Knowledge of what happens inside a board as it dries has increased tremendously during the past several years. Even though we are far from a complete understanding of the mechanisms involved, our limited knowledge of drying stresses has had a marked influence on drying procedures now in use.

The stresses that develop in wood as it dries both influence and are affected by the drying process. They cannot be ignored and are always present. They vary considerably with the temperature and humidity conditions employed in drying. They determine to a considerable extent the rate at which drying may be permitted to proceed in its various stages without development of excessive drying degrade.

The fact that drying stresses are dependent on drying conditions means, however, that they are not beyond the control of the dry-kiln operator. Further, the stresses are not all bad. By understanding them, the kiln operator or the wood technologist can develop drying procedures that take advantage of the stresses without allowing undesirable drying defects. He can control initial drying conditions to avoid surface and end checks, retain maximum dimension, and curtail warping. He can modify intermediate and final kiln conditions to speed drying without producing honeycombing. And he can apply conditioning treatments to relieve stresses at the end of drying, thereby avoiding distortion and splitting in subsequent machining.

Basic Factors Underlying Stress Development

The formation and effects of stresses in drying wood are influenced by several factors:

1. As any portion of a piece of wood loses moisture below the fiber-saturation point, it tends to shrink.
2. If the normal shrinkage is restrained, a tensile stress is developed in that portion.
3. Portions of the material that do the restraining tend to develop compressive stresses.
4. The tendency of one portion of the wood to restrain the shrinkage of an adjacent portion produces shearing stress between them.
5. When a material is stressed, it deforms or is strained, as illustrated in the stress-strain curves of Figure 1. Stress that develops slowly and continues for long periods produces some inelastic (or plastic) strain. Such inelastic strain remains after removal of stress. This permanent strain is known as plastic deformation, creep, or set.

General Stress-Set Pattern In Drying Wood

What happens to a typical case-hardening test section during drying is shown at the top of Figure 2. Early in drying, the prongs turn out as in A. At the end of drying, typical case-hardening is evident as in B. After proper stress relief, the section should look like C. This type of test gives us a rough idea of the stress pattern in drying wood. However, we need more exact tests to give a real understanding of drying stresses.

A better picture of drying stress distribution is obtained by cutting 10, instead of 3, prongs in the test section. Diagram D of Figure 2 shows a 10-prong section cut early in drying. As each prong is cut, it shortens if it is released from tension or lengthens if it is released from compression. A modification of just such a procedure forms a basis of the technique currently used at the Forest Products Laboratory to investigate stress development in drying wood. Green planks are marked off into sections and each section into slices, as in Figure 2. E. Sections are cut from the plank at various stages of drying. The length of each slice is measured before, F, and immediately after it is cut free from the section, G. The difference in length indicates the elastic strain, which is directly related to the average stress acting in the slice just before it is cut free. The permanent strain, or set, is shown in Figure 2, H. The outside slices, which exhibit less than normal shrinkage, were set in tension. The interior slices, which exhibit more than normal shrinkage, were set in compression.

This so-called “slicing” technique has been used to investigate drying stress development in several species of hardwoods. Consequently, the general pattern of stress development in hardwoods is now fairly well known. Much less is known about stress development in softwoods.

Typical of the results obtained by the slicing technique are those shown in Figure 3 for the drying of a two-inch-thick heartwood plank of a refractory hardwood. The relative contraction of a slice released from tension is indicated by a bar extending below the zero line; the relative elongation of a slice released from compression is shown by a bar extending above the zero line. These contractions and elongations are actually strains, but are labeled “stress” since they show the direction of stress and give an indication of its magnitude.

The main features in drying-stress development, as shown in Figure 3, are typical of many hardwoods. Tensile stress in the outer layers reaches a maximum within a few days after drying begins, then subsides somewhat more slowly. Tension set begins to develop in the outer layers shortly after the start of drying and gradually increases to a maximum within a week or two. As drying proceeds, the zone of tensile stress gradually moves from the outside toward the mid-thickness as the interior portions of the wood dry and their shrinkage is restrained by the tension-set outer portion. Cora-
pressive stress is simultaneously induced in the outer layers. Maximum tensile stress developed in the interior, however, is less than that developed in the outer portion during the early stages of drying.

In the early stages of drying, the mid-thickness zone gradually attains a maximum compressive stress, though much later than maximum tensile stress occurs in the outer portion. The build-up of compressive stress in the interior leads to compression set in that part of the plank. Stress reversal is completed when the center layers take on a tensile stress. A maximum tensile stress in the center layers and a maximum compressive stress in the outer layers are soon developed. These maximums occur when the center of the wood is still very near the fiber-saturation point. The stresses then continue about the same to the end of drying.

The fact that softwood lumber is susceptible to surface and end checking, honey-combing, and case-hardening leads to the belief that the general pattern of stress development in such material is not radically different from that in hardwood lumber. The limited data presently available on drying stresses in softwoods indicate, however, that the surface layers remain under tensile stress relatively longer in softwoods than in hardwoods, perhaps until the average moisture content of the material reaches 15 to 20 per cent. These data also indicate that a sudden lowering of relative humidity after stress reversal can redevelop tensile stress, or at least markedly reduce compressive stress, in the outer portion of the wood. Somewhat similar tendencies as to late stress reversal have also been observed in sapwood of hardwoods, indicating that the more rapid moisture movement, and hence the flatter moisture gradient, in such material may be at least partially responsible for such deviation from the general drying-stress pattern in hardwoods.

Effects Of Drying Stresses On Drying Behavior

Drying stresses are unavoidable in normal wood as it dries. Some years ago it was as common practice to attempt stress relief treatments intermittently during the drying operation. Modern methods avoid this practice and aim at using stresses to advantage during the drying operation, since such stresses can be relieved most economically at the end of drying.

One manner in which drying stresses can be used to advantage is in the manipulation of set development, either in tension or in compression, in the various portions of the drying board. The severest stresses and the greatest amount of set are developed in tension in the outer portion of the wood. The inner portion that becomes set in compression comprises much more wood, however, and therefore exerts a much greater influence on the total shrinkage of the board. Consequently, if total shrinkage is to be minimized during drying, it appears that compression set in the interior of the wood must be kept to a minimum. Measurements of set and shrinkage that occur during drying at various temperature and humidity conditions have indicated that low temperature and humidity result in less compression set and less total shrinkage than do high temperature and humidity. Thus, a kiln schedule developed entirely on the basis of speed of drying and avoidance of visible defects may possibly result in a maximum of shrinkage.

The problem of warp during drying is also closely related to set and shrinkage. Tension set early in drying can be used to restrain subsequent warping by limiting the deformation of the dry exterior portions of the board. Here, too, compression set must be taken into consideration, since an excessive amount of compression set can nullify the beneficial restraining effect of the tension set. Maximum compression set normally occurs later in the drying process than does maximum tension set, so information on the time and rate of set development under various drying conditions should make possible the development of schedules as to minimize shrinkage and warp. Proper piling and sticking, however, are still considered the best deterrents to excessive warp now available for one-inch lumber.

The effect of drying conditions is more pronounced in thicker lumber. Other drying defects that are more commonly associated with drying stresses are surface checks, end checks, and splits. These defects all have the same basic cause, reduction of the surface moisture content so
much early in drying as to cause tensile stresses that exceed the perpendicular-to-grain tensile strength of the wood. Such stresses are large with respect to wood strength, even under proper drying conditions, so the operator must be very careful to establish the proper drying conditions and maintain excellent control of such conditions in the early stages of drying.

Additional surface and end checking need not be feared after stress reversal. Ordinary surface checks are closed tightly after stress reversal, but such closing does not repair the damage to the wood. The checks may be opened by subsequent moisture regain in drying or in normal use.

Collapse is another defect encountered early in the drying process. It may be caused by excessive compression in the interior of the wood, by internal liquid tension in saturated cell cavities, or by both of these mechanisms operating concurrently. In any case, it occurs when the walls of interior cells are wet and easily deformed, and is a particular hazard when high temperatures are used.

Honey-combing, or internal checking, is characteristic of the drying period that follows stress reversal. The most common form is a tension failure along the wood rays. In quarter-sawed lumber of woods with weak summerwood-springwood interfaces, honey-comb may occur in the form of ring separation. The basic cause is always internal perpendicular-to-grain stress that exceeds the strength of the wood. Internal checks may occur in several ways, but they are formed chiefly as a result of deepening of surface checks or extension of end checks as zones of tensile stress move into the wood from the surfaces and ends toward the center of the mid-thickness. They may also form spontaneously during normal drying, or in association with collapsed cells. Honey-combing is generally associated with high drying temperatures, since high temperatures reduce the perpendicular-to-grain tensile and shearing strength of wood, particularly when the moisture content of the interior of the wood is above or near the fiber-saturation point. The obvious remedy is to avoid raising temperature until the interior of the wood is well below the fiber-saturation point. Honey-combing is rather unusual under normal air-drying conditions; and when it does occur, it is the result of extension of surface and end checks.

Case-hardening, the stress-set condition in dried wood, is the result of normal stress and set during drying. Case-hardened is a condition of stress and set in which the outer fibers are under compressive stress and the inner fibers under tensile stress, and the stresses persist when the wood is uniformly dry. Case-hardening, not always a defect, may give serious trouble after any machining that results in a change in stress distribution. Examples would be resawing, irregular machining, and tongue-and-grooving. Fortunately, case-hardening can be relieved by a proper conditioning treatment, either directly after kiln-drying or later.

Closely related to case-hardening, and producing a similar but opposite effect, is the stress-set condition known as reverse case-hardening. This condition is caused by excessive surface water absorption in stress relief treatments or in subsequent wetting that not only relieves tension set but also induces compression set in the surface layers. When reverse case-hardened lumber attains a uniform moisture content, the outer layers are under tensile stress and the inner layers are under compressive stress. Severe reverse case-hardening is quite uncommon if modern conditioning procedures are followed. Although it was previously thought there were no practical means of relieving reverse case-hardening, there are indications that high-temperature treatments may make such relief possible.

Drying Stresses And Kiln-Drying Schedules

The effects of temperature and relative humidity have become reasonably well known in the past several years. It is now generally accepted that, for each species of wood, there is a critical temperature that cannot be exceeded during the initial stages of drying without jeopardizing the results of the entire drying operation. Temperature control is also important after the initial stage of drying has been passed. Control of relative humidity
is most important during the early stages, when the steepness of the moisture gradient must be restricted. Ample allowance for the effects of temperature and relative humidity is made in the Forest Products Laboratory kiln schedules. For a more detailed discussion on the effects of these factors on stress and set, with the aim of improvement and speeding up of the schedules, the reader can consult a more complete report.

More thought, however, should be given to the time factor. Whether time is written into a kiln schedule, as is common in much softwood drying, or merely assumed as being required in the common hardwood schedule based on moisture content, it is an important factor in schedule design. Aside from the purely economic aspects, time of drying can affect the perpendicular-to-grain mechanical properties of the drying wood and the stress and set pattern during drying.

Prolonged exposure to high temperature, particularly at high humidity, can weaken wood. Most drying conditions and times are not severe enough to be in the time-temperature range considered dangerous to wood strength for ordinary applications. However, there is some indication that the perpendicular-to-grain properties are more severely reduced than the usually considered parallel-to-grain properties under comparable heating conditions. The duration-of-heating effect could reduce the ability of the interior zones of the wood to resist tensile stresses in the intermediate and later stages of drying. The time-temperature effect probably has little bearing on surface end checking, however, since an increase in drying temperature seems to reduce the time required to attain maximum tensile stress in the outer layers of the wood. Wood to be used where strength will be critical should be dried at relatively low temperatures, not exceeding 150°F.

In addition to time-temperature effects, important time-load effects exert a considerable influence on the behavior of wood as it dries. Such effects are directly responsible for all set development. A constant load will, as time passes, increase the kind of deformation known as creep. Likewise, as time passes, less and less load will be required to maintain constant deformation; this effect is known as stress relaxation. Both creep and stress relaxation operate concurrently in wood as it dries.

Besides causing set, creep has the important effect of producing failure at lower stress levels than those indicated in a standard strength test. Stress relaxation, on the other hand, has the important effect of reducing the internal stresses and thus reducing the creep and likelihood of failure. Both creep and relaxation are accelerated at high temperature and high moisture content. However, the precise effect on drying behavior is not yet understood. Work now under way at the Forest Products Laboratory is aimed at developing a better understanding of the relationship between these time-load effects and drying behavior.

**Stress Relief**

Conditioning procedures are available for relieving stresses after a drying run has been completed. Conditioning is a precise treatment that must be carried out properly under good control if it is to result in complete and uniform stress relief. A good conditioning treatment requires that the average moisture content of the whole charge of lumber be accurately known and that the moisture content of the charge be quite uniform. A spread of more than three per cent moisture content between the wettest and driest kiln samples generally indicates that an

---

equalizing treatment should precede conditioning. In an equalizing treatment, the drying of the driest boards is stopped while that of the wettest boards continues.

A successful conditioning treatment requires:
1. Increasing the existing stresses to cause sufficient plastic deformation to cancel out the original sets.
2. Plasticization of the wood by high temperature at a slightly higher moisture content than exists at the end of drying.
3. Sufficient time for the required plastic deformation to take place.
4. A symmetrical distribution of original sets, so that relief forces will be balanced.

Besides relieving stresses, a successful conditioning treatment establishes a uniform moisture content throughout the thickness of each piece. Further details on the method of stress relief now recommended at the Forest Products Laboratory are available in reports.

Fundamental Research On Drying Stresses

Data obtained on stress-strain relationships across the grain in red make possible the mathematical translation of strain recovery values derived by the slicing technique into actual values of stress (pounds per square inch) at any point on the cross section of a drying red oak board. An example of the results of such stress calculations is shown in Figure 4, which indicates stresses present in a two- by seven-inch red oak plank after four days of drying at 80° F. The diagrams show the distribution of stresses in the upper right-hand quarter of the cross section of the plank. It is assumed that the stresses are distributed symmetrically around the midpoint of the cross section.

The three parts of Figure 4 show the tensile (-I-) and compressive (—) stresses in the width direction of the plank (A), in the thickness direction (B), and the associated shearing stresses (C). The three parts are actually all superimposed in the plank and represent the same cross section at the same stage of drying. The lines connect the points of equal stress.

Part A of Figure 4 shows the steep tensile stress gradients near the outer faces of the board, from 0 at a point 0.2 inch below the surface to about 700 pounds per square inch at the surface at mid-width. It also shows that the maximum compressive stress is not at the center of the board, but at a point at mid-width about halfway between the mid-thickness and the surface.

Part B of Figure 4 indicates that tensile and compressive stresses in the thickness direction are concentrated toward the edges of the plank near the mid-thickness at the stage of drying considered.

Part C of Figure 4 locates the point of maximum shear stress at a point about 1/2 inch from the edge of the plank and about a third of the distance from the surface to the mid-thickness.

The curves of Figure 4 illustrate what can be done by way of drying stress determination. Considered together with similar stress distribution diagrams based on other stages of drying and other drying conditions, they provide a basis for a more complete understanding of stresses that develop in a drying board. Such information should lead to significant improvements in drying schedules and conditioning treatments.

FIGURE 4.—Distribution of stress in the width (X) direction (A), and in the thickness (Y) direction (B) of red oak, and associated shear stress (C) indicated by lines connecting points of equal stress.