MONITORING BOND STRENGTH DEVELOPMENT IN PARTICLEBOARD DURING PRESSING, USING ACOUSTO-ULTRASONICS[1]

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ABSTRACT

As with other composite products, the quality of particleboard is sensitive to the manufacturing process. However, there is still no efficient on-line technique available to monitor and control the most critical process in particleboard manufacture, adhesive cure during pressing. The objective of this study was to develop a technique, using Acousto-Ultrasonics (AU), to nonintrusively monitor the bonding development of particleboard during hot-pressing. A series of tests were run in a 610-by 610-mm laboratory press, in which a tone-burst signal with a fixed frequency of 60 kHz was injected into one platen via a waveguide and the signal received at the other platen. Phenol-formaldehyde resin was used for preliminary experiments and urea-formaldehyde resin for the main study. The degree of resin curing was assessed by measuring internal bond (IB), which was compared with an AU parameter, root mean square (RMS) voltage. During consolidation, RMS reacted primarily to the change of press pressure; subsequently, it followed the increase in IB and reached a plateau when the resin was completely cured. With extended pressing, RMS decreased, reflecting the degraded condition of the board. These results showed that RMS could be an index for the desired endpoint in pressing.

Keywords: Adhesive cure, acousto-ultrasonics, internal bond, composite panels, hot-pressing, on-line sensing, nondestructive evaluation.

INTRODUCTION

Adhesives are used widely in wood products, a high proportional of which are hot-pressed composite panels, such as medium-density fiberboard, particleboard, and oriented strandboard. Although produced for diverse uses, these panel products have a similar manufacturing process with a variety of means to maintain consistent quality. However, there is no commercial on-line system to monitor the most critical part of the process where panel strength develops, hot-pressing.

Hot-pressing consolidates a loose mat of wood furnish and thermosetting resin into a solid panel between platens in a hot-press by simultaneous application of heat and pressure. Although heat and pressure during pressing can induce wood particles to plasticize and raise the temperature level to cure the resin, stresses develop from residual elasticity of

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pressed furnish, and steam pressure builds up in the mat. If the adhesive does not develop sufficient strength to overcome these internal stresses, the mat will blow apart when pressure is released at the end of pressing. Even without a blow, the panel can have an unacceptably low internal bond (IB) if the press is opened too early. Although bonding quality improves with an increase in press time, this is contrary to cost control.

In wood composite mills, trial-and-error methods are used to determine the appropriate press cycle for a particular condition. If a blow occurs, extending press time is commonly used as a remedy. However, in avoiding blows, time in the press is likely to overshoot because there is no real-time feedback information for the press operator. Because of the lack of a feedback method, off-line destructive testing, typically IB determination, is used to track panel properties. However, this is time- and material-consuming, and involves a very limited sampling. Therefore, properties can vary among commercially available panels, even from the same supplier (Cassens et al. 1994). The composite panels that use urea-formaldehyde (UF) resin are the most sensitive to press conditions. If the press is opened too early, panels can suffer from a low IB, but this can also cause excessive formaldehyde emissions. In contrast, extending press time would likely cause overcuring and therefore degradation. The objective of this study was to develop a new nonintrusive nondestructive evaluation (NDE) technique, using acousto-ultrasonics (AU), to monitor the bond development in particleboard and to identify the endpoint in pressing.

METHODS TO DETECT RESIN CURING

Hot-pressing is a very complex operation including mechanical, physical, and chemical changes during the process, involving a three-dimensional gradient of temperature, gas pressure, and moisture content changing through the mat with time. These local conditions influence not only wood densification but also adhesive curing. Therefore, interactions between initial mat conditions (moisture content, resin content, density) and press conditions (press temperature, press time, and cycle) may significantly affect resin curing and bonding behavior, and therefore panel properties. A number of methods have been used, largely in the laboratory, to determine the curing process under simulated commercial conditions.

Non-acoustic methods

Surface analysis techniques have been used to investigate the adherend surface to infer its bonding performance. Due to the relatively modest cost of the equipment, contact angle measurements have been used to estimate the wettability or the surface free energy of wood (Bodig 1962; Chen 1972; Freeman and Wangaard 1960; Gray 1962; Herczeg 1965), and these data were assumed to reflect the bonding performance of the adhesion system. Because of the inherent complex nature of the wood surface, much variation and inconsistency exist in this correlation. Other surface analytical instruments, such as X-ray photoelectron spectroscopy and infrared spectroscopy, have been used to measure the chemical topography of the wood surface to estimate the potential bonding ability (Buchert et al. 1996; Gardner 1991). However, wood adhesion is not controlled just by chemical properties. Physical properties, such as density and porosity, will also influence adhesive formation and performance.

Thermal analysis techniques, such as differential scanning calorimetry, dynamic mechanical thermal analysis, and torsional braid analysis, measure the changes related to either the chemical reaction or the mechanical properties of the curing resin. Although these techniques can provide useful information for the extent of resin cure, samples for wood adhesion measured by these methods are usually in the form of bulk resin, mixtures of resin and wood powders, resin-impregnated glass cloth, or wood wafers (Humphrey 1990; Humphrey and Bolton 1979; Steiner and Warren 1987; Young

1985; Marcinko et al. 1999). Because of the lack of the true interaction between resin and wood, optimum conditions for resin curing determined by these methods may not be relatable to bonding processes during pressing.

Several techniques, such as an optical fiber method and dielectric analysis, have been applied to monitor the curing of bulk polymers or wood-based composites during pressing (Dorighi et al. 1996; Druy et al. 1990; Wolcott and Rials 1995). Since properties can respond only to the change of resin conditions, these techniques are unlikely suitable for the hot-pressed wood composites in which a fully cured resin may not indicate a highly integrated bond. Moreover, these techniques are intrusive, requiring embedded sensors or electrodes in the test materials or platens.

Ultrasonic methods

Ultrasonic testing (UT) techniques have been used for polymer cure monitoring with a variety of probe arrangements to excite different kinds of waveforms, such as longitudinal (Papadakis 1974; Sofer and Houser 1952), shear (Fanconi et al. 1984; Yew 1984), and interface waves (Rokhlin 1983). Because of the direct connection between the transmission of sound waves and the mechanical properties of the material, information on the extent of resin cure and bonding strength between resin and adherend can be obtained by measuring various ultrasonic parameters.

Among all ultrasonic parameters, the measurement of velocity is considered the most direct. In a simple linear elastic material, acoustic propagation methods are based on relationships between acoustic velocities and elastic moduli. For viscoelastic materials, relationships between acoustic and elastic properties become more complex. Moreover, with the introduction of advanced composite materials, in order to deliver strength to a particular direction without extra materials in other unnecessary directions, these composites are made with highly anisotropic constituents. An interesting phenomenon associated with anisotropic or non-homogeneous materials is the deviation in direction that can exist between group and phase velocities (Rose et al. 1987). The precision of velocity measurement can be compromised by the difficulty in detecting the first arrival of the wavefront. Therefore, probe arrangements and interpretation of velocity measurements in such materials are critical.

As a sound wave propagates through a material, the amplitude of the wave decreases. Energy losses may be attributed to geometrical effects (wave spreading) and intrinsic effects (interactions between the wave and the material). For monitoring resin cure, wave amplitude decreases initially as the gel point is reached and increases during the solidification of the resin (Kline et al. 1994). It has been reported that the changes in peak amplitude can be related to the results of dynamic mechanical tests (Johnson et al. 1994). However, the use of wave amplitude in acoustic methods either requires very consistent acoustic coupling between the transducer and the test material or the use of deconvolution with reference signals to avoid the associated instabilities (Kapur et al. 1990).

Measurements in signal attenuation (usually derived from the peak amplitude of a waveform) are also used as indices for monitoring resin cure. In addition to attenuation from viscosity change, losses can be caused by conversion to heat, scattering from reflections, refraction from the coherent redirection of the wave, and/or mode conversion. Moreover, attenuation is also frequency-dependent, making the analysis highly complex (Heyman et al. 1989).

Acousto-ultrasonics

Acousto-ultrasonics is an analytical ultrasonic NDE technique that combines the advantages of acoustic emission and conventional UT. In AU, a passive acoustic emission system with its signal analysis methodology is combined with an active ultrasonic transmitter having a configuration similar to a UT send-receive system. The first AU research was conducted to detect flaw distribution and evaluate associated changes in mechanical properties of fiber-reinforced composites (Vary and Lark 1979). Subsequently, AU techniques have been used for a wide range of applications (Duke 1988).

Typical uses of AU are with laminated composites and composite-like materials that are highly heterogeneous and anisotropic. As ultrasonic waves propagate through such materials, overlapping, scattered, and mode-converted signals are inevitable. However, this disparate feature also permits AU to simultaneously convey information in multiple wave modes. Moreover, unlike the conventional UT that usually measures velocity and attenuation, AU affords more flexibility to assess different properties using diverse parameters.

Since its development to evaluate fiber-reinforced composites (Vary and Lark 1979), most AU studies have concentrated on the post-evaluation of the formation and performance of composites and composite-like materials (Duke 1988). It was not until 1987 that the first AU research relating to the cure monitoring of wood adhesion had been reported, in which a lap joint of hard maple was used with a transmitter and receiver mounted on either side to monitor the curing of an epoxy bond line (Beall 1987). As the waves propagated through the bond line, they interacted with the curing resin and RMS transmission was used to monitor curing development.

Because of the similarity between fiber-reinforced composites and wood, AU is very appropriate for wood and wood-based materials. Most wood products involve the use of adhesives, and a high proportion of these products are hot-pressed panels. Since the hot-pressing process is dynamic and its products are highly dependent upon processing factors, the technique required for cure monitoring must not only minimize the interference caused by the press but also provide a precise feedback. Because multiple reflections are one of the prerequisites for AU, well-defined pathways are not important. Moreover, since AU provides various parameters to assess different mechanical properties of interest, it is an excellent candidate to monitor the hot-pressing process.

Acousto-ultrasonic techniques can be classified as wide-band and narrow-band systems. Wide-band systems use single spikes or half-cycle square waves to excite wide-band transmitters to provide broad frequency signals. Tone-burst is commonly utilized by narrow-band systems with either wide-band or resonant transmitters to deliver a fixed input frequency. Narrow-band signals can also be generated with resonant transmitters excited by single spikes or square waves to deliver the particular characteristic frequency spectrum of the transducer.

Selection of the signal excitation mode for the transmitter and the bandwidth of the receiver are well understood. Sensitivity is a concern when the test material is highly attenuative and dispersive. Because of its inhomogeneity, porosity, and anisotropy, wood is a material with high attenuation and dispersion. Therefore, a single spike pulse does not develop sufficient energy for the wave to travel through composite mats, especially in the early stage of pressing. Tone-burst permits the transmitter to deliver the maximum energy at a well-defined frequency, but at the expense of frequency content.

In contrast with the transmitter input signal of up to several hundred volts, the signals from the receivers range from microvolts to several volts. The received signals may also exhibit frequency characteristics that are much different from the input. For example, if wide-band systems are used, high frequency components in the signals may be attenuated or filtered out due to interactions with the test material. Although wide-band receivers can cover a wide range of frequencies, their sensitivities are lower and the signal-to-noise ratio decreases as the bandwidth increases. Such transducer losses can be improved by operating near the resonant frequency of resonant receivers. However, if the received signal has a wide frequency range, a resonant receiver will overemphasize the peak frequency and mask other frequency components.

Common piezoelectric transducers are affected by the level of temperatures used in composites pressing. Waveguides are useful to protect transducers from such unfavorable conditions. When ultrasound transmits in the axial direction of the waveguide, it spreads and interacts with the side wall, which introduces mode conversion (Hughes 1949). Multiple wave modes are especially useful for monitoring the physical/mechanical changes of curing resin from liquid to a gel and finally to a hardened solid. For example, the attenuation of shear waves is infinite when the resin is in a liquid form, which allows only longitudinal waves to propagate. Since longitudinal waves reflect shear and bulk behaviors, attenuation for both shear and longitudinal waves will decrease as cure progresses (Lindrose 1978). Ultrasonic techniques combining embedded acoustic waveguides (AWG) have been used to monitor the cure progress of diverse materials and composites (Harrold et al. 1996). This combination is common when transducers are required to be isolated from the harsh conditions of industrial environment. Although AWG were developed to guide ultrasound energy through the test material, a large fraction is not guided but is carried via plate modes in the host material. Therefore, the function of the embedded waveguide is only to couple energy in and out of the material (Ehrlich et al. 1994).

AU parameter selection

One of the objectives in this study was to determine which AU parameter could be best correlated with strength development of particleboard during pressing. Like other NDE techniques, the most suitable AU parameter for a particular property is determined on a case-by-case basis. This requires giving attention to the experimental setup and procedure since experimental conditions and changes in material properties can greatly affect the transmission (Kiernan and Duke 1991).

A significant effect of elastic anisotropy on wave propagation is that the energy flux vector tends to align with the direction of highest stiffness nearly irrespective of the original direction of the wave. The highest velocity and lowest attenuation can be observed in the highest stiffness direction, and hence it appears to present a "path of least resistance" for wave energy (Dickens et al. 1996). Therefore, the two most common parameters used in ultrasonic measurements, velocity and attenuation, might not be sensitive enough to represent the diverse curing conditions in pressing.

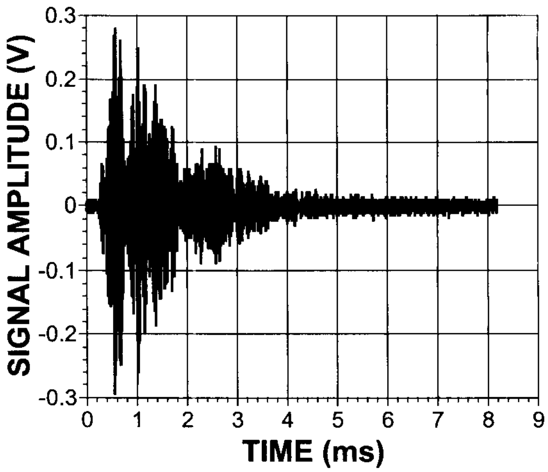

FIG. 1. Typical waveform of AU signal in time domain.

As shown in Fig. 1 (a typical signal in this study), there was much background noise from the mechanical movement of the press, vibration of the hydraulic pump, and oil circulation of the heating system. Therefore, flight-time parameters that depended on the threshold level, such as arrival time, transit time, threshold crossings, and wave duration, were difficult to determine. Although an ensemble averaging technique can be used to enhance the measurement of these parameters by averaging serial signals to decrease background noise, such a technique also may introduce incorrect information and/or eliminate useful parts of the waveform associated with the dynamic changes of pressing process and rapid curing. Consequently, flight-time parameters derived from the ensemble averaging technique were judged to be inappropriate for this study.

Spectral analysis is an alternative approach to extract AU parameters from the received signal by performing FFT to transform the signal to obtain its frequency spectrum in the form of magnitude/frequency or power spectrum density/frequency plots. Based on the frequency spectrum, signal filtering is performed to eliminate the electrical or mechanical interference from the system. Because of the use of high-power, narrow-band tone-burst as the input signal in this study, spectral analysis showed that frequency components of the received signal were still confined to the narrow range of the input signal frequency; therefore, there was little value in spectral analysis.

Because of the use of waveguides, the received signal contains spurious delayed ultrasonic echoes, also termed trailing echoes (Jen et al. 1997). Such trailing echoes always arrive later than the directly transmitted or reflected longitudinal echoes, and may be encompassed within the signals containing desirable information. Because of this, time-domain gating could not be used in the study, thereby necessitating an AU parameter one that included the maximum information of the entire wavetrain with minimal interference.

The simplest form of description for a random signal that includes the whole wave envelope is given by its mean-square value or the positive square root of this quantity known as root-mean-square (RMS) voltage (Beauchamp and Yuen 1979). RMS measures signal amplitudes averaged over a period of time to represent the signal intensity:

$$RMS = \sqrt{\frac{1}{T}\int_0^T V^2\,dt}$$

where V is the voltage of the signal and T is the period of voltage measurement.

Because the background noise in this study came primarily from mechanical vibration, the additional level of RMS voltage from this continuous noise was similar in every signal, and, therefore, would not affect signal comparisons. Furthermore, RMS has been used successfully in a series of studies in monitoring curing behavior of wood adhesives in laminates (Beall 1989, a, b; Biernacki and Beall 1993). In addition, it has been shown that moisture, while it can affect AU parameters such as transit time and time centroid, does not affect RMS over a wide range of moisture content (Beall et al. 1998). Thus, RMS was selected as the AU parameter to best represent the AU transmission level for this study.

EXPERIMENTAL APPROACH

Board fabrication and formation

To simulate commercial particleboard materials, both furnish and resin were obtained from Georgia-Pacific Corporation. The furnish was a blend of 20% white fir, 20% Douglas-fir, and 60% pine particles that had passed through a screen with openings of 12.7 by 1.53 mm. Phenol-formaldehyde (PF) resin (GP®70CR66) was used for the preliminary study and urea-formaldehyde (UF) resin (GP®3635) for the main study. Before blending, the furnish was kept in a 6% EMC room. To reduce the variability that might be caused by additives, the UF resin included a heat-activated latent hardener. Both PF and UF resins were stored at 5°C to prolong storage life and assure stability.

Prior to blending, resins were removed from cold storage and kept at 20°C to maintain a constant viscosity. Blending was done in batches in a drum without other additives. The spray system was a single internal mix air-atomizing nozzle with 480 kPa air pressure and 210 kPa liquid pressure to produce a flat spray pattern. Furnish moisture content after storage was 7 ± 0.5%; after blending it was 10 ± 2%. Since it is very difficult to make uniform three-layer particleboard without an automatic forming system, only homogeneous boards were made. The mat was hand-formed on a 5-mm-thick aluminum caul that was the same area as the platen. The mat was prepressed at 2 kPa to to avoid problems of surface precuring, and to reduce variability in initial mat density. Before the mat was placed in the hot-press, two type-T thermocouples were inserted to record temperature changes in the core and surface. The surface thermocouple was located between the mat and caul, and the core thermocouple was placed in the vertical center of the mat, both junctions at a 100-mm depth (from the edge).

The mat was pressed in a single-opening press with a maximum system pressure of 15.5 MPa. The platens were 610 × 610 mm and were oil-heated. The press was position-controlled using a computer that was also used for data acquisition. Target thickness was reached within 60 s (press closing time) at a maximum pressing pressure of 3 to 4 MPa, depending on board variables. After reaching the target thickness, the pressure was reduced to avoid further densification. The area of the particleboard was fixed by the platen dimensions of 610 × 610 mm. Panels had a target density of 650 kg/m^3. When removed from the hot-press, boards with UF were forced-air cooled with 5°C air to room temperature to arrest the curing reaction, and were stored in a 12% EMC room.

AU equipment

With the previously discussed limitations, a narrow-band AU system was used that consisted of three parts: transmitting equipment, waveguides, and receiving equipment. Figure 2 shows the block diagram of the AU system and its integration with the press.

The transmitting equipment used included: (1) frequency generator (Krohn-Hite 2200) to establish a continuous sinusoid waveform with a fixed frequency of 60 kHz; (2) reference sweep generator (OK Electronics 204) to gate the continuous waveform into tone-burst with the duration of 333 μs and repetition rate of 50 Hz; (3) power amplifier (Krohn-Hite 7500) to increase the amplitude of the tone-burst to 300 V peak-to-peak; and (4) transmitter (AET 175 piezoelectric transducer) to transform the electric voltage into ultrasonic waves.

Stainless steel waveguides (200 mm long) were screwed into threaded wells in the platens with the other end having a conical horn attached to the transducers. This configuration not only protected transducers from the high temperature of the hot-press but also integrated the transducers to make each platen act as a transmitter or receiver. The waveguide arrangement at opposite edges of the platens was to assure maximum interaction between the AU signal and the particulate materials.

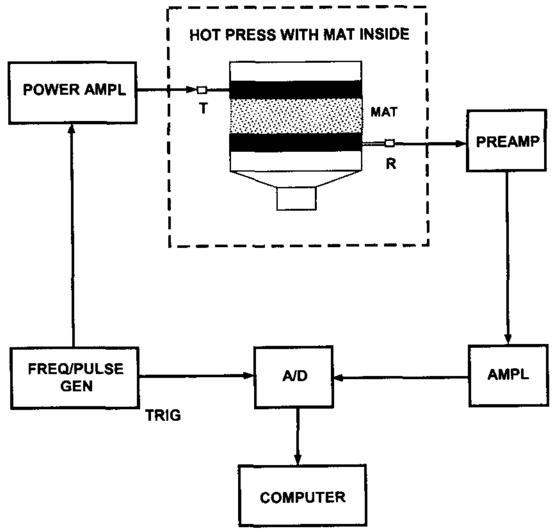

FIG. 2. Schematic diagram of the AU system.

The receiving equipment included: (1) receiver (AET 75 piezoelectric transducer); (2) preamplifier (AET 140B) with 40 dB gain and 30 kHz to 1 MHz bandpass; (3) amplifier (AET 208) for an additional 20 dB gain; and (4) analog-to-digital converter (Sonix STR 832) to acquire the signal. The received signal was digitized at a sampling rate of 1 MHz for 8192 points. Individual signals were acquired at a 1-s interval during pressing.

Experimental trials

A feasibility study was made to examine the overall response of AU transmission to resin curing. The mat was adjusted for equal mass for the two experiments: using 6% resin in one and no resin but the mass equivalent in furnish in the other. Because of its slower curing rate,

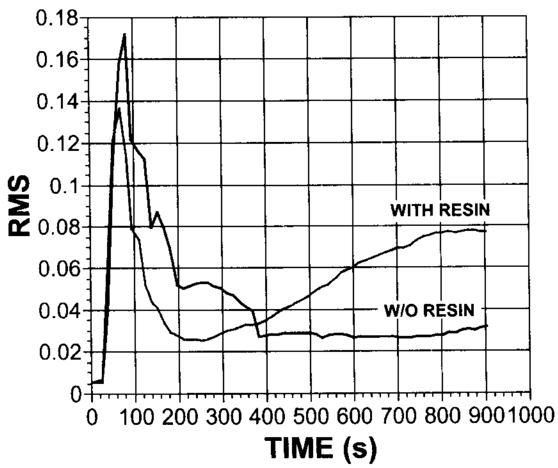

FIG. 3. Preliminary experiment for AU transmission of 20-mm particleboard pressed at 200°C with and without 6% PF resin.

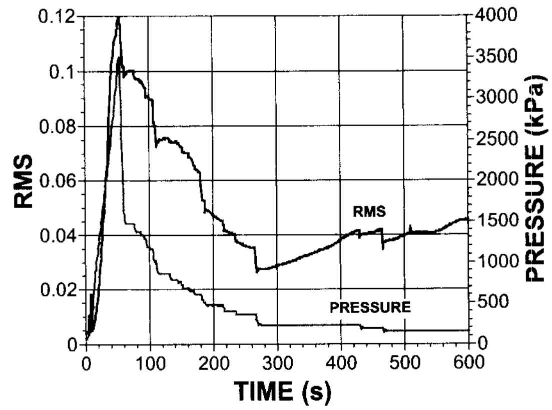

FIG. 4. Variations in press pressure and RMS output during the 600-s press cycle of 20-mm particleboard pressed at 160°C and with 6% UF resin.

PF resin was used to prolong the reaction. The boards were made at 200°C with a 20-mm target thickness.

Following the resin-no resin feasibility test, a board of 20-mm thickness, 6% UF resin content, and 160°C press temperature was made in a 600-s press cycle. The RMS output obtained, which was assumed to reflect the extent of strength development of the board, was used as a master curve for a series of shorter duplicate runs with endpoints of 240, 255, 270, 285, 300, 315, 330, 345, 360, 375, 390, 420, 480, and 540 s. Each board was cut into 50 specimens for IB tests (ASTM D 1037). The 50 IB specimens were averaged to represent the IB value of a single board, which was used as a means of assessing the extent of strength development. The IB results were used to map the AU transmission (RMS) curve to establish the correlation between AU transmission and strength development of the board.

RESULTS AND DISCUSSION

The AU transmission (RMS) of the resin-no resin feasibility study is shown in Fig. 3. Both curves went through peaks of RMS output, and then declined as the mat consolidated. The curve without resin had a very erratic decrease to a minimum level at around 380 s and no increase thereafter. The curve with resin showed a much more rapid decrease to a minimum at about 200 s, and then at about 270 s increased to a plateau that started at 800 s. Obviously, the difference between the curves was affected by the presence of resin that served as a linkage between the furnish particles, increasing the board stiffness, and, hence the AU transmission level.

From these results, the AU technique showed promise for monitoring resin curing during pressing. However, many phenomena in these two curves were in need of clarification:

- Does the value of the RMS curve represent the degree of bond strength development?
- What is the true meaning of the final plateau in resin curve?
- Can the AU technique distinguish subtle differences of various mat or press conditions? If so, how sensitive would it be?

In this paper, we address the first two of these questions.

Figure 4 shows the AU transmission (RMS) and pressure during pressing, which were the data of the board having the longest press time (600 s). Both RMS output and press pressure reached maximum values in 60 s, and then declined to a minimum at 270 s. Thereafter,

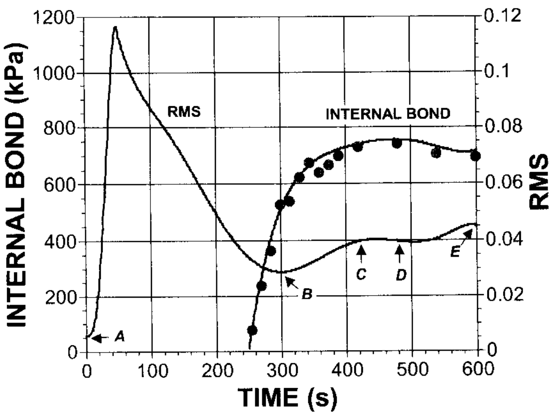

FIG. 5. IB and RMS output at different press times, where the RMS is for the board with the longest press cycle (600 s) and IB data were obtained from boards removed from the press at different press times.

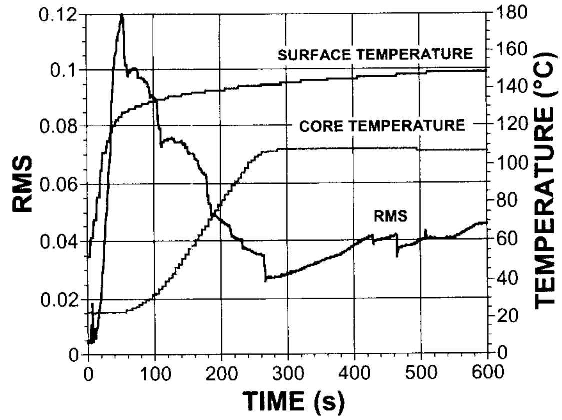

FIG. 6. Changes in press pressure and mat temperatures during the press cycle.

the press pressure was maintained at a minimum to hold the board at the intended thickness. In the meantime, the RMS output began to increase, reaching a plateau at about 420 s. Prior to minimum press pressure, the RMS output was strongly pressure-dependent. The buildup of stress in the mat, caused by rapid closing, resulted in a very high ultrasonic coupling pressure between the mat and platens. However, with stress relaxation, this coupling pressure decreased to a constant level, which could be verified by the constant RMS output level of the board without resin in the preliminary study, as shown in Fig. 3.

As compared with the results using PF resin in the preliminary experiment shown in Fig. 3, the RMS output in Fig. 4 also decreased to a minimum but with about a 70-s delay. The lower temperature used in UF boards was the main reason for the delay. Although both boards contained 6% resin, the higher solids content of UF, resulting in the lower moisture content in the mat, also contributed to this time lag. One very interesting phenomenon shown in both plots was that the minimum RMS value for all three boards, with or without resin but of the same density, was at the same level (0.026 to 0.027 V). This suggested that the uncured core was the dominant region of the mat and would attenuate or disperse most of the acoustic energy.

Figure 5 shows results of measured IB values from 14 boards at different press times with the RMS output curve superposed. The RMS output curve for the longest press time (600 s) was smoothed for clarity. Based on the RMS curve variation, it can be divided into 4 segments: A–B (0 to 300 s), B–C (301 to 420 s), C–D (421 to 480 s), and D–E (481 to 600 s) to represent different stages of bond development.

Stage A–B: Press pressure dependence

In stage A–B, the RMS output depended mainly on the change of the press pressure. When compressed to the target thickness, the built-up stress from the mat caused the highest ultrasonic coupling pressure between the mat and platens and, therefore, a maximum in the RMS output. With the release of trapped vapor, relaxation of the built-up stress, and progression of resin curing, the press pressure and RMS output decreased to a minimum at the end of this stage. As a rule-of-thumb in the industry, UF resin is expected to cure within 30 s after the core temperature reaches 100°C. Although the core temperature had reached 100°C at 243 s (Fig. 6), the board had only developed 67% of maximum IB strength at the end of stage A–B, implying that bond development was not solely temperature-dependent. This suggests that curing progress is not only dependent on temperature, but is also influenced by moisture distribution in the mat. Although the heat content released by the vapor caused the temperature to increase, the consequent accumulated moisture resulting from the condensed vapor could interfere with the curing reaction of the UF resin, delaying bond development.

Stage B–C: Development of bond strength

The increase of the RMS output defined the transition to stage B–C. Since the pathway of wave propagation was through the thickness of the board, any uncured layer or area in the mat would act to attenuate or disperse the AU energy. During this period, the bonds that developed between furnish particles increased the board stiffness, increasing the IB, and therefore the RMS output. At the end of this stage, IB had achieved 98% of its maximum.

Stage C–D: Completion of bond development

The beginning of stage C–D was defined as the point where the RMS output curve reached a plateau. Theoretically, with the resin completely cured, both the apparent strength of the board and the AU transmission level (RMS) should cease to increase. This can be observed visually from C–D in Fig. 5, where both curves reached plateaus at about the same time. During C–D, the board gradually developed the remaining 2% of its strength.

Stage D–E: Deterioration of bond quality

A decline of IB strength and leveling of RMS initiated stage D–E. After the board developed its maximum IB in stage C–D, the effect of the extended pressing began to impact bond quality. Although an increased press time can improve board properties, extended pressing can also degrade the board. At temperatures higher than 150°C, thermal decomposition of methylene linkage takes place that degrades UF resin (Szesztay et al. 1993). Instead of decreasing with the IB throughout this

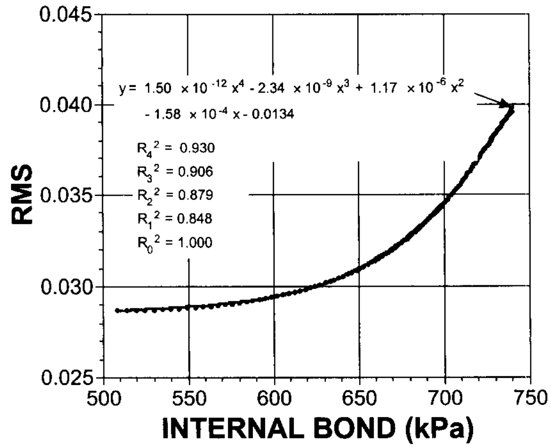

FIG. 7. Relationship of RMS voltage to internal bond after 300 s (minimum RMS output).

stage, the RMS output very slightly decreased in the first 40 s, and increased thereafter. This could be caused by the effect of the degraded board surface increasing the coupling of ultrasound. By the end of this stage, the board had lost about 5% of its IB strength, an effect that is commonly observed with UF resin in overextending press time.

The relationship of RMS output to IB over the three segments (B to E) is shown in Fig. 7. Note that the change in RMS is greater at higher IB values, and therefore has its greatest sensitivity in the desired range of press opening.

Based on the preceding results, the AU technique developed in this study has demonstrated a capability to monitor the strength development of particleboard and to assess its bond quality during pressing. After stage A–B where the RMS depended mainly on the change of press pressure, the increase of RMS output reacted directly to the increase of the board strength through stage B–C. As the resin completely cured, which was verified by the IB strength in stage C–D, the RMS output reached a plateau. With extended pressing, the RMS output in stage D–E reflected the degraded condition of the board. In conclusion, by real-time observation of the change of RMS output using the methodology of this study, the strength development of the board during pressing can be monitored *in situ.*

The technology and principles described are now covered under a patent (Beall and Chen 2000).

CONCLUSIONS

Although only a limited number of boards were made, the AU technique developed in this study has shown promise for monitoring the strength development of particleboard during pressing. Based on the results and discussion, the following conclusions can be drawn:

1. The use of waveguides attached to the platens provides an efficient means of transmitting signal without intruding in the pressing process. Such configurations also allow this technique to be adapted easily into the industrial application with a minimum modification of the press.
2. RMS is an effective index for monitoring the resin curing which correlates with the IB strength development of the board during pressing.

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