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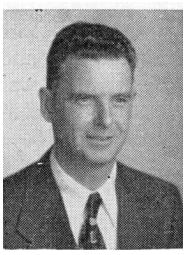
Drying Stresses in Red Oak[1]



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The effect of relative humidity variation on tensile and compressive stresses, perpendicular to grain, during drying of 2-inch red oak at 110° F. is reported. The general pattern of strains was the same as previously found for other hardwoods. Details were affected by humidity differences. Both external set and internal set occurred. The external set tending to decrease shrinkage, was proportional to severity of humidity schedule. Shrinkage, strain, and external set started while only a small portion of the wood was below 30 percent moisture content. The centers were still above 30 percent when maximum internal tensile strain occurred.

EARLY STUDIES in the air drying and kiln drying of wood at the Forest Products Laboratory disclosed that internal stresses of considerable magnitude are built up in the wood as it dries. Knowledge of the nature and magnitude of these stresses is important both for understanding the fundamental physical properties of wood and for the practical development of kiln schedules, control of material dimension, and relief of residual stresses and sets. Numerous experiments at the Forest Products Laboratory have yielded valuable information about these stresses. Only during the past few years, however, has it been possible to get under way a comprehensive investigation of this subject. The studies have been made on red oak, one of the most important Eastern woods and one that takes so long to dry that any resultant savings in drying time will be very well worthwhile. This report covers the first study in the series. It concentrates on the effects of relative humidity changes on tensile and compressive stresses in 2-inch red oak during kiln drying at 110° F.

A general concept of how the stresses develop inside of wood as it dries can be gained by visualizing the moisture content gradient as observed on a cross section of a board after one-tenth of its total moisture has been evaporated. The outer zone appears to be dry; at the very surface it is down below the fiber saturation point. Thus, the fibers at the surface are dry enough to try to shrink. Their shrinkage is restrained, however, by the underlying wood, which is in a relatively green condition and above the fiber saturation point. Because of this restraint, the outer fibers are stressed in tension. As a reaction, the inner fibers are stressed in compression. These stresses are perpendicular to the grain of the wood. As the wood continues to dry from the outside, the zone attempting to shrink moves further in towards the center. The outer zone becomes drier and drier. As it loses its moisture, it becomes set in a dimension close to the green dimension. Because of this set in the outer zone, when drying progresses to where the interior fibers begin to go below the fiber saturation point and want to shrink, the stresses reverse. The interior undergoes a tensile stress while the exterior is subjected to compression. It is during the first stage, exterior tensile stress, that surface and end checks tend to form. During the second stage, that of internal tensile stress, surface and end checks tend to be converted into honeycomb checks. Under some circumstances, honeycomb may form spontaneously.

Early wood tehnologists (1)[4] in this country knew about the need to avoid set in obtaining good shrinkage values. The term "caseharden" had come into use by 1895, and Roth (4) recognized that there was some connection between casehardening and checking. Tiemann (5), however, probably was the first to begin to understand stresses and set in wood and to make prong analyses of stresses. A short while later, Tiemann (6) made a hypothetical slice analysis of drying stresses. All through this period of early exploration, only general knowledge of drying stresses was gained. Such knowledge probably was helpful, however, in setting up the

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[3] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

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[4] Numbers in parentheses refer to Literature Cited at end of paper.

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conservative kiln schedules and set-relief methods appropriate for the drying equipment then in use.

So far as the author is aware, however, the first attempts to actually measure stress analysis slices and to follow the development and reversal of stresses from the beginning of drying through conditioning were made at the Forest Products Laboratory in 1924 by E. C. Peck. In 1929, W. K. Loughborough, then on the Laboratory staff, used prong measurements to demonstrate set and its relief. Also, about this time staff member O. W. Torgeson and collaborators W. L. Greenhill and Ian Langlands started to study the strength of wood in tension perpendicular to the grain at different moisture content values and at different temperatures under Loughborough's supervision.

When the woodworking industry began to make considerable use of southern hardwoods, it was only natural for kiln-schedule research on them to turn to stress analysis. Peck used the slicing technique on magnolia, among other woods. Results on blackgum (2) were published in 1940. This work indicated that drastic lowering of relative humidity could be used after the reversal of stresses. A subsequent, more comprehensive study on sweetgum heartwood was made by Loughborough and H. H. Smith, and the results were published in the Kiln Certification Manual (8). Later Rietz (3) described how the principles developed in these studies were used in setting up a new concept of kiln drying schedules. In 1951, Torgeson (7) brought out a whole new series of kiln schedules for American woods based on these principles.

To make further advances in kiln schedules and to shorten the work of developing schedules for foreign woods that have no established schedules, a more thorough knowledge of the effect of drying conditions on internal stresses is required. To gain this knowledge is the objective of the present series of studies. The procedure used is the slicing technique. Sections are cut from the wood at various times in the drying period. The sections are measured at various places across the thickness of the piece, then they are cut into slices to release the stresses. The slices either contract or elongate. The difference between measurements before and after slicing is taken as an indication of the strain to which the wood was subjected as a result of the stresses. Without any method of measuring the stresses directly, the observable strains give us valuable information on them. Contraction is an indication of tensile stress; elongation is an indication of compressive stress.

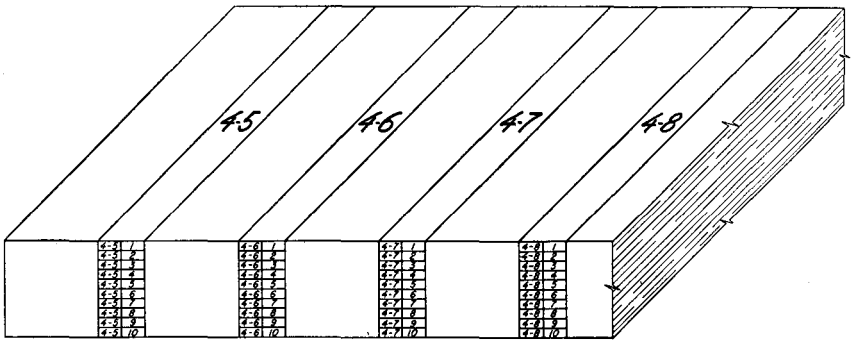

Figure 1.—Method of marking test specimens.

Material Tested

The material used was green, flat-sawed 2-inch red oak, presumably *Quercus rubra*, obtained in plank form from a sawmill in Sauk City, Wis. The rough planks, $2^1/_8$ inches by 8 inches by 8 feet were kept wet in a 35° F. storage room pending use. Test specimens 5 feet long and free from defects were obtained by dressing both broad faces and trimming and dressing the narrow faces to a green width just under 7 inches. The ends were coated with aluminized phenolic-resin varnish, and the specimens were protected from drying during preparation and measurement. Initial moisture content was about 90 percent, specific gravity was 0.57 and number of rings per inch was about 9.

Test Methods

Each experimental run consisted of drying one test specimen in a small internal-fan kiln with automatic control of temperature and humidity. Each green specimen was marked off with a 1-inch section every 3 inches along the grain Each section was marked for 10 slices, as shown in figure 1. The slices were numbered consecutively, beginning at the side of the specimen toward the convex side of the rings The width of the green specimen was measured between midpoints on the ends of each slice and recorded These measurements were used to compute shrinkage of the board as a whole at various intervals of drying, and to compute also the ultimate shrinkage of the slices when dried to an ovendry condition.

The prepared specimen was placed in the kiln on stickers, and void space was baffled so that air velocity over the specimen's surface was about 250 to 400 feet per minute. After each interval of drying, one section was cut off the specimen and wrapped in foil. The remainder was end coated and replaced in the kiln. While the section was still intact, the width of each slice was measured to get the before-cutting dimension, as in figure 2. The differences between the green dimensions and the before-cutting dimensions, converted to a percentage-of-green-dimension basis,

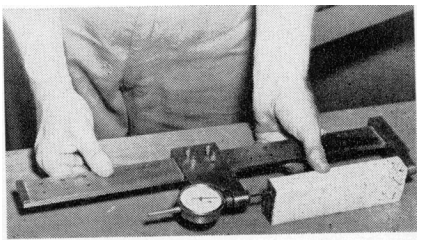

Figure 2.-Measurement of slices in section before cutting.

were used as indications of shrinkage of the board as a whole. Then the section was laid on its side, and the slices were marked on the cross section by indelible carbon paper. The foil wrapper was removed, and the section was rapidly cut into slices on a thin bandsaw. Each slice was enclosed in a tared foil wrapper, then measured as shown in figure 3 for the after-cutting dimen-

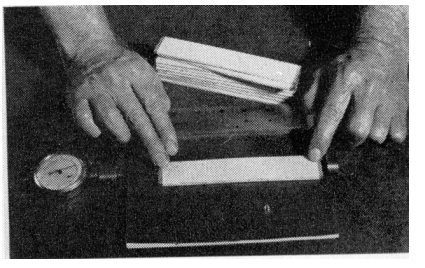

Figure 3.—Remeasurement of slicer after cutting.

sion. The differences between the before-cutting and after-cutting measurements, converted to a per-inch basis, were considered as unit strains. After measurement, each wrapped slice was weighed. Then the slices were unwrapped, piled in a stickered bundle by use of the jig shown in figure 4, and carefully dried so as not to induce any new set. Drying generally consisted of 1 day in the kiln at 110° F. and 80 percent or more relative humidity, 1 day in the room, and 1 day in the oven at 214°–221° F. When ovendry, the slices were cooled in a dessicator, then reweighed for moisture content calculations and remeasured for ultimate slice-shrinkage calculations. Differences be-

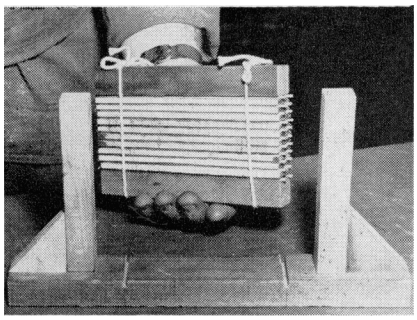

Figure 4.—Stickered bundle of slices ready for careful drying to determine set.

tween observed ultimate shrinkage and the inherent shrinkage of the wood were considered indications of set.

The drying schedules varied from run to run to show the effect of relative humidity variations at a 110° F. temperature. Changes generally were made at points of comparable loss of evaporable moisture (E).

$$E = \frac{\text{Current moisture content—equilibrium moisture content}}{\text{Original moisture content—equilibrium moisture content}}$$

In the five runs covered by this report, dry-bulb temperature was held constant at 110° F. until E was down to 0.25 or 0.30, then raised to 120° F., and finally at E = 0.20 or 0.25, raised to 130° F. In all runs, the first reduction in relative humidity was made when E = 0.60. In runs 1, 2, and 3, the humidity-reduction pattern was a mild one, with succeeding reductions at E values of 0.52, 0.45, 038, 0.30, 0.25, and 0.20. In run 4, the relative humidity was reduced about the same amounts as in the previous runs, but more rapidly in terms of evaporable moisture. In run 5, the same relative humidity drop was made at E = 0.60, as in previous runs, but when tensile strain in the outer zone had receded to 80 percent of its maximum value, relative humidity was abruptly dropped to 26 percent.

Results

Tension and Compression: The unit strains observed in run 3 are shown in figure 5. Drying time, average moisture content of the specimen, and kiln conditions are shown at the bottom of each bar graph. Relative humidity conditions have been converted to wood equilibruim moisture content (E.M.C.) values at that temperture and relative humidity. Preliminary runs 1 and 2 were made with essentially the same schedule but for only the first 20 days of the run. They gave essentially the same results. They are not reported here, but their more frequent observations during the first phase of the runs justifies the smooth curves shown in the succeeding figures.

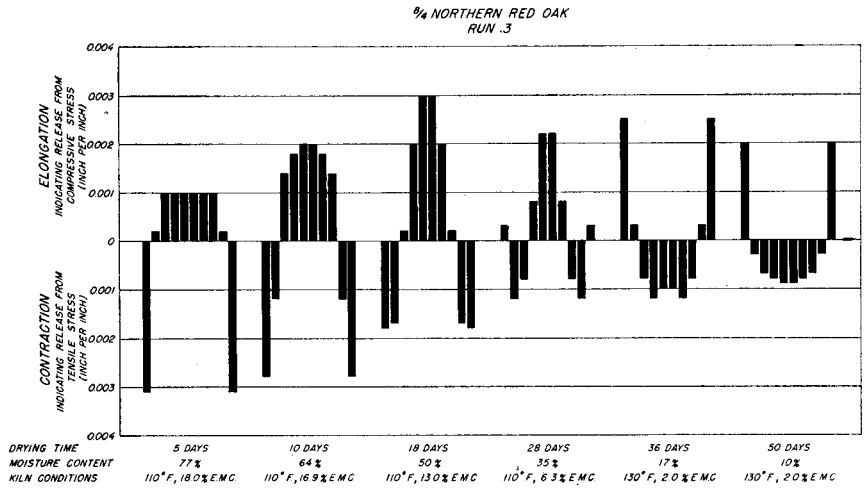

Figure 5.-Strain diagrams for 2- by 7-inch red oak dried at 110° F. with a mild humidity schedule,

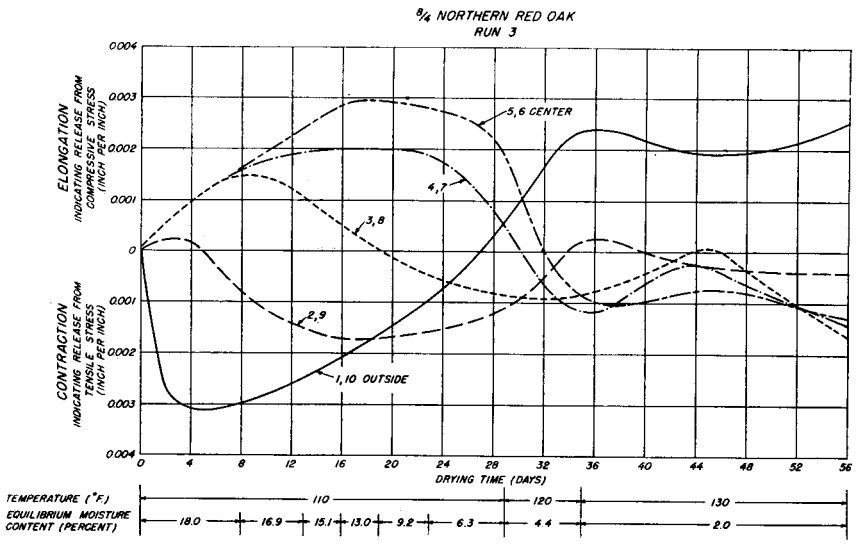

Figure 6-Strain curves for 2- by 7-inch red oak dried at 110° F. with a mild humidity schedule.

At the end of 5 days of drying, the specimen in run 3 had dried to 77 percent moisture content. The maximum tensile strain of the outer slices, about 0.003 inch per inch, had been attained. For the purpose of this analysis, the results of the two slices equidistant from the center were averaged, and the average value was assigned to each. Often there was considerable difference between these individual values.

At the 5-day point, only the outer slices were in tension. Slices 2 and 9 were in slight compression. All other slices showed a compressive strain of about 0.001 inch per inch. After 10 days of drying and the first slight change in relative humidity, average moisture content was 64 percent. The outer slices still had a great deal of tensile strain. Slices 2 and 9 had gone into tension. The interior slices had greater compression. After 18 days of drying, moisture content had dropped to 50 percent. Slices 2 and 9 had reached maximum tension of about 0 0017 inch per inch, but tension was still slightly greater in slices 1 and 10. The center slices reached a maximum of compression, 0.003 inch per inch. Compressive strain in slices 3 and 8 had dropped almost to 0.

At the fourth stage, after 28 days, the moisture content was at 35 percent, and reversal of stresses had started. In the fifth stage, after 36 days, reversal was complete. Moisture content was down, on the average, to 17 percent. Compressive strain of the outside slices had reached a maximum of almost the same magnitude as their maximum tensile strain at the start. Remember, these are strains, not actual stresses. The stresses for the same strains become considerably greater as moisture content goes down. The sixth bar graph shows strains as the wood enters its final drying stage at 10 percent moisture content, with the outside in compression and all interior slices in tension.

In terms of the effect of the stresses on wood, the danger of surface checking was greatest during the first stage

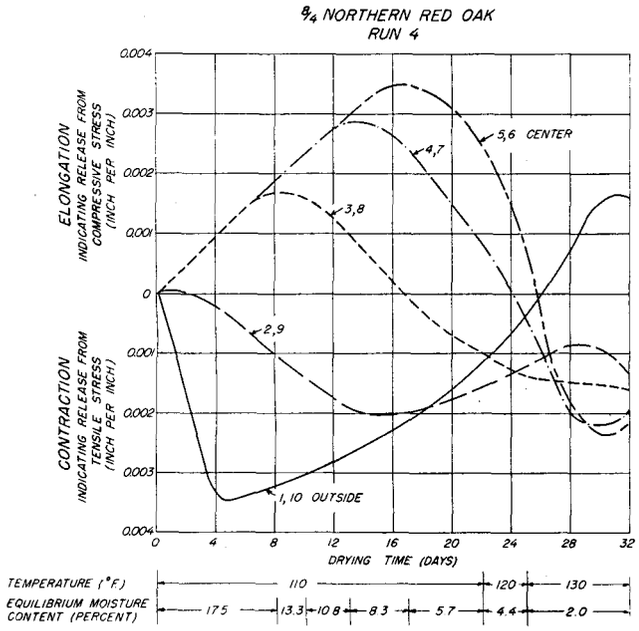

Figure 7.—Strainurves far 2- by 7-inch red oak dried at 110° F. with a medium humidity schedule.

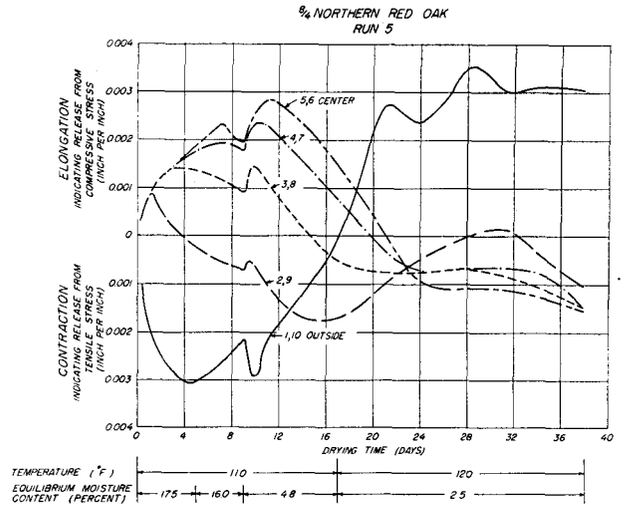

Figure 8.-Strain curves for 2- by 7-inch red oak dried at 110° F. with a severe drop in relative humidity.

of drying, when the tensile stress in the outer zones was the greatest. The possibility of compression set or compression collapse was greatest when the compressive stress in the center zones was greatest. The condition promoting honey-comb was the worst when the outer zones were at maximum compressive stress and the inner zones at maximum tensile stress. The final condition of the wood is what we know as casehardening.

Figure 6 shows a linegraph of the strain curves in run No. 3. The data for runs Nos. 1, 2, and 3 generally justify the smooth curves drawn, but small irregularities, which are not shown, did occur. Some of these no doubt were experimental errors; some of them probably were not.

Figure 7 shows a linegraph of strain curves for run No. 4. In this run, a medium rate of relative humidity reduction was followed. The effect was slightly higher maxima of tensile and compressive strains, plus a considerable pushing together of the curves timewise. Stress reversal occurred at 26 days. The maximum tensile strain in the center slices after stress reversal, 0.0023 inch per inch, was greater than the maximum with the milder schedule.

Figure 8 shows the strain curves for run No. 5. In this run, the initial conditions were the same as run No. 4. The second condition also was mild. Then, when the tensile strain in the outer slices had fallen off to 80 percent of its maximum value, the relative humidity was drastically lowered to a 4.8 percent equilibrium moisture content condition. This resulted in an increase of tensile strain in the outer slices, but to a value less than the maximum that occurred at 5 days. Considerable increases in compressive strain occurred in the third, fourth, and fifth slices. All zones appeared to have resumed their normal strain patterns after 2 days of exposure to the new conditions. Sweetgum (3,8) had not shown such a disturbance of strain curves when relative humidity was abruptly dropped. It is, perhaps, significant that checking did not occur under the increased tensile stress. The actual stress in pounds per square inch probably was greater at this point because the wood was drier and had a higher modulus of elasticity. On the other hand, the resistance to checking probably was higher also.

In general, all the results showed the same general strain pattern and with about the same maxima of tensile and compressive strains at the 110° F. temperature studied. Differences in amount and rate of relative humidity lowering, however, did alter the details of the strain pattern.

Board Shrinkage: Measurement of the slices "before cutting" showed that the shrinkage of the specimen as a whole began immediately upon the start of drying. Figure 9 shows the shrinkage-time curves for outside and center slices of run No. 3. During the first part of drying, the outer slices were forcing the contraction of the board as a whole, as represented by the center slices. After stress reversal, the center slices were forcing the contraction of the outer slices. The observed shrinkage of the center slices, before slicing, was always less at any particular time than that of the outer slices because the center slices were always higher in moisture content than the outerslices.

Shrinkage continued at a uniform rate until about the 26th day, which marked the point of stress reversal for slices 1 and 10. There was a jump in shrinkage rate until the 40th day, which was slightly after the first maxima of the reversed strains had been passed. Thereafter, shrinkage proceeded at about the same rate as during the first 26 days of the run. A similar board-shrinkage relationship was found for run No. 4, only shrinkage rates were somewhat faster. Figure 10 shows the shrinkage curves for run No. 5. In this run, there was an abrupt jump in board

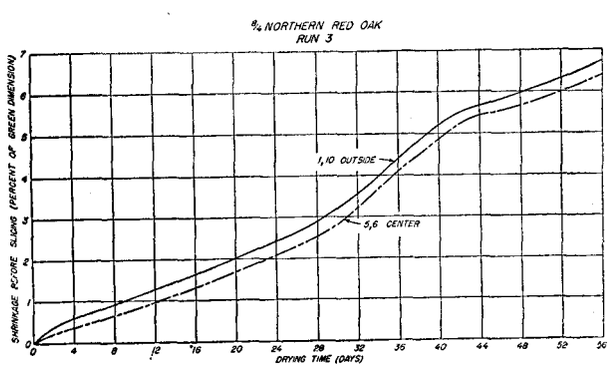

Figure 9.—Board-shrinkageurves for 2- by 7-inch red oak dried at 110° F. with a mild humidity schedule.

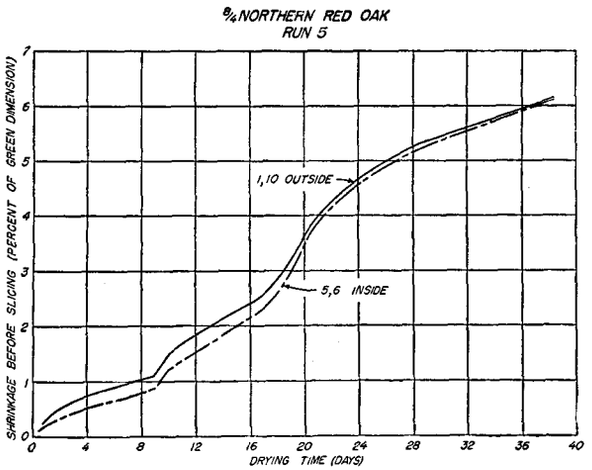

Figure 10.—Broad-shrinkage curves for 2- by 7-inch red oak dried at 110° F. with a severe drop in relative humidity.

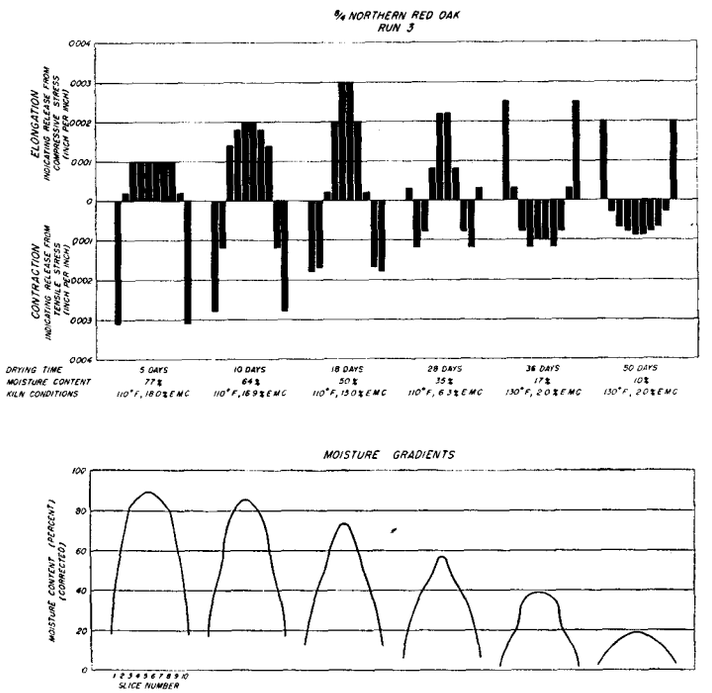

Figure 12.-Strain diagrams and moisture gradients for 2- by 7-inch red oak dried at 110° F. with a mild humidity schedule.

shrinkage after 9 days, when relative humidity was drastically lowered. Then, because of the low equilibrium moisture content, shrinkage continued at a rapid rate. Again there was an upswing in the curves during the period of 18 to 24 days of drying. After this, the rate was about the same as for run No, 3.

Set: Stresses and strains are always involved when wood is dried. Another thing that usually occurs is called set. Set is defined as a permanent deformation occurring when the wood has been strained beyond the proportional limit. In other words, if the load or stress were released, the wood would not return to its original dimension. An engineer might define set as a strain remaining after removal of stress.

One way to determine the presence of set is to observe ultimate shrinkage to the ovendry condition of a portion of the wood and compare it to the normal shrinkage of set-free wood. Set does not remove the wood's inherent tendency to shrink, but it modifies the observed shrinkage. When a strip of wood is set while under a tensile stress, its observed shrinkage is less than normal shrinkage. The magnitude of the difference between observed shrinkage and true shrinkage is a measure of set.

The formation of a set in the outer zones, while the wood is under tension, has been recognized and accepted in lumber-drying technology for many years. Although not so readily recognized, the compressive stresses inside of wood may be so great as to strain the wood beyond the proportional limit, and give it a set making its apparent shrinkage greater than normal shrinkage. The data in this study give positive indications along this line.

Figure 11 shows ultimate shrinkage curves for slices in runs Nos. 3 and 5 as a function of drying time. Here again the somewhat irregular data have been smoothed out to give the curves shown. This and subsequent research have shown that a very careful slice-drying technique is required to avoid extraneous set effects. In this study, it appeared that immediate placement of the stickered bundle of slices in a kiln at 110° F. and an equilibrium moisture content of 16 percent or higher for 1 day, followed by 1 day in room conditions at 70° to 80° F., and 1 day in the oven was satisfactory.

In the graphs of figure 11, it may be assumed that slices 2 and 9 had the most nearly normal shrinkage because, as shown in figures 6 and 8, they departed least from the zero strain line in the first part of the run. The normal shrinkage of run No. 3 was thus 7.7 percent, and normal shrinkage of run No. 5 was 8.7 percent. Set developed immediately in the outer slices in both cases. In run No. 3, the development was gradual, and maximum set in the outer slices was not attained until 22 days. Thus, set was still building up after maximum tensile strain had passed and continued almost until tensile strain dropped to zero. External set formed more rapidly and to a greater degree in run No. 5. Here again, the maximum did not occur until the 14th day, when the tensile strain was nearly back to zero. Slice shrinkage curves were not prepared for run No. 4, but they would be expected to show intermediate results.

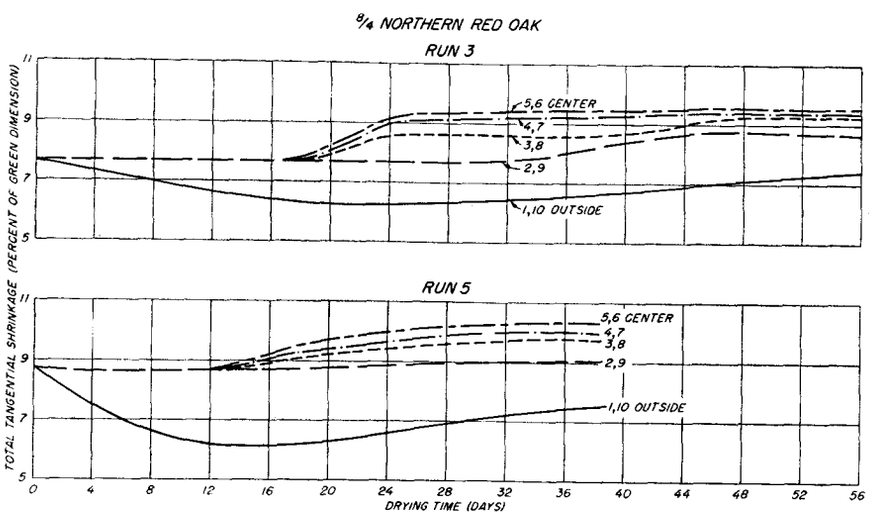

Figure 11.—Total shrinkage of slices in runs Nos. 3 and 5, showing influence of set.

An internal set apparently did occur in both runs. In run No. 3, the start of internal set occurred on the 18th day. This coincided with the time to maximum compressive strain in the center slices. Slices 4 and 7 exhibited almost as much internal set as slices 5 and 6, and slices 3 and 8 exhibited only slightly less. The magnitude of the maximum set in both directions was about the same; that is, about 1.8 percent of green dimension, In run No. 5, internal set started on the 12th day, again about the time of maximum compressive strain. Here the magnitude of the internal set was considerably less than that of the external set. The magnitude of the internal set was somewhat less than that in run No. 3.

In both runs, the external set was relieved or counteracted somewhat by long-time loading under compressive stress after stress reversal. Somewhat higher temperatures after 29 days in run No. 3 and after 17 days in run No 5 probably had a part in this relief.

In run No. 3, there was an upswing in shrinkage of slices 2 and 9. Subsequent research has shown that this upswing is a common occurrence under most conditions. The significance of the upswing and why it did not occur in run No. 5 are not known. In the case of run No. 3, however, the start of the upswing coincides with a brief interval when slices 2 and 9 were in compression.

Moisture Gradients: In considering the development of drying stresses in wood, it must be recognized that moisture content plays an important part. Strength values are inversely proportional to moisture content below the fiber saturation point. Dry wood is much stronger than green wood. The strength to proportional limit, the maximum strength, and the stress-strain ratio are all influenced by moisture content. Shrinkage also is inversely proportional to moisture content below the fiber saturation point. By definition, there should be no shrinkage above the fiber saturation point. Information on the moisture content of the slices at various stages should be of primary interest in interpreting the foregoing strain, shrinkage, and set data.

Such data for run No. 3 are shown in figure 12. The averaged and smoothed moisture gradients for various pairs of slices are shown in the upper portion of the figure. At the time of maximum tensile strain in the outer slices, only a small portion of these slices was below 30 percent moisture content. Similarly, the greater portion of slices 2 and 9 was above 30 percent when, as shown in the third bar graph, these slices were at their maximum tensile strain. In this condition, they were subject to low proportional limits and high plasticity. Thus, they were susceptible to permanent deformation or set. As shown in the third bar graph, when the interior slices were under maximum compressive strain, they were far above the fiber saturation point. Even when stresses had reversed and the interior slices were under maximum tensile strain, they were still above the fiber saturation point, as shown in the fifth bar graph. Thus, they would be very susceptible to honeycombing at this stage, if temperature were raised drastically, These interior moisture content values above 30 percent existed when the moisture content of the 2-inch stock was down to 17 percent. Experience has generally shown that high final kiln temperatures must be avoided until the wettest point in the interior, usually the midthickness, is below the fiber saturation point. The average moisture content for 2-inch stock is lower for this point than the average for 1-inch stock because of the hump-shaped moisture gradients common to thick stock of slow-drying species in contrast to the parabolic curves of 1-inch stack.

Effect of Temperature: Subsequent research with similar red oak, and using a mild relative humidity reduction schedule, has shown that the general strain pattern is the same for temperatures ranging from 80° F. to 140° F. In general, the maximum tensile strain in slices 1 and 10 and the maximum compressive strain in slices 5 and 6 are about the same order of magnitude in all cases up to 125° F. At 140° F., the maximum tensile strain of slices 1 and 10 is considerably greater, and the maximum compressive strain of slices 5 and 6 is considerably less than those at the lower temperatures. External set in slices 1 and 10 is about the same in most cases, but internal set in slices 5 and 6 varies considerably with temperature. The details of these data are the subject of another paper.

Conclusions

1. Red oak was shown to experience the same general pattern of internal stresses during drying as was previously found in sweetgum heartwood, blackgum, magnolia, and other hardwoods.

2. This stress pattern is such as to cause surface and end checking and external set during the first stage, internal set during the second stage, honeycombing during the third stage, and leave the wood in a casehardened condition.

3. Maximum tensile strains in outer slices and maximum compressive strains in center slices were approximately the same order of magnitude for the different humidity schedules tested, but these maxima and reversals of stresses occurred earlier with more rapid rates of relative humidity reduction.

4. In red oak, it is possible to reestablish near maximum tensile strain in the outer zones by abrupt reductions of relative humidity after the maximum has been passed. Corresponding increases in compressive strains can occur in the interior zones. The specimens in this study did not check under such conditions.

5. Set, or permanent deformation, occurred in the drying of oak, both a set tending to decrease shrinkage in the outer zones and a set tending to increase shrinkage in the interior zones. The magnitude of the external set was proportional to the severity of the relative humidity schedule.

6. Shrinkage of the whole boards occurred from the start of drying and continued on a steady rate until accelerated 'during the period between stress reversal in the outer zones and the first maxima of the reversed stresses; thereafter shrinkage resumed a steady rate.

7. The shrinkage rate was abruptly increased by an abrupt lowering of the relative humidity during the first part of the drying.

8. Shrinkage, tensile strain, and external set all started when only a small portion of the wood was below the fiber saturation point.

9. Moisture content in the center was still above the fiber saturation point when maximum internal tensile strain occurred.

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