid increase in events was not associated with a strictly temperature-related phenomena (i.e., it was not related to an increase in the temperature of the transducer or thermal expansion in wood).

25-mm samples

With the 25-mm samples, surface checking occurred in three of four samples. Events per minute were analyzed. AE data presented for the 25-mm samples will be restricted to transducer number 1 information since surface checking predominately occurred in the vicinity of this transducer. For those samples that checked, checks became visible between one and three hours into the run.

The AE events per minute for samples S13144 (no observed surface checking) and L12444 (observed surface checking), with event data separated into peak amplitude groups, are given in Figs. 4 and 5, respectively. Only AE activity during the initial 15 hours is shown in these plots. As observed in these figures, the event rate maximum at the second peak (labeled B) was significantly greater for sample L12444 and occurred earlier in the run. The local maximum for sample L12444, occurring at approximately four hours into the run, corresponded to the time when the surface checks had reached approximately half of their maximum length. The rate of events having a peak amplitude between 50 and 59 dB was relatively constant for sample S13144, whereas event activity in this range exhibited a local maximum at approximately 4.5 hours in sample L12444. The increase and subsequent decrease 50–59 dB activity observed in sample

L12444 coincided to the time period during which both surface checks were propagating. Both checks had reached maximum length after six hours. The trend observed with the 50–59 dB events for sample L12444 was, however, unusual in that the rate of 40–49 and 50–59 dB event activity in the other samples generally remained constant or decreased during the time when checks were actively propagating.

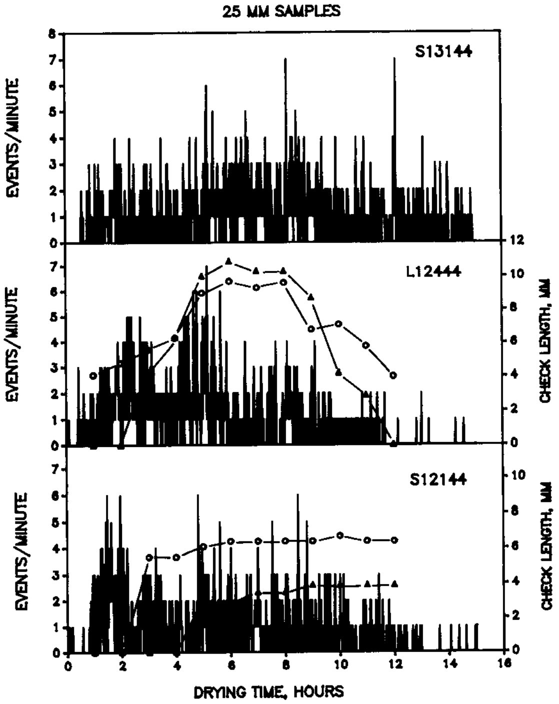


FIG. 6. High peak amplitude events (between 60 and 79 dB) and check length as a function of drying time for the 25-mm samples S13144, L12444, and S12144. The length of each observed check is indicated by the curves connecting the circles and triangles. Checking was not observed in sample S13144.

It was evident from the figures that the event rate for events with peak amplitudes greater than 60 dB was greater and reached the maximum value earlier in the run for sample L12444 compared to sample S13144. It was also evident that the absolute number of high peak amplitude events per minute was relatively small (as indicated in Table 1). The small number of high peak amplitude events and their relationship to check development suggested that it may be possible to detect severe checking by simply counting events having a large peak amplitude, e.g., greater than 60 dB. The number of 60–79 dB events per minute for samples S13144, L12444, and S12144 is shown in Fig. 6. The length of each individual surface check through 12 hours of drying is also shown. Figure 6 shows that the occurrence of 60–79 dB events in samples L12444 and S12144 corresponded to the period when check propagation was occurring. Outside this window, AE activity was significantly lower. It should be noted that although checks reached maximum length in a relatively short period of time, propagation normally continued with increases in check width, and presumably check depth, although depth could not be measured. Thus, after maximum check length was reached, high peak amplitude events were associated with increases in check width and depth. The occurrence of high peak amplitude events through the initial 8 hours in sample S13144 was less than that of sample L12444, though this pattern was not as clear when compared to sample S12144. Evidence of surface checking was noticed on the back (unobserved) side of sample S13144, and the AE activity between 6 and 8 hours could have been associated with that. The majority of high peak amplitude activity observed in sample S13144 was in the 60–69 dB range, with events in the 70–79 dB range only occasionally exceeding 1 per minute (Fig. 4). As shown in Fig. 5, high peak amplitude activity in sample L12444 was much greater than that observed in sample S13144, and emphasizes the importance of the higher amplitude activity. A similar trend was observed with the other 25-mm sample, although the activity level was lower than even sample S13144.

A summary of AE and check information for the 25-mm samples is given in Table 2. Information given in this table confirms the trends observed in Figs. 4 though 6. The maximum level of event activity per time interval in samples where checking occurred was much greater than when checking did not occur. In order to quantify this observed lag in AE ac-

TABLE 2. *Summary of event and check activity for the 25 mm samples. No checking was observed in samples S13144 and S02184.*

Sample	Thickness, mm	Check number	Elapsed time to initial observation, h	Maximum length, mm	Maximum event activity/interval[1] (elapsed time to maximum, h)[1]		Elapsed time to 0.5 normalized events for each interval	
					1 min	10 min	1 min	10 min
S13144	25	—	—	—	155	1,400	6.5	7.9
					(6.4)	(6.5)		
S12144	25	1	2	6.5	575	5,900	4.2	4.4
		2	4	3.9	(1.2–2.2)	(1.5–2.0)		
S12344	25	1	1	13.9	500	4,900	3.6	4.2
		2	1	8.0	(1.6)	(1.5)		
S12444	25	1	1	11.0	500	5,000	4.1	4.0
		2	2	10.0	(4.1)	(3.8)		
S02184	50	—	—	—	98	818	9.5	—
					(7.5)	(7.5)		
S03184	50	1	5	45.0	245	2,131	7.5	—
					(3.0–3.5)	(2.7–3.3)		
L03284	50	1	7	19.0	403	3,986	5.3	—
					(3.1)	(3.0)		
L02284	50	1	7	10.9	217	2,153	7.0	—
		2	7	27.7	(9.2)	(9.5)		

[1] Excluding maximum at 0.5 hours.

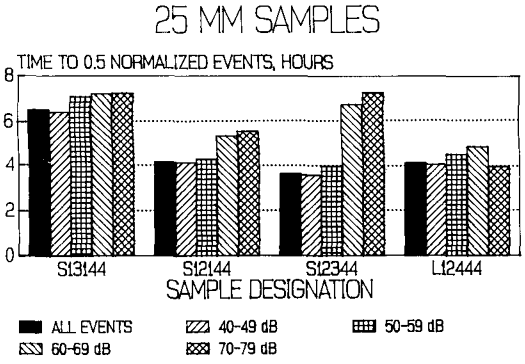
tivity observed in Figs. 4 and 5, the event rate for each sample was normalized to the total events for that sample. The time to 0.5 normalized events is also given in Table 2. Note that the time to 0.5 normalized events for sample S13144 was between 35 and 45% greater than for the other 25-mm samples. The time to 0.5 normalized events for each sample and peak amplitude group is given in Fig. 7. With the exception of the 60–79 dB peak amplitude groups for sample S12344, the trends for each group were consistently the same, with the time to 0.5 normalized events occurring much earlier in samples where surface checking was observed.

50-mm samples

As was the case with the 25-mm samples, surface checking was observed in three of the four 50-mm samples. Checking that did occur consistently developed after approximately six hours. Discussion will be limited to the checks that occurred in the vicinity of transducer number 1 (as was the case with the 25-mm samples). A summary of AE and check development information is given in Table 2.

As illustrated in Figs. 2 and 3, the event rate plots for the 25- and 50-mm samples were similar. The 40–49 dB and 50–59 dB event rate plots for the 50-mm samples were also very similar to those observed in the 25-mm samples (Figs. 4 and 5), and therefore will not be presented here. The previously discussed lag in AE activity, indicated by the difference in time to 0.5 normalized events for each peak amplitude group, was also observed with the 50-mm samples. Within any peak amplitude group, the time to 0.5 normalized events was greater for the check-free sample (S02184). The time to 0.5 normalized events for the 40–59 dB peak amplitude groups was approximately 10 hours for the check-free sample, compared to approximately 6 to 7 hours for the samples in which checking was observed. The most significant difference occurred with the 60–69 dB and 70–79 dB peak amplitude groups, where the time to 0.5 normalized events was significantly greater for the check-free sample.

The relationship between check propagation and the occurrence of high amplitude events (between 60 and 79 dB) was very strong for the 50-mm samples. The results for three 50-



SAMPLE S13144 CHECK FREE

FIG. 7. The time to 0.5 normalized events, segregated by peak amplitude group, for the 25-mm samples.

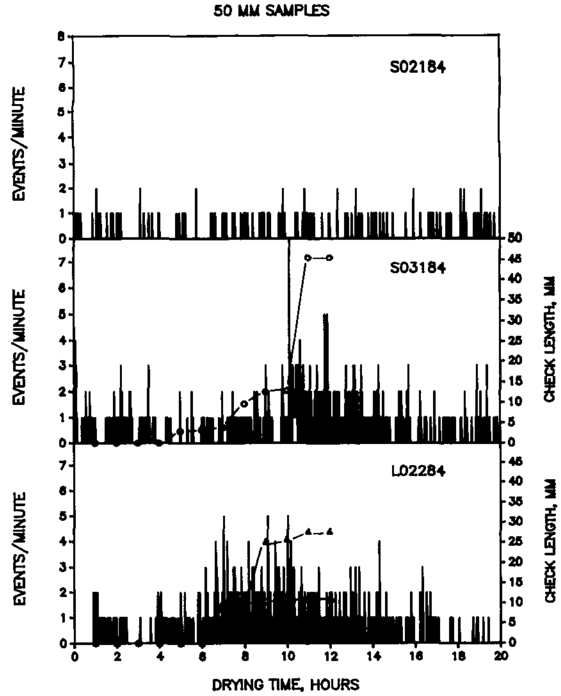


FIG. 8. High peak amplitude events (between 60 and 79 dB) and check length as a function of drying time for the 50-mm samples S02184, S03184, and L02284. The length of each observed check is indicated by the curves connecting the circles and triangles. Checking was not observed in sample S02184.

mm samples (the check-free and two others) are shown in Fig. 8. These results were consistent with those observed for the 25-mm samples. The occurrence of high amplitude events was minimal in the check-free sample, with the number of such events only occasionally exceeding one per minute. There was a significantly greater increase in AE event activity in the samples where surface check was observed. The increase in high peak amplitude AE events coincided with the observed increase in check length, as shown in Fig. 8, and check width and depth (from visual observations).

Occurrence of internal checking

At the conclusion of each run, the specimen was removed from the kiln and inspected for the presence of internal checking (honeycomb) and collapse. During these inspections, it was observed that every sample had developed extensive internal checking. Therefore, two additional tests were conducted to determine, at the drying conditions used in these experiments, the time at which internal checking initiated in the 25- and 50-mm samples. Four end-matched samples from each thickness group were dried during each test. One of the four samples was mounted on the weighing platform. The run was interrupted at fixed intervals so that samples could be pulled and evaluated for the occurrence of internal checking. Shell and core moisture sections were cut from each sample. The 25-mm samples were pulled at 14, 22, 30, and 38 hours into the run, and the 50-mm samples were pulled 24, 34, 44, and 54 hours into the run.

The moisture content and the 60–79 dB events per 10-min interval for the 25- and 50-mm samples are shown in Figs. 9 and 10, respectively. Results from these tests showed that the internal checking was visible after 30 and 44 hours, for the 25- and 50-mm specimens, respectively. The average moisture content of the 5-mm shell layer at the time internal checking was observed was approximately 17% for both thicknesses, and the average core moisture content was 43% and 63%, respectively, for the 25- and 50-mm specimens.

As previously discussed, more than 90% of all events eventually detected through the run occurred during the initial 15 to 20 hours, in-

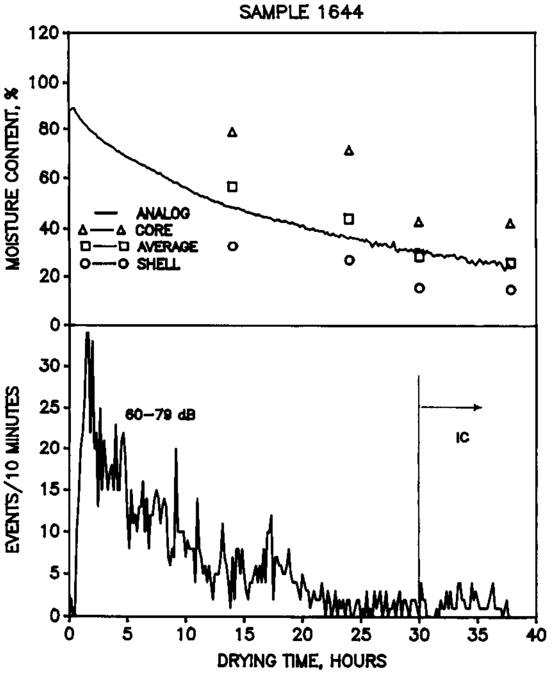


FIG. 9. Moisture content and 60–79 dB events per 10 minute interval as a function of drying time for the 25-mm samples. The time of occurrence of internal checking is designated by IC.

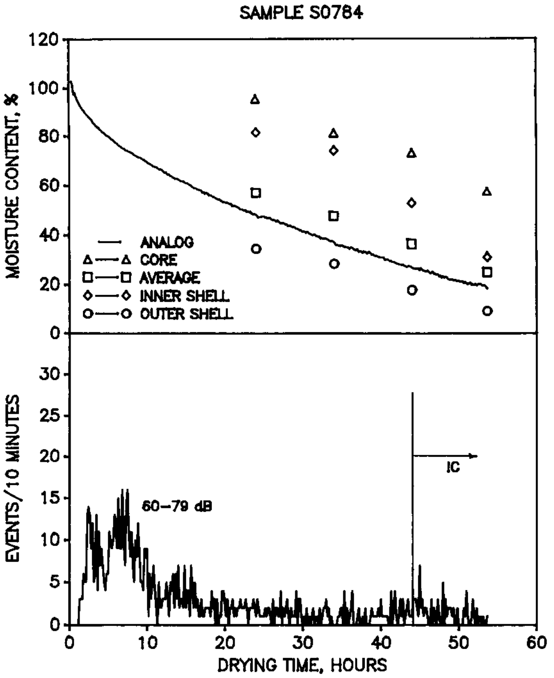


FIG. 10. Moisture content and 60–79 dB events per 10 minute interval as a function of drying time for the 50-mm samples. The time of occurrence of internal checking is designated by IC.

dicating that few of the detected events could be associated with internal checking. The low peak amplitude events rate was constant throughout the period during which internal checking was occurring. AE event data given in Figs. 9 and 10 show that there were very few high amplitude events associated with internal checking in the 25-mm sample. AE activity in the 50-mm samples increased slightly during the period when internal checking was occurring. In either case, the amount and duration of AE activity associated with internal checking were minimal compared to that for surface checking, and indicated that wave guides or imbedded probes would be necessary to detect internal defects such as internal checking, and probably collapse.

SUMMARY AND CONCLUSIONS

The ability to segregate events into peak amplitude groups proved to be very useful for monitoring check development and propagation. Results from these experiments have shown that high peak amplitude events (defined in this study as those greater than 60 dB) were consistently associated with the propagation of surface checks. Results indicated that low peak amplitude AE (i.e., those less than 59 dB) corresponded to precursor activity, e.g., the development of micro-checks, which lead to visible checks. There was a delay between the maximum level of low peak amplitude events and subsequent visible check propagation.

Although it is clear that AE can be used to monitor the development and propagation of surface checks, data presented here indicated that surface-mounted transducers cannot be used to detect internal checking because they appear to produce insufficient AE activity. Wave guides or embedded transducers may be required to detect internal checking and collapse. Additional research in this area is currently being conducted.

ACKNOWLEDGMENTS

The author gratefully acknowledges the help of Mr. Tom A. Breiner in conducting these experiments, writing software, and reviewing the manuscript.

REFERENCES

BECKER, H. F. 1982. Acoustic emissions during wood drying. Holz Roh Werkst. 40(9):345–350 (German).

HONEYCUTT, R. M., C. SKAAR, AND W. T. SIMPSON. 1985. Use of acoustic emissions to control drying rate of red oak. Forest Prod. J. 35(1):48–50.

KAGAWA, Y., M. NOGUCHI, AND J. KATAGIRI. 1980. Detection of acoustic emissions in the process of timber drying. Acoustic Letters 3(8):150–153.

MICHALSKI, G. V. 1983. An analysis of end check damage in red oak boards in relation to acoustic emission count rate/stress wave factor. M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. 135 pp.

MILBURN, J. A. 1973. Cavitation studies on whole *Ricinus* plants by acoustic emission detection. Planta 112(4): 333–342.

NOGUCHI, M., Y. KAGAWA, AND J. KATAGIRI. 1980. Detection of acoustic emissions during hardwood drying. Mokuzai Gakkaishi 26(9):637–638.

———, ———, AND ———. 1983. Acoustic emission generation in the process of drying hardwoods. Mokuzai Gakkaishi 29(1):20–23 (Japanese).

———, S. OKUMURA, AND S. KAWAMOTO. 1985. Characteristics of acoustic emissions during wood drying. Mokuzai Gakkaishi 31(3):171–175.

———, S. KITAYAMA, K. SATOYOSHI, AND J. UMETSU. 1987. Feedback control for drying *Zelkova serrata* using in-process acoustic emission monitoring. Forest Prod. J. 37(1):28–34.

OGINO, S., K. KAINO, AND M. SUZUKI. 1986. Prediction of lumber checking during drying by means of acoustic emission technique. J. Acoustic Emission 5(2):61–65.

QUARLES, S. L. 1990. Acoustic emission during drying. Proceedings Western Dry Kiln Association. Pages 51–60.

———, AND L. ZHOU. 1987. Use of acoustic emission to detect drying defects: a preliminary report. Pages 95–111 *in* Proceedings/Sixth Nondestructive Testing of Wood Symposium. Washington State University, Pullman, WA.

SADANARI, M., AND S. KITAYAMA. 1989. Waveform analysis of acoustic emissions generated in the wood drying process. Mokuzai Gakkaishi 35(7):602–608 (Japanese).

SKAAR, C., W. T. SIMPSON, AND R. M. HONEYCUTT. 1980. Use of acoustic emissions to identify high levels of stress during oak lumber drying. Forest Prod. J. 30(2):21–22.

TYREE, M. T., AND M. A. DIXON. 1983. Cavitation events in *Thuja occidentalis* L. Plant Physiology 72(4):1094–1099.

WASSIPAUL, F., M. VANEK, AND A. MAYRHOFER. 1986. Klima und schallemissionen bei der holztrocknung. Holzforchung und Holzverwertung 38(4):73–79.