MONITORING IN-SITU DENSITY CHANGE FOR IN-PROCESS MEASUREMENT AND CONTROL OF HOT-PRESSING

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Abstract
The hot-press is undoubtedly a key piece of equipment in composite panel production. Process control of the pressing procedure can be divided into preprocess, in-process, and postprocess measurement and control stages. This paper presents an in-process measurement and control technique during the pressing cycle and discusses application possibilities based on the study. There are different curing conditions between the core layer and the surface layers of a panel, resulting in the core layer always having higher in-press expansion than the surface layers. This in-press expansion can be monitored by measuring in-situ density changes as the press platens open. It is proposed that when a predetermined value of controlled expansion is reached, the press process controller can immediately stop normal press opening and prolong the pressing cycle to ensure sufficient resin cure and prevent substandard production. Results showed that both the prolonging and secondary closing procedures could improve panel performance and prevent substandard production. In-process measurement and control of hot-pressing is made possible by monitoring internal density changes during press opening.

The hot-press is undoubtedly a key piece of equipment in composite panel production. It determines the performance of products and the processing efficiency of the whole production line. There is a philosophy that says in simple terms: when the press closes, 90 percent of the cost of production has been incurred and 96 percent of the oriented strandboard (OSB) panels must be good panels because quality can not be added in the warehouse (4). In pressing, a number of factors are involved, including the resin type and level, wax type and level, pressing temperature, wood species and furnish geometry, mat density and distribution, mat moisture level and distribution, press closure rate, and pressure. As is usual in the board manufacturing process, all of these factors interact.

Wood-based composites such as OSB, plywood, laminated veneer lumber (LVL), medium density fiberboard (MDF), and particleboard are typically cured under pressure in multi-platen presses using thermosetting adhesives. Most wood-based composites processing done today is controlled by a fixed "time and temperature recipe" based on empirical observation of the process variables and resin chemistry (5). These recipes must be overly conservative to allow for the variability inherent in the process. The result is a costly compromise in both process time and product quality. In addition to the common lot-to-lot variations associated with adhesive systems, the processing of wood-based composites is further complicated by variations in wood species, moisture content (MC), pH, and seasonal plant environmental effects.

Process control of the pressing procedure can be divided into preprocess, in-process, and postprocess measurement and control (8). Preprocess measurement and control may be required to monitor or control the materials or parts entering the process or to control the product or the process based on input measurements (2). The measurement may include physical or chemical characteris-
tics of the materials moving into the blending and forming process. The physical and chemical characteristics of materials include furnish MC and pH value, species and mixture ratio, resin and wax characteristics, furnish geometry, and so on. The resin and wax level, mat density and distribution, and mat MC and distribution are major factors that should be measured and monitored in the blending and forming process. During the past decade, a lot of new on-line, continuous measurement techniques have successfully been used in the panel industry, for example, in-line mat density and furnish moisture measurement.

The postprocess control technique is based on the measurement of quality characteristics of the completed product. These quality characteristics are the physical and mechanical performance of the panel as determined from laboratory evaluation after pressing. To reduce substandard production costs, some new in-line measurement and monitoring techniques are either currently being used, or being developed for future use. Example of these include in-line panel thickness measurement, in-line real-time monitoring of density profiles, and in-line nondestructive strength measurement of panels.

Control applied from in-process measurement is based on the measurement of a controlled quality characteristic of the product itself as it is generated. This in-process measurement and control can initiate signals to regulate or stop the process in order to prevent substandard production. Pressing temperature, pressing cycle, closure rate, pressing pressure, and press platen position can be precisely measured and controlled. These pressing parameters undoubtedly are very important control factors. However, the measurement and control of these parameters are not an in-process measurement and control technique. It may be important to design in-process measurement devices within the pressing equipment to measure and control mat performance during pressing.

**IN-PROCESS MEASUREMENT AND CONTROL**

Springback is a thickness-swelling phenomenon of wood-based panels, for which there is a lack of a definition. Kelly (3) defined springback as the irreversible thickness swelling (TS) that occurs when a finished particleboard, in equilibrium with a given elevated humidity, or liquid water, is subsequently returned to the original humidity and temperature condition. Neusser (7) and Deppe and Ernst (1) have used the term springback to characterize the thickness increase of particleboard immediately out of the press. This expansion occurs for most particleboard upon pressure release in the hot-press. Neusser (7) used this initial expansion as a measure of the curing rate of various adhesives; the more completely the resin cured in the press the less was this immediate expansion. Deppe and Ernst (1) found this initial expansion to be a problem with very short press times at MCs above 10 percent. This initial or immediate expansion is not a problem in properly produced particleboard where the resin is sufficiently cured.

The following two definitions were used in this study:

**In-press expansion:** In-press expansion results from pressure release of the press. The in-press expansion occurs during and after press opening. In-press expansion always results in the out-of-press panel thickness being greater than the real distance between the top and bottom press platens. Failing to reach target density due to high in-press expansion can result in poor product performance.

**Out-of-press springback:** Out-of-press springback results from nonuniform panel MC distribution and subsequent equilibration at room conditions after the panel leaves the hot-press. When moisture is absorbed by the panel after the panel is out of press, an increase in thickness takes place. However, the panel generally does not return to its original thickness when the absorbed moisture is removed by drying. This increased thickness after swelling and shrinking of the panel is called irreversible swell (6).

In-press expansion is an important characteristic of composite panels as it has an effect on many board properties. One of the direct results is panel thickness variation. In-press expansion is mainly dependent on the elastic recovery of wood materials and internal bond strength of the panel. If the resin is not sufficiently cured internal bond will be low, resulting in high in-press expansion which will affect the product quality. Delamination will occur in severe cases. Although in-press expansion is a phenomenon which cannot be avoided, expansion that is the result of insufficiently cured resin can and should be controlled.

As there are different resin curing conditions between the core and surface layers of the mat, the core layer always has a tendency to have greater in-press expansion than the surface layers. Insufficient development of internal bond strength results in significant expansion differences between the core and surface layers when press pressure is decreased at the end of the pressing cycle. Suppose the expansion in the core layer is significantly higher than the surface layer expansion when pressing conditions are suitable for acceptable product quality. Suppose the expansion can be precisely measured as the press platen opens. When the predetermined value of the controlled expansion is reached, a press process controller could be used to stop the normal press opening procedure immediately and prolong the pressing cycle to make sure that the resin cures sufficiently and prevents substandard production. These in-process measurements and controls would be finished before pressing pressure goes to zero.

To prevent the delamination or blowout resulting from suddenly releasing pressing pressure, there is the degas stage at the end of the pressing cycle. The in-press measurement and control of expansion can be done during the degas stage, which is just seconds before the end of the pressing cycle. Many reasons can cause variation in expansion, for example, resin cure rate, hardener level, pressing temperature, pressing time, wood extractives, mat MC, mat density variation, wood species and variation in press control.

The objectives of this study were to develop an in-process measurement and control technique during the pressing cycle and to discuss application possibilities based on the results. The main study included measuring expansion differences among the vertical layers during the press opening procedure and the effects of prolonged pressing cycles on panel performance.

**EXPERIMENTAL METHOD**

**BOARD FABRICATION**

All boards were fabricated at the following conditions. Southern pine fur-
nish was obtained from an OSB mill. The furnish was conditioned to 4.7 percent MC. The target panel density and thickness were 43 pcf (0.689 kg/cm³) and 0.5 inch, respectively. A commercial liquid phenol-formaldehyde resin was applied to the furnish at a rate of 3.5 percent per dry wood weight in a rotating blender. An emulsion wax was applied at a rate of 0.5 percent per dry wood weight. A special mat forming technique was used that incorporates a collapsible forming box, in which the mat is formed between two pieces of OSB panel material. The mat is then trimmed to its final desired size while it is held prepressed between the OSB panel materials. This technique allows for trimming of the loose edge of the mat prior to pressing and was developed specifically for use with our in-press radiation monitoring system that requires a well-formed mat edge for enhanced in-situ radiation measurement accuracy. Mats measured 18 by 18 inches before trimming and 16 by 16 inches after trimming.

**Pressing and in-situ density measurement**

All panels were produced at a platen temperature of 204°C and a press closure time of 20 seconds. Closure time was defined as the time required to reach final position from the initial contact of the mat with the upper platen for the up-acting press. Table 1 shows press schedules for all boards. Schedules A, B, D, and F were used to measure differences in in-press expansion. Under the same total pressing cycle (330 sec.), panels were made based on schedules Control and C to F, to study the effects of prolonging and secondary closing procedures on panel performance. The prolonging procedure means that the ongoing press opening is interrupted before press pressure decreases to zero and the press is maintained at that position for an extra pressing period. The secondary closing procedure means that the ongoing press opening is interrupted before press pressure decreases to zero and the press is again closed to its final position where it remains for an extra pressing period. The intermediate opening position was selected based on prior experiments where press opening position was related to pressure.

The three in-situ radiation beams for density measurements during pressing were positioned at 18.7, 50, and 81.3 percent of mat thickness, measured from the top of the mat (9). The position of the moving platen is determined by a programmable logic position-control system. The press control system, radiation monitoring system, and temperature acquisition electronics allowed radiation count data, press position, compression pressure, and temperature to be recorded in real-time.

**Testing**

After pressing, thickness \( T_1 \) of each board was immediately measured. Then boards were conditioned at 65 percent relative humidity and 20°C until they reached equilibrium with the surrounding environment. The thickness of each board after conditioning \( T_2 \) was then measured. The out-of-press springback of each board out of press was calculated using the following equation:

\[
\text{Out-of-press springback} = \frac{\left( T_2 - T_1 \right)}{T_1} \times 100 \%
\]

where \( T_1 \) = panel thickness immediately after pressing; \( T_2 \) = panel thickness after conditioning.

The 24-hour TS and water absorption (WA) tests were performed in accordance with the ASTM 1037-92 A (1992) procedure. The total thickness swelling (TTS) for a given specimen was calculated as:

\[
TTS = \frac{(T_{soak} - T_o)}{T_o} \times 100 \%
\]

where \( T_{soak} \) = specimen thickness after 24-hour water soak; \( T_o \) = specimen thickness before 24-hour water soak.

At the end of each water-soak exposure, all specimens were again conditioned to equilibrium in a chamber under the 20°C and 65 percent relative humidity conditions. Their weight and thickness \( T_{con} \) were again measured. The irreversible thickness swelling (ITS) was calculated as:

\[
ITS = \frac{(T_{con} - T_o)}{T_o} \times 100 \%
\]

where \( T_{con} \) = thickness of specimens conditioned to equilibrium in a chamber under 20°C and 65 percent relative humidity.

Reversible thickness swelling (RTS) was calculated as:

\[
RTS = TTS - ITS
\]

The ratios of ITS and RTS on the TTS were calculated as:

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Control</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting position (in.)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>1st closure rate to final position (in./sec.)</td>
<td>0.081</td>
<td>0.875</td>
<td>0.875</td>
<td>0.109</td>
<td>0.109</td>
<td>0.109</td>
<td>0.109</td>
</tr>
<tr>
<td>Hold at final position for (sec.)</td>
<td>290</td>
<td>290</td>
<td>290</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>1st open to intermediate position ( a ) (in./sec.)</td>
<td>No ( b )</td>
<td>0.875</td>
<td>0.875</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>Hold at this position for (sec.)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>2nd closure rate to final position (in./sec.)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>0.007</td>
<td>No</td>
<td>0.007</td>
<td>No</td>
</tr>
<tr>
<td>Hold at final position for (sec.)</td>
<td>28.3</td>
<td>28.3</td>
<td>28.3</td>
<td>28.3</td>
<td>28.3</td>
<td>28.3</td>
<td>28.3</td>
</tr>
</tbody>
</table>

\( a \) The intermediate position is 104 percent of final position.

\( b \) The "No" means this step was not included for the schedule.
ITS ratio = \( \frac{IT}{IT + TS} \times 100 \) [%]

RTS ratio = \( \frac{RT}{RT + TS} \times 100 \) [%]

**DATA ANALYSIS**

Radiation count data taken through the mat during pressing is converted to *in-situ* density information. Based on the ratio of the air counts to the counts through the test material, *in-situ* densities at the top, middle, and bottom layers were calculated (9). The average densities over a 40-second period before and after the press begins to open to 104 percent of the final position were calculated. The density changes were calculated using the following equation:

\[
\text{Density change} = \frac{(D_2 - D_1)}{D_1} \times 100 \%
\]

where \( D_1 \) = average densities over a 40-second period before the press begins to open; \( D_2 \) = average densities over a 40-second period after the press begins to open.

**RESULTS AND DISCUSSION**

**PRESSING PRESSURE AND EXPANSION**

*Figure 1* shows the pressing pressure change on the mat with schedule Control during hot-pressing. The laboratory press used in this research was controlled by the position-control system. There was no step to control the final panel thickness. Automatic position control was governed by sensors that monitor platen position. The programmable logic controller (PLC) compared the position signal to the prescribed condition. Appropriate control signals were then sent to the mechanisms that control hydraulic oil pressure. The compression pressure, shown in *Figure 1*, is in fact identical to the total resistance to compression of the mat during the press cycle. After the press reached final position, the pressing pressure or total resistance to compression of the mat quickly went down due to stress relaxation, enhanced by rising internal mat temperatures. The pressing pressure was only 300 psi at a pressing time of 120 seconds. However, about 180 psi pressure needed to be applied to the mat to maintain final platen position moments before the press was ready to be opened. This counter pressure resulted in in-press expansion as pressing pressure was decreased at the end of the cycle from 180 psi to zero. The pressing time of schedule Control was 18 seconds per millimeter of panel thickness. The panel...
industry is using about 12 to 20 seconds per millimeter of panel thickness, therefore a similar degree of in-press expansion is an inevitable symptom for industrial production.

Table 2 shows that the out-of-press panel thickness in schedule A was 0.503 inches, which is significantly higher than the panels made under schedules B to F. The major reason is that the pressing cycle of schedule A was 165 seconds, much shorter than the 330 seconds pressing time of schedules B to F. Therefore, sufficient resin cure and stress relaxation was unable to occur resulting in higher in-press expansion.

### Density change and in-press expansion

Table 3 shows the in-situ density changes during the press opening procedure. Schedules A and B have similar pressing schedules only with different periods at which the press was maintained at final position. The pressing time at final position in schedules A and B were 125 and 300 seconds, respectively (Table 1). When press pressure was reduced, density reductions at the top, middle, and bottom layers of the panel during schedule B were 0.782, 3.102, and 1.037 percent, respectively. On the contrary, the pressing time at final position in schedule A was much shorter than both industry normal OSB pressing schedules and schedule B. When press pressure was reduced in schedule A, the densities of the three layers decreased more significantly than schedule B. Density reductions at the top, middle, and bottom layers were 3.577, 5.429, and 2.848 percent, respectively; these were much higher than those for schedule B. The reason for this degree of density reduction was that the pressing pressure reduction resulted in unusually high expansion. The out-of-press panel thickness for schedule A was 0.503 inch, which was higher than 0.460 inch for schedule B, proving that there was larger expansion in the case of schedule A. The 125 seconds of pressing time at final position in schedule A was not enough to sufficiently cure the resin in the core. The 1.37 percent out-of-press springback of panel A was significantly higher than other boards (Table 2).

Schedules D and F gave similar trends. The pressing time at final position in schedules D and F were 127 and 216 seconds, respectively (Table 1). The press pressure was decreased earlier in schedule D which resulted in 4.552 percent middle layer density reduction, comparing with 1.878 percent in the case of schedule F.

### Prolonging and secondary closing procedures

As was mentioned earlier, in-press expansion is inevitable in industrial panel production. In-press expansion causes, to some extent, the failure of the resin bond links that have formed in the mat if they are unable to contain residual stresses upon press opening. The failure of these resin bonds undoubtedly results in quality reduction of the product that is being made. In severe cases, product quality may be substandard. Two techniques are possible to reduce in-press expansion and avoid substandard panel quality: the prolonging procedure and the secondary closing procedure.

Table 2 shows the effects of the prolonging procedure and secondary closing procedure on the product performance. Panels C to F gave similar 24-hour TS results as the Control panel. Total pressing cycles of the Control panel and C to F were 330 seconds. Panels C and E used the second closing procedure. Panels D and F used the prolonging procedure. The press in schedules C and D began its first opening after being held at final position for only 127 seconds, while for schedules E and F this period was 216 seconds.

Figure 2 shows the compression pressure change of the panel for schedule D during hot-pressing. The compression pressure was only about 20 psi during the prolonging procedure. Figure 3 shows the pressure change of the panel for schedule E during hot-pressing. The compression pressure rose from about 20 to 120 psi during the prolonging pro-

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**TABLE 2. — Results of experimental boards.**

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Control</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstandard thickness (in.)</td>
<td>0.5056</td>
<td>0.5030</td>
<td>0.4600</td>
<td>0.4704</td>
<td>0.4948</td>
<td>0.4698</td>
<td>0.4764</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>6.691</td>
<td>0.737</td>
<td>0.810</td>
<td>0.774</td>
<td>0.729</td>
<td>0.737</td>
<td>0.746</td>
</tr>
<tr>
<td>Density (pcf)</td>
<td>43.2</td>
<td>46.0</td>
<td>50.6</td>
<td>48.3</td>
<td>45.5</td>
<td>46.0</td>
<td>46.6</td>
</tr>
<tr>
<td>Post springback conditioned at room temperature (%)</td>
<td>0.23</td>
<td>1.37</td>
<td>0.83</td>
<td>0.68</td>
<td>0.61</td>
<td>0.60</td>
<td>0.08</td>
</tr>
<tr>
<td>24-hour thickness swelling (TTS) (%)</td>
<td>0.24</td>
<td>32.8</td>
<td>25.7</td>
<td>23.5</td>
<td>24.7</td>
<td>22.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Reversible thickness swelling (RTS) (%)</td>
<td>4.29</td>
<td>2.13</td>
<td>1.39</td>
<td>2.91</td>
<td>4.26</td>
<td>3.23</td>
<td>3.27</td>
</tr>
<tr>
<td>Irreversible thickness swelling (ITS) (%)</td>
<td>19.7</td>
<td>30.64</td>
<td>24.3</td>
<td>20.6</td>
<td>20.5</td>
<td>19.2</td>
<td>22.2</td>
</tr>
<tr>
<td>Reversible thickness swelling ratio (%)</td>
<td>17.9</td>
<td>6.50</td>
<td>5.41</td>
<td>12.4</td>
<td>17.2</td>
<td>14.4</td>
<td>12.8</td>
</tr>
<tr>
<td>Irreversible thickness swelling ratio (%)</td>
<td>82.1</td>
<td>93.5</td>
<td>94.6</td>
<td>87.6</td>
<td>82.8</td>
<td>85.6</td>
<td>87.2</td>
</tr>
<tr>
<td>24-hour water absorption (%)</td>
<td>54.8</td>
<td>57.9</td>
<td>44.4</td>
<td>48.6</td>
<td>50.4</td>
<td>50.1</td>
<td>51.9</td>
</tr>
</tbody>
</table>

**TABLE 3. — In-situ density change at three mat locations during the press opening procedure.**

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Top</th>
<th>Middle</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-3.577</td>
<td>-5.429</td>
<td>-2.848</td>
</tr>
<tr>
<td>B</td>
<td>-0.782</td>
<td>-3.102</td>
<td>-1.037</td>
</tr>
<tr>
<td>C</td>
<td>-2.002</td>
<td>-4.268</td>
<td>-2.359</td>
</tr>
<tr>
<td>D</td>
<td>-2.138</td>
<td>-4.552</td>
<td>-1.468</td>
</tr>
<tr>
<td>E</td>
<td>-0.636</td>
<td>-1.859</td>
<td>-1.686</td>
</tr>
<tr>
<td>F</td>
<td>0.046</td>
<td>-1.878</td>
<td>-0.974</td>
</tr>
</tbody>
</table>
procedure, which was a little higher than before press opening.

Table 2 also gives the reversible TS and irreversible TS. The 24-hour total TS increases as the irreversible TS ratio increases. The 24-hour total TS of panel A was 32.8 percent and the irreversible TS ratio was 93.5 percent, which is higher than the other boards except for panel B.

**Conclusion**

About 180 psi of pressure applied to the mat maintains final platen position towards the end of a traditional hot-pressing cycle. Counter pressure of the mat results in in-press expansion as pressing pressure is decreased from 180 psi to zero. The in-press expansion is an inevitable symptom of industrial wood composite panel production.

As expected, there was significant in-situ density reduction during the press opening procedure. Both the prolonging and secondary closing procedures can improve panel performance and prevent substandard production. It may be possible to carry out in-process measurement and control of hot-pressing through monitoring the internal density change during press opening. A future study could be done to investigate the effect of prolonging and secondary closing procedures on panel thickness.

**Literature Cited**


