MAINTAINING LUMBER QUALITY IN PRESS DRYING BY MANIPULATING SAWING PATTERNS[1]

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ABSTRACT

Lumber is traditionally dried in kilns by processes that often take several weeks to complete. Considerable research has been conducted on more rapid processes. Press drying can dry common 25-mm-thick lumber in 1 to 2 hours instead of several weeks. However, little success has been achieved with this technique because intolerable drying defects usually accompany such rapid drying. This paper reports on a press-drying technique that offers considerable promise in avoiding honeycomb that usually develops. In this technique the sawing pattern of boards from logs is changed from the usual flatsawn pattern to quartersawn. The honeycomb that usually develops occurs at interfaces of ray tissue and the surrounding tissue and is caused by internal tensile forces that develop during drying. With flatsawn boards the wide face, which makes contact with the platens during drying, is parallel with the critical internal tensile forces. By using a quartersawn pattern, the direction of the critical internal tensile forces is effectively rotated by 90 degrees. The critical internal tension is then perpendicular to the wide face of the board.

The hypothesis of the study was that the compressive pressure of the press therefore opposes the internal stresses and prevents honeycomb. In this study honeycomb in press-dried quartersawn red oak was significantly less than in press-dried flatsawn red oak. Small compressive forces of the platens were less effective than large forces in reducing honeycomb in quartersawn oak, thus verifying the hypothesis.

Keywords: Drying, press drying, high-temperature drying, rapid drying, oak, drying defects, honeycomb.

INTRODUCTION

This paper is a report on a recent development that appears to allow rapid drying with a minimum of structural damage.

Wood as formed in living trees has moisture contents ranging from 40 to over 100% (dry basis). For most end uses, lumber must be dried to 6 to 15% moisture content to perform satisfactorily in service. Lumber is usually dried commercially in batch processes in dry kilns that may hold from 75 to 250 m^3. It is usually dried by proven schedules of temperature and relative humidity that vary with species of wood and lumber thickness. The temperatures and relative humidities are changed throughout the drying process according to moisture content level and represent empirically determined compromises between drying as rapidly as possible, but not so rapidly as to cause structural damage. This sensitivity to structural damage has prevented the acceptance of rapid drying processes (usually requiring high drying temperatures where wood becomes weaker) that could reduce drying time from days or weeks to only 1 to 2 hours.

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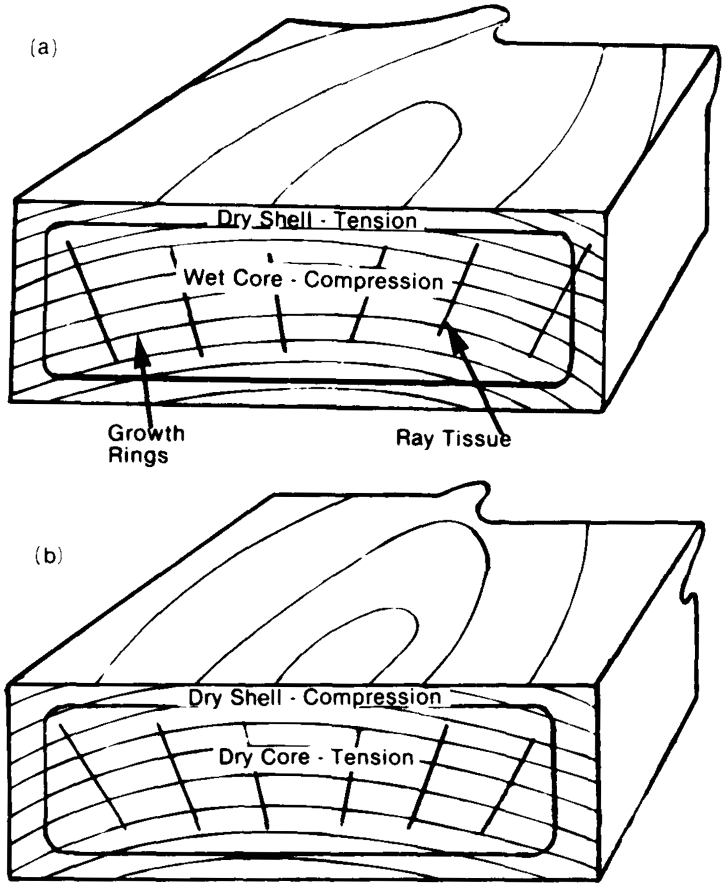

FIG. 1. End view of board showing development of drying stresses early in drying (a) and later in drying (b).

DRYING DEFECTS

Drying defects from structural failure can be traced to either differential shrinkage, stresses caused by liquid tension forces, or both. Differential shrinkage between the shell and core of lumber during drying results when the outer fibers in the shell dry and attempt to shrink. However, the core has not yet begun to dry or shrink, and consequently the shell is restrained from shrinking by the core. The shell thus goes into tension and the core into compression (Fig. 1a). If drying in the shell progresses too rapidly, it is stretched beyond the elastic limit and dries in a permanently stretched condition without attaining full shrinkage. Sometimes surface fractures occur during this stage of drying. As drying progresses, the core begins to dry and attempts to shrink. However, the shell is set in a permanently expanded condition and prevents normal shrinkage in the core. This causes the stresses to reverse—the core goes into tension and the shell into compression (Fig. 1b). The internal tension stresses may be severe enough to cause or contribute to internal fractures commonly termed honeycomb. Honeycomb can occur in conventional kiln-drying as well as in the more rapid drying processes.

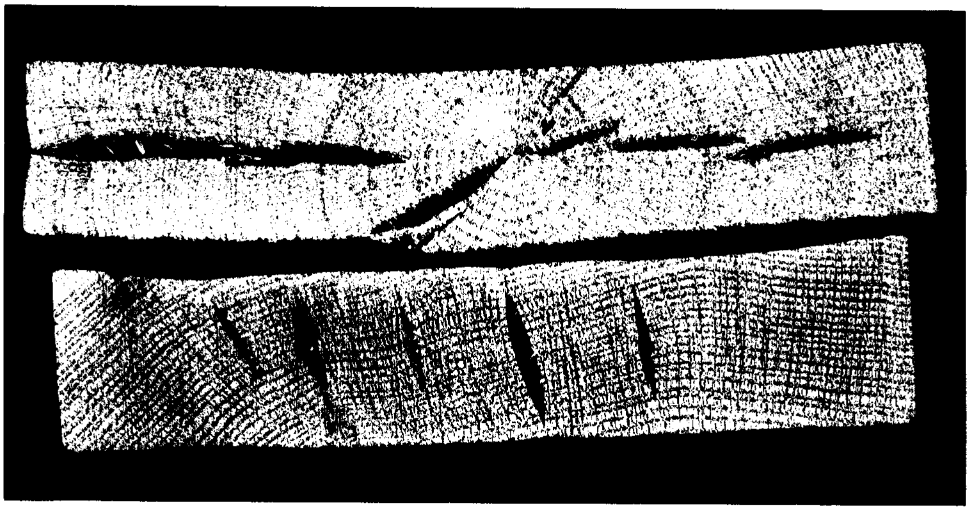

FIG. 2. Collapse and orientation of honeycomb fractures in quartersawn (top) and flatsawn (bottom) lumber.

Liquid tension forces lead to a drying defect known as collapse, and also contribute and may even be a major cause of honeycomb. Some of the cells of wood contain both air bubbles and water in the lumens and some contain only water. Liquid tension is set up in these cell lumens according to the capillary pressure equation:

$$p_o - p = 2\sigma/r \tag{1}$$

where

p_o = air pressure,
p = liquid pressure,
σ = surface tension of liquid, and
r = radius of air-water interface.

When a cell lumen contains no air bubbles, the air-water interface becomes the pit openings in cell walls. As evaporation progresses from the menisci of these pits, large tension forces develop according to Eq. (1) and pull inward on the cell walls, collapsing them and often causing honeycomb. Both honeycomb and collapse are illustrated in Fig. 2.

PAST RESEARCH IN RAPID DRYING

High frequency electrical energy, hot presses, and jet impingement drying have all been used in research on rapid drying processes. Schmidt (1967) press dried 25-mm-thick European beech from 80% moisture content to 7% at temperatures of 150 to 170 C in 1 to 2 hours. As long as tyloses were not present, the beech blanks were free from drying defects. Hittmeier et al. (1968) press dried nine hardwood species at 170 C platen temperature to 6% moisture content in from 20 to 200 minutes, depending on thickness (12 or 25 mm) and species. All species showed drying defects, ranging from minor for some of the lower density hardwoods 12 mm thick, to major for the higher density hardwoods 25 mm thick.

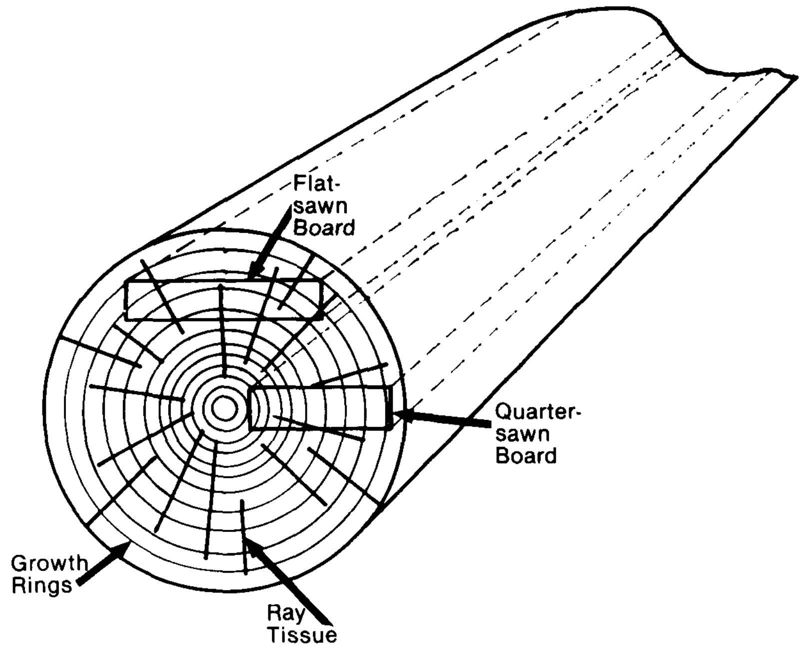

FIG. 3. Cross-sectional schematic of a log showing orientation of flat- and quartersawn lumber to growth rings and ray tissue.

Haygreen and Turkia (1968) press dried aspen and paper birch at 170 C in from 80 to 130 minutes and noted major defects in aspen heartwood. Quality of the paper birch was apparently acceptable. Wang and Beall (1975) press dried small 150-mm squares of red oak and noted moderate honeycombing and end checking. Chen (1978) press dried 25-mm-thick walnut and noted the presence of honeycomb. Alternating ambient air drying with press drying significantly reduced the occurrence of honeycomb but extended the drying time and did not completely eliminate honeycomb. Chen and Biltonen (1979) showed that prefreezing reduced but did not eliminate honeycomb in press-dried walnut. Chen (1980) did further press-drying work on American beech and yellow-poplar (12 and 25 mm thick × 100 mm × 254 mm) and found no occurrence of honeycomb. Rosen and Bodkin (1978) jet dried 25- and 50-mm-thick silver maple at air temperatures ranging from 107 to 204 C and air velocities of from 5 to 45 m/s. Drying times ranged from 1.2 to 37 hours. Honeycomb was present and severe in all 50-mm boards. It was less severe in 25-mm boards, but still present in 25 to 40% of the boards. Ward and Anderson (1964) reported complete freedom from any defects in drying 25-mm-thick red oak in 15 minutes by high-frequency electrical energy. Simpson (1980) found severe honeycomb and surface checking in high-frequency drying 25-mm-thick red oak.

SAWING PATTERN AND RAPID DRYING

How lumber is sawn from logs and how some of the key anatomical features of wood relate to sawing patterns are critical to defect development in lumber during drying. Figure 3 shows a cross section of a log and the two common sawing

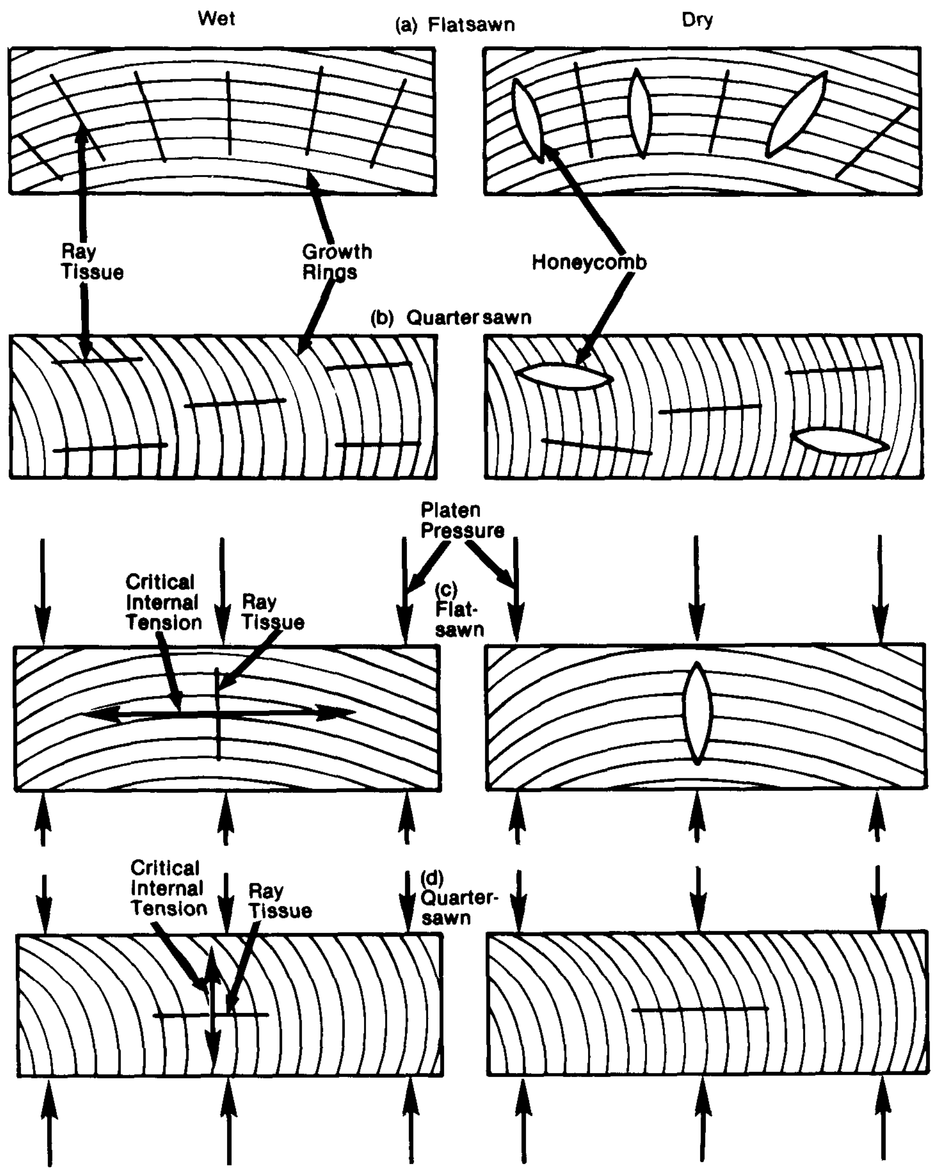

FIG. 4. Schematics showing how honeycomb can be avoided in press drying by manipulating sawing pattern: flatsawn board developing honeycomb (a), quartersawn board developing honeycomb (b), press-dried flatsawn board developing honeycomb (c), press-dried quartersawn board free of honeycomb (d).

patterns (flat- and quartersawn). Because of processing and yield efficiencies, most lumber is flatsawn, i.e., the growth rings are parallel to the wide face of the board and the ray tissue is perpendicular to the wide face. The less common sawing pattern produces quartersawn lumber where the growth rings are perpendicular to the wide face of the board and the ray tissue is parallel to the wide face.

Honeycomb fractures usually occur in ray tissue or at the interface of ray tissue

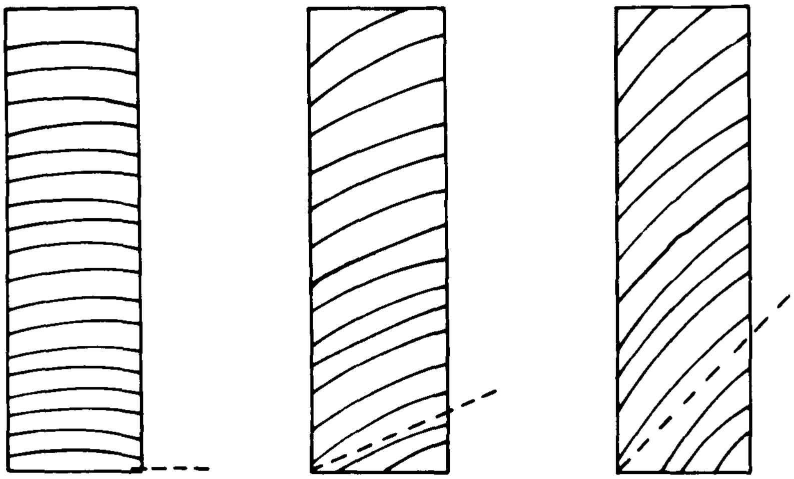

FIG. 5. Schematic of angle of growth rings to board faces in press drying.

and the surrounding tissue. Figure 2 shows a comparison of the orientation of honeycomb in flat- and quartersawn lumber. In flatsawn lumber the honeycomb fractures are oriented perpendicular to the wide face of the board, and in quartersawn lumber they are oriented parallel to the wide face of the board.

As mentioned earlier, the major barrier to development of rapid drying processes that require only 1 to 2 hours compared to the usual days or weeks in conventional dry kilns is honeycomb fractures. Manipulation of sawing pattern in combination with press drying between heated platens offers a potential way to reduce or eliminate honeycomb and at the same time reduce drying time to only 1 to 2 hours. Platen temperatures are in the range of 150 to 175 C and, when pressure is applied through the platens to the wide face of a board, excellent heat transfer occurs.

Besides aiding heat transfer from platen to wood, it is hypothesized that the pressure can accomplish another benefit. Figure 4a shows the cross section of a flatsawn board with growth rings parallel to the wide face and ray tissue perpendicular to the wide face. Since the ray tissue is the plane of failure in honeycomb fractures, the critical internal tension is parallel to the wide face of a flatsawn board and honeycomb develops as shown. Figure 4b shows a quartersawn board with growth rings perpendicular to the wide face and ray tissue parallel to the wide face. In this case the honeycomb fractures that develop are oriented parallel to the wide face. Figure 4c represents a flatsawn board being press dried with heated platens. The critical internal tension is parallel to the wide face and the compression of the platens is perpendicular to the wide face. Honeycomb fractures still develop during drying. Figure 4d illustrates a quartersawn board being press dried. The critical internal tension is now perpendicular to the wide face of the board and is counteracted by the compression of the press.

The major objective of this research was to test the hypothesis that the compression applied to a quartersawn board during press drying will counteract the internal

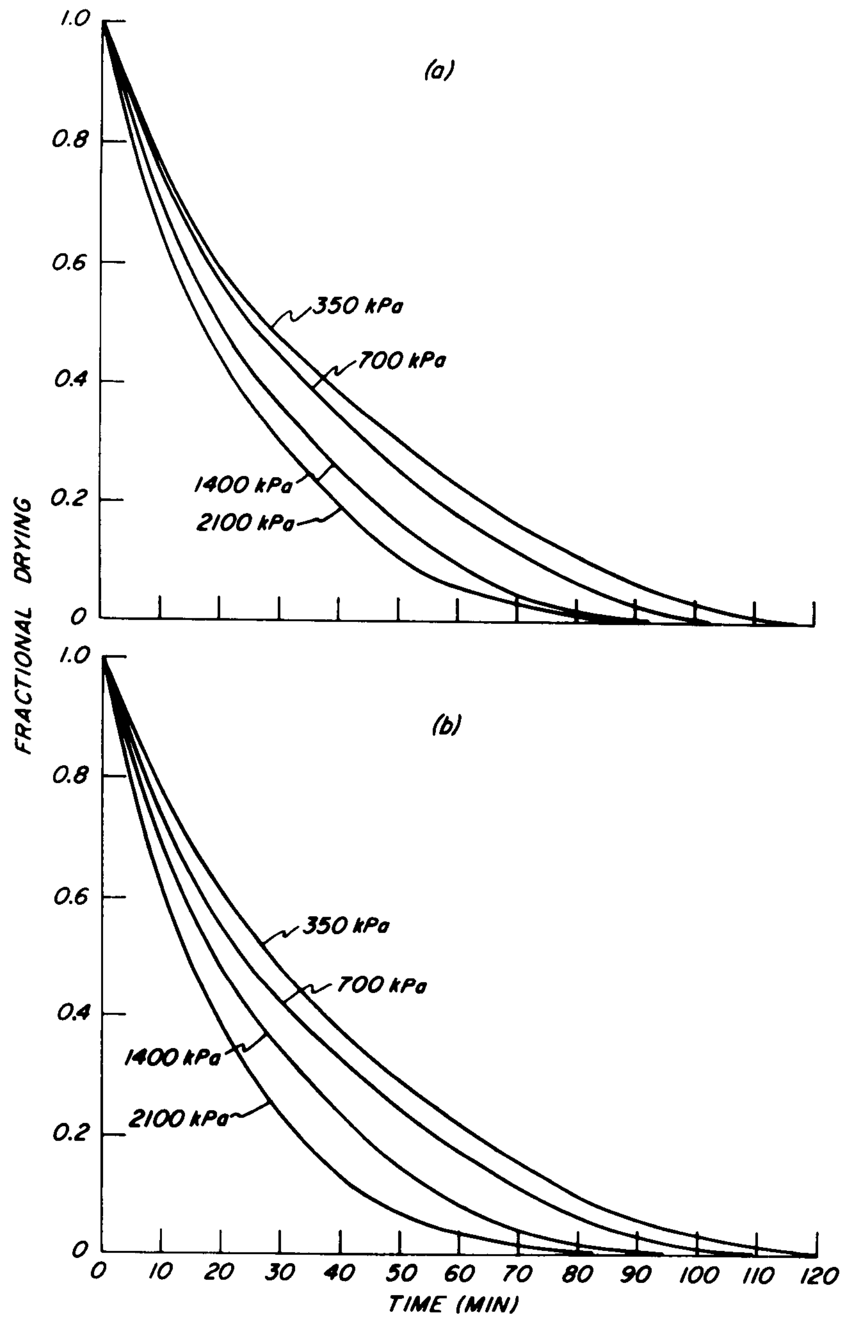

FIG. 6. Press drying rate curves for flatsawn (a) and quartersawn (b) 25-mm-thick red oak.

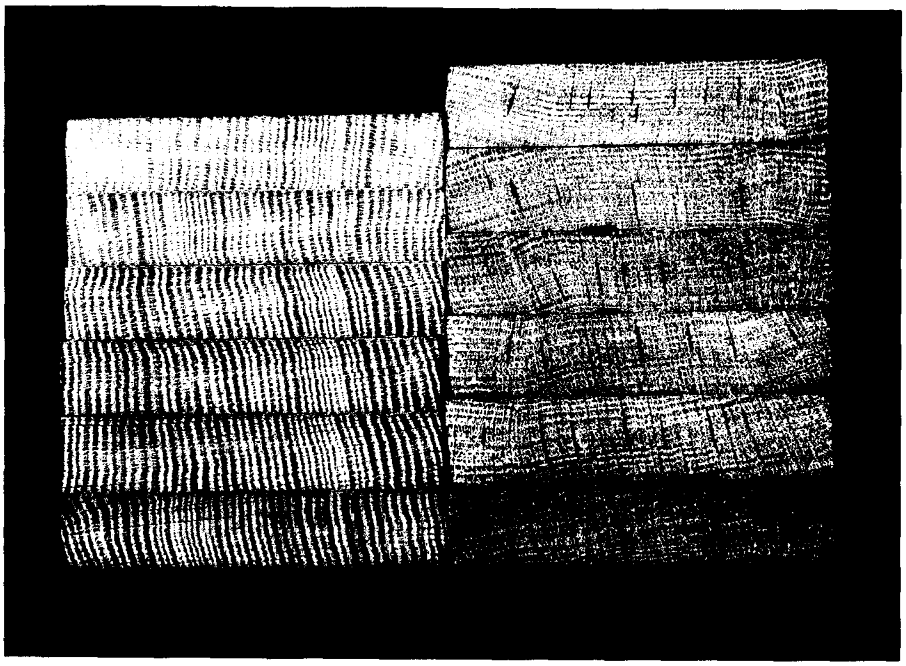

FIG. 7. Comparison of quality in red oak boards after press drying. Quartersawn boards (left) are free of honeycomb, while flatsawn boards (right) have extensive honeycomb.

tensile drying stresses and reduce honeycomb. Because it may not always be practical to manufacture perfectly quartersawn lumber, a further objective was to determine if honeycomb can still be reduced with growth ring angles that deviate from those of perfectly quartersawn lumber.

MATERIALS AND METHODS

The experiment was conducted in two parts. In the first part honeycomb was compared in press-dried quartersawn versus flatsawn lumber, and the effect of platen pressure on honeycomb in quartersawn lumber was evaluated. Once the major hypothesis of the study was confirmed, the second part of the study dealt with the question of variations of ring angle from zero degrees to the narrow face of a board (perfectly quartersawn) to 45° to determine the consequences of deviations from perfectly quartersawn.

A total of 13 logs of the commercial red oak group was obtained from southern Wisconsin. Each log was 2.6 m long and the diameters ranged from 0.4 to 0.6 m. One log was used to provide boards for estimating drying rates for both parts of the experiment. In establishing these drying rates, boards were removed from the press every 10 minutes, weighed, and then returned to the press. This pattern was continued until no more weight loss was observed, which indicated that oven-dry weight had been achieved. Drying rates were determined for both quarter- and flatsawn lumber in combination with each of the various experimental platen pressures. Drying rates were interpolated for ring angles between quarter- and flatsawn. In all cases final target moisture content was 6 to 8%.

TABLE 1. *Comparison of number of honeycomb fractures per 25 mm of board width in flatsawn boards to the number per 25 mm of thickness in quartersawn boards.*

	Platen pressure (kPa)				
	350	700	1,050	1,400	2,100
	Number of honeycomb fractures				
Flatsawn[1]	5.40	2.79	—	1.15	2.57
Quartersawn[1]	0.63	0.04	—	0.05	0
Quartersawn[2]	0.44	0.17	0.06	—	—

[1] Part one of experiment.
[2] Part two of experiment.

In the first part of the experiment, the response of quarter- and flatsawn lumber in press drying was compared at four levels of platen pressure—350, 700, 1,400, and 2,100 kilopascals (kPa) (50, 100, 200, and 300 psi). Five of the remaining 12 logs were sawn into two 1.3-m-long halves. All flatsawn boards were sawn from one half, and all quartersawn from the other half. After boards were cut from logs, they were machined to 25 mm thick by 102 mm wide by 914 mm long. This material provided three replicate boards for most combinations of sawing pattern and platen pressure, although in several cases only two replicates were available. A total of 110 boards was press dried. Platen temperature was 175 C. Aluminum cauls with 3-mm-diameter holes on 25-mm centers were used. A 3-mm channel connected the holes along the board length.

The remaining seven logs were used for the second part of the experiment. Each log was cut into three equal-length bolts. Each bolt provided all boards for one angle of growth rings to board face. The three angles were zero, 22.5°, and 45° between the growth rings and the narrow face of the boards (Fig. 5). Individual boards were 25 mm × 102 mm × 760 mm. Platen temperature was 175 C as in the first part of the experiment. Platen pressures were 350, 700, and 1,050 kPa (50, 100, and 150 psi). The combinations of seven logs, three ring angles, three platen pressures, and three replicates totaled 189 boards that were press dried in this part of the study.

RESULTS AND DISCUSSION

Drying rates

Drying rate curves are shown in Fig. 6. Initial moisture contents were in the 80 to 90% range. Drying times to 6% moisture content (fractional drying equal to approximately 0.07, Fig. 6) ranged from 50 to 90 minutes. As expected, the improved heat transfer with higher platen pressures resulted in a decrease in drying time as pressure was increased. Sawing pattern did not have a large effect on drying time. At 350, 700, and 1,400 kPa quartersawn boards reached 6% moisture content 1 to 3% faster than flatsawn boards, which is only a matter of several minutes difference. At 2,100 kPa platen pressure, the quartersawn boards dried to 6% moisture content approximately 16% faster (about 10 minutes difference).

Honeycomb development

In the first part of the experiment, where only flat- and quartersawn boards were dried and evaluated, the most striking result was that while the flatsawn

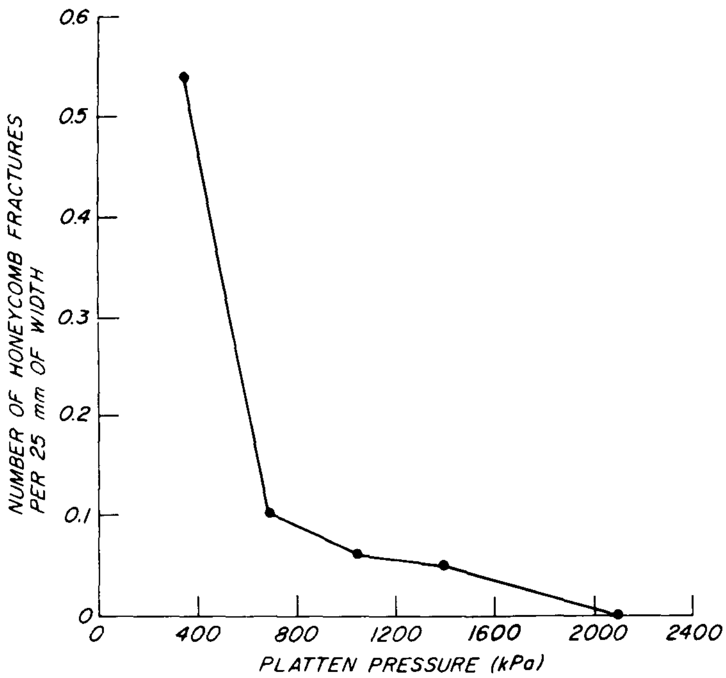

FIG. 8. Effect of platen pressure on number of honeycomb fractures in quartersawn red oak during press drying (average of first and second parts of experiment).

boards were riddled with honeycomb the quartersawn boards were almost completely free of honeycomb (Fig. 7). Results were evaluated by cross cutting each board into six equal lengths to expose five internal cross sections where the number of honeycomb checks were counted. The data in Table 1 show nearly complete elimination of honeycomb in quartersawn boards. The honeycomb data for the quartersawn boards from the second part of the experiment are also included in Table 1. This result showed clearly that honeycomb could be reduced dramatically in press drying red oak by quartersawing instead of flatsawing, and opens up a new potential for a successful rapid drying process.

The next question I attempted to answer was whether or not the level of platen pressure on quartersawn boards influenced the number of honeycomb checks. This question was addressed for the quartersawn boards of the five logs of the first part of the experiment and the quartersawn (zero degrees ring angle) boards from the seven logs of the second part of the experiment. A randomized complete block analysis of variance was employed where the randomized blocks were logs so that between-log variation would not obscure the results. The analysis of variance showed that increased platen pressure reduced the number of honeycomb checks. The reduction was statistically significant at the 97.5% level. This result is shown graphically in Fig. 8. Thus, as the hypothesis states, the compressive force of the platens in press drying did counteract the internal tension forces in drying and reduced honeycomb. In any practical application, therefore, optimum platen pressure will have to be determined.

In a practical production system, it may not always be feasible to manufacture

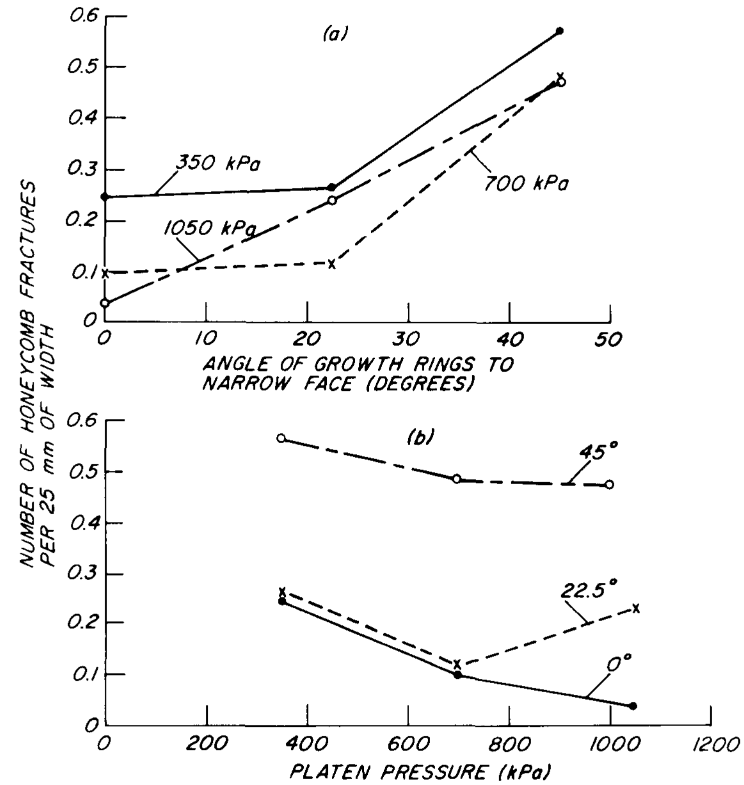

FIG. 9. Effect of angle of growth rings (a) and platen pressure (b) on the number of honeycomb checks in red oak after press drying.

perfectly quartersawn lumber. Thus, the second part of the study addressed the question of whether or not honeycomb could still be reduced significantly if growth ring angle deviated from zero degrees to the narrow face. The honeycomb data of this second part of the study were analyzed by a 3 × 3 factorial randomized complete block analysis of variance. The factors were growth ring angle (zero, 22.5°, and 45°) and platen pressure (350, 700, and 1,050 kPa). The results are shown in Fig. 9. The analysis of variance showed that growth ring angle was a statistically significant factor (99.9% level), and the number of honeycomb fractures increased with ring angle (Fig. 9a). The number of honeycomb fractures did not appear to increase greatly from zero to 22.5°, but did increase greatly from 22.5° to 45°. Platen pressure did not prove to be a statistically significant factor, which is in contrast to the result when only the zero degree ring angle was analyzed (Fig. 9b). The data in Fig. 9b for 22.5° show an inconsistency. The number of honeycomb fractures decreased between platen pressures of 350 and 700 kPa as expected, but then increased markedly at 1,050 kPa. There does not appear to be any explanation for this observation.

It is usually not valid to discount a portion of experimental data without very good reasons. However, an observation of the honeycomb results of the second part of the experiment should at least be noted. In evaluating the dried boards

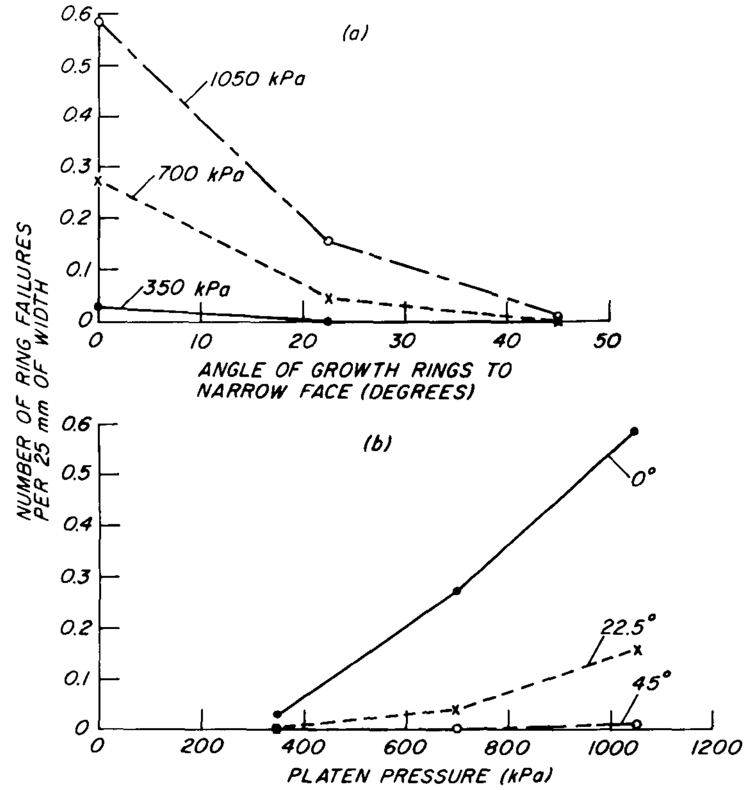

FIG. 10. Effect of angle of growth rings (a) and platen pressure (b) on the number of ring failures in red oak after press drying.

and observing honeycomb, it was obvious that a disproportionate amount of the quality problems were in boards from two of the seven logs. If the data from these two logs are eliminated from the analysis of variance, the result is quite different. In the analysis of variance, platen pressure became a significant factor in addition to ring angle, and the data in Fig. 9 are reduced to approximately one-half the number of honeycomb fractures.

Ring failure

The earlier discussion on the relationship between the orientation of ray tissue and the wide face of a board (Fig. 4) explained how honeycomb could be suppressed by platens in press drying. However, the effect on ring failure was just the opposite. Platens suppressed ring failure in flatsawn boards but not in quartersawn boards. In the second part of the experiment, the number of ring failures were counted on boards from the seven logs. The results were analyzed by a 3 × 3 factorial analysis of variance similar to that used in the honeycomb analysis. The analysis showed that both platen pressure and ring angle were statistically significant (99.9% level) factors in ring failure. Ring failures increased with increasing platen pressure and decreased with increasing growth ring angle (Fig. 10). The decrease with increasing ring angle is explained by the shift toward an orientation where platen pressure opposed stresses that caused ring failure, just as

TABLE 2. *Average and standard deviation of thickness shrinkage for red oak after press drying.*

Growth ring angle	Platen pressure	Average thickness shrinkage	Standard deviation of thickness shrinkage
Degrees	*kPa*	*Pct*	
0	350	17.3	2.03
0	700	22.9	3.60
0	1,050	28.3	3.70
0	1,400	33.4	5.82
0	2,100	39.8	4.80
22.5	350	18.2	2.05
22.5	700	23.0	3.80
22.5	1,050	29.5	4.42
45	350	15.8	2.16
45	700	21.9	3.39
45	1,050	27.6	5.75

the increase in honeycomb with increasing ring angle is explained by the shift away from the orientation where platen pressure opposed internal tension stresses. The reason for the increase in ring failures as platen pressure increased is not clear, but it may have been due to mechanical damage done by the higher level stresses. Most of the ring failure was confined to boards from the two problem logs previously mentioned.

Shrinkage and strain relief

One of the consequences of press drying is increased thickness shrinkage because of platen pressure. One of the consequences of drying quartersawn lumber is increased thickness shrinkage because the tangential direction coincides with that of the platen pressure. Thickness shrinkage and standard deviations are given in Table 2, and can serve as a guide to determining green thickness necessary to arrive at a specified dry thickness. Thickness shrinkage increased as platen pressure increased. The standard deviation also increased as platen pressure increased. This increase in variability may have been caused by the fact that, at low platen pressure, variability in thickness loss was due to variability in shrinkage properties only, but as platen pressure increased the added variability of mechanical properties was introduced.

Without a detailed knowledge of the relevant stress and/or strains, it was not possible to thoroughly analyze the effect of the relief offered by the compressive force of the press. However, some insight can be gained by consideration of the factors involved and a limited knowledge of relevant strains. In order for a honeycomb fracture to occur in a quartersawn board during press drying, the internal tensile strain due to drying stresses minus the compressive strain caused by the press must exceed the strain at failure of the wood, i.e.

$$\epsilon_f \leq \epsilon_i - \epsilon_r \qquad (2)$$

where

ϵ_f = strain at failure,
ϵ_i = internal drying strain, and
ϵ_r = strain relief from press.

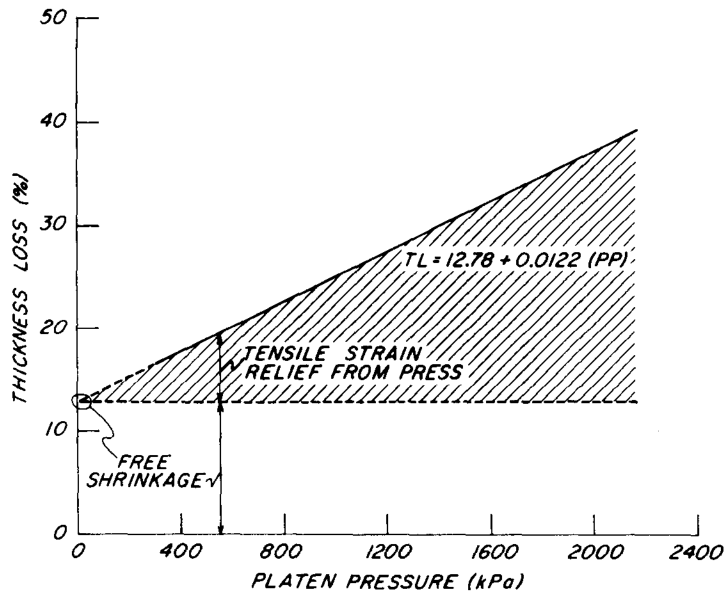

FIG. 11. Thickness loss during press drying as a function of platen pressure. Subtraction of free shrinkage from thickness loss results in an estimate of tensile strain relief from the press.

Strain relief from the press, ϵ_r, was estimated in this experiment by measuring board thickness before and after drying. After plotting thickness loss during drying against platen pressure, extrapolation to zero platen pressure offered an estimate of free shrinkage. Subtraction of this free shrinkage from thickness loss at any platen pressure resulted in an estimate of ϵ_r. Figure 11 illustrates that result for this experiment. By fitting the data to a simple linear regression model, thickness loss can be represented by

$$\text{Thickness loss} = 12.78 + 0.0122 \times \text{platen pressure.}$$

Shrinkage at zero platen pressure was 12.78%, and the slope of the relationship was used to estimate ϵ_r; e.g., at a platen pressure of 350 kPa, where honeycomb was observed, ϵ_r was 4.3%. At 700 kPa, where honeycomb was virtually eliminated, ϵ_r was 8.5%.

Estimates of the strain at failure for oak at an angle of zero degrees to the growth rings are available in the literature. Unfortunately, for application to this experiment, these estimates require extrapolation to about 25 C beyond the experimental temperature range evaluated, and the data from the two known sources, Youngs (1957) and Bello and Kubler (1975), do not agree. Youngs' results suggested a strain at failure of approximately 4%, while Bello's work suggested about 10%. Also, assumptions about what the moisture content is when honeycomb occurs is required.

Available estimates of internal drying strains, ϵ_i, are also poor. McMillen (1955) developed a technique to estimate internal strains during drying. However, the technique only measured the elastic response to a release of drying strain. Neither viscoelastic response nor cell-wall tension due to liquid tension forces were measured. The result was a very low value of apparent internal tensile strain—only about 0.1%. Even considering the uncertainty of the strain-at-failure values in the literature, it is unlikely that strains this low could cause failure. The viscoelastic and liquid tension strains apparently are very significant in formation of honeycomb.

If the effective level of strain relief lies somewhere between approximately 4.3 and 8.5%, and strain at failure somewhere between 4 and 10%, then Eq. (2) suggests that in cases where honeycomb occurs internal drying strains might range from 8.3 to 18.5%.

General observations and comments

There are several miscellaneous comments that should be made about the study and results. In terms of ultimate practical application the entire study was directed toward press drying quartersawn or nearly quartersawn lumber. The orientation of platen pressure on the wide face of a quartersawn board fits in naturally with conventional hot presses. However, it seems likely that honeycomb could also be reduced if side pressure were applied to the edges of flatsawn boards in addition to platen pressure on the wide faces for heat transfer. Equipment for this type of restraint and drying is not available, and would seem more complex than current hot presses. However, this restraint might be considered as an alternative to avoid some of the inefficiencies associated with manufacturing quartersawn lumber.

Even though honeycomb was almost entirely eliminated at platen pressures of 1,400 and 2,100 kPa (200 and 300 psi) other aspects of quality of the boards were not good. As mentioned earlier ring failure increased as platen pressure increased. Collapse also began to appear occasionally at the higher pressures, and overall thickness shrinkage became unrealistically large. Boards also often showed severe darkening at these higher pressures. Several boards showed evidence of explosive ring failures. The higher platen pressures may have retarded moisture loss from the surfaces. Caul design may be related to some of the above problems and should be studied in further development of the process.

CONCLUSIONS

The overall results of this study are very promising for the future development of a press-drying process that reduces the drying time of red oak from days or weeks to only 1 to 2 hours, and without development of unacceptable drying defects. In this process the compressive force of platens opposes the internal tension forces that develop during drying. Specific conclusions and observations are as follows:

1. Honeycomb in press-dried quartersawn red oak was significantly less than in press-dried flatsawn red oak.
2. An increase in compressive force of platens reduced the amount of honeycomb that developed in perfectly quartersawn lumber (growth rings at zero degrees to the narrow face). This was the major hypothesis of the study and the results were confirmed by a statistical analysis of variance.
3. The number of honeycomb checks increased as growth ring angle progressed from perfectly quartersawn (zero degrees) to perfectly flatsawn (90°).

4. There is evidence, but not conclusive, that increasing compressive force of platens reduced honeycomb at growth ring angles of 22.5° and 45°.
5. The amount of ring failure decreased as growth ring angle increased from 0° to 45°.
6. The amount of ring failure increased with platen pressure at growth ring angles of zero and 22.5°.

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