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Machining and Related Characteristics of Southern Hardwoods

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By E. M. Davis, *senior wood technologist, Forest Products Laboratory,*[2] *Forest Service*

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INTRODUCTION

Machining properties relate to the behavior of a wood when planed, shaped, turned, or put through any of the standard woodworking operations. Wood in general is easy to cut, shape, and fasten. For some purposes the difference between woods in machinability is negligible, but for others the smoothness and facility with which they can be worked, as in such products as furniture and fixtures, may be the most important of all properties, because unless a wood machines fairly well and with moderate ease it is not economically available for such uses regardless of its other virtues. Thus, along with specific gravity and the tendency toward splitting and warping, machinability is of the first importance to the worker.

Unlike the physical, chemical, and mechanical properties, machining properties of wood have had little systematic study and there are few publications in this field. Some of the everyday working qualities and machining characteristics of American hardwoods have, however, been under systematic study at the Forest Products Laboratory during recent years. This bulletin records in part the results of this study and is written primarily for wood turners, cabinetmakers, furniture manufacturers, and other woodworkers.

A number of minor hardwoods, particularly in the South, find relatively little use in the woodworking industries. Lack of information concerning their machining properties has been an obstacle to wider use. A primary object of this study, therefore, was to measure

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[2] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

the machining properties of these little-used woods so that they might be accurately compared with the established woods in respect to machinability. With such a yardstick available the hardwood user can undertake with assurance the use of new woods.

The study also embraced, as far as practical, the influence of some of the factors within the wood and in the various machines that affect machining results. Since such factors can be combined in literally hundreds of ways, it was impracticable to explore the possibilities of all combinations; instead, one or more sets of fairly representative working conditions were selected for each operation and applied uniformly to all woods. These of course could not be the optimum for all woods, but the results show rather what actually happens under the specified conditions.

Close contact was maintained with the woodworking trade both during the planning of the study and during the conduct of the tests. Engineers in woodworking industries, and manufacturers of woodworking machinery and of various hardwood products were frequently consulted.

Shipments of any given wood from different mills may vary significantly in weight, in texture, and in workability because of differences in forest and growth conditions. In order to get a fair cross section of such variations the test samples were largely collected at 34 different sawmills scattered in selected areas from western Virginia to eastern Texas, the region that yields about two-thirds of the yearly cut of hardwoods. To provide some basis for comparing these less known woods with the established northern hardwoods, additional samples were obtained from one Wisconsin source. Two high class cabinet woods were also included for comparison—mahogany from Central America and black walnut from Indiana, Kentucky, Tennessee, and Missouri.

The samples themselves were 4-foot boards, and large enough to permit making all the different machining tests on the same material. Data were also obtained from these samples on specific gravity, number of annual growth rings per inch, cross grain, warp, and shrinkage, all of which affect either the machining or the utility of the woods.

In the United States, smoothness of surface is more important than power consumption as a criterion of workability, and results were accordingly judged on smoothness characteristics. Several mechanisms were devised and tried experimentally in attempting to discover a mechanical means of measuring the smoothness of a machined surface, but results were unsatisfactory. Search through contemporary literature on smoothness measuring devices for metal and other materials revealed none that was practical for use with wood. Accordingly a method of visual inspection was developed and used here. In each operation, each test sample was examined for machining defects and graded on a numerical scale. A grade of 5 was considered excellent, 4 good, 3 fair, 2 poor, 1 very poor, and 0 a reject. The words excellent, good, and fair as used in the tables in this publication refer to these numerical grades. This method of grading shows both the frequency with which a given defect occurs and its degree when present, as applied to the strictly machining properties of planing, shaping, turning, boring, mortising, and sanding. In the related properties of steam bending, nail splitting, and screw splitting, the occurrence of breaks or splits was made the basis of comparison.

Fifty samples of each wood were used in each test, or where one kind of wood was collected in two well-established producing regions, 50 samples from each region. Data on specific gravity, number of rings per inch, and shrinkage were based on several hundred samples of each wood as a rule, including the foregoing 50 samples. The machining samples were commercial flat grain and did not include the extremes of weight and number of rings per inch.

Botanists recognize only one species each of yellowpoplar, beech, and sweetgum. But in each of the other woods studied at least two species are recognized, and in oak, maple, ash, hickory, and some other hardwoods there are more than 20 species each. These species are not available separately on the market, and even if one species is specified by a consumer there is often no adequate test of compliance. This study is, therefore, based on commercial lumber just as the consumer buys it and not on botanical species. Consequently, where certain woods of several species are commonly separated by the lumber trade into two classes, the standard commercial designations shown below are used. One exception should be noted in the case of elm. The commercial separations, soft elm and rock elm, are used almost wholly in the North. The elm samples tested in this study were southern elm without distinction as to type, and are, therefore, referred to in this study simply as elm.

Genus	*Commercial separations*
Acer	Hard maple, soft maple.
Carya (=*Hicoria*)	Hickory, pecan.
Nyssa	Blackgum, tupelo.
Populus	Cottonwood, aspen.
Quercus	Red oak, white oak.
Ulmus	Soft elm, rock elm.

Different species of basswood are commercially lumped together without any attempt at separation and the same is true of hackberry, magnolia, sycamore, and willow.

MACHINING PROPERTIES

Planing

Planing is the most important of the machining operations studied, since nearly all hardwood lumber is planed before use. In addition to the factors that affect all machining operations, such as species, specific gravity, and moisture content, planing is affected by many different adjustments of the machine itself, making it probably the most complex of woodworking operations.

METHOD

The tests described here were made on a modern cabinet planer, a type designed for fine work. The results obtained might reasonably be expected to apply to other types of planing machines because of the general similarity of their cutting action. The 50 test samples of each wood were clear, flat-grained, ¾ inch by 4 inches by 3 feet in size, and free from all extremes of either specific gravity or growth rate.

In each run, all the factors except the one under consideration were kept uniform. Among the variables investigated were rate of feed and speed, cutting angle of the planer knives, depth of cut, amount of jointing of the knives, and moisture content of the wood.

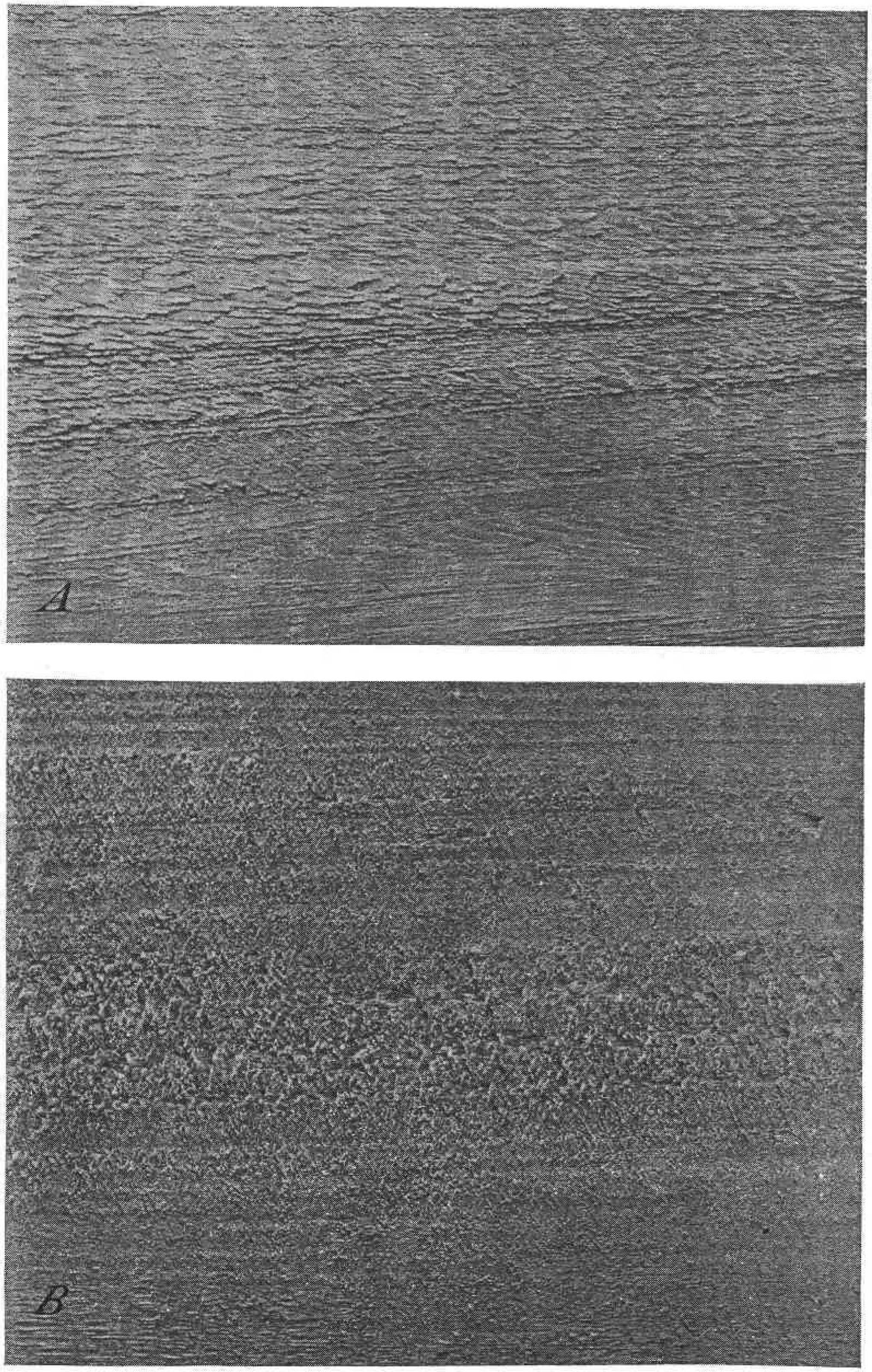
Among the factors that may be considered in judging the "planability" of different woods are power consumption, speed of operation, rate of dulling of knives, and smoothness of the planed surface. American woodworkers consider the last to be the most important factor, and accordingly the planing tests were judged on that basis. For any fine work it is always necessary to sand a planed surface before applying the finish. However, the amount of necessary sanding may be greatly increased by the presence of certain defects that often result from planing, namely, raised grain, fuzzy grain, chipped grain, and chip marks (pls. 1 and 2). More than one kind of defect may be present in a board, and any given defect may vary in degree in different boards. The best basis for comparing different woods and for evaluating the effect of different factors was found to be the percentage of defect-free pieces. If in some instances this percentage seems surprisingly small, it must be remembered that some of the planing conditions were far from optimum for certain woods and also that many of the defective pieces were only slightly defective.

RESULTS

Planing quality was determined from a series of six runs for each wood at cutting angles of 15°, 20°, and 25° combined first with a cutter head speed of 3,600 r. p. m. and a feed of 36 feet per minute and then with a cutter head speed of 5,400 r. p. m. and a feed of 54 feet per minute. The three cutting angles include the optimum, and they cover the most commonly used cutting angles for hardwoods. Averaging the three gives a deserved advantage to those woods that plane well over a fairly wide range of conditions. Moisture content of the woods was 6 percent. The best two woods yielded about four times as many defect-free pieces as did the two poorest woods (table 1).

TABLE 1.—*Planing: Relative freedom of hardwoods from defect*

Kind of wood	Defect-free pieces	Kind of wood	Defect-free pieces
	Percent		*Percent*
Red oak	91	Black walnut	62
Pecan	88	Hard maple	54
White oak	87	Willow	52
Mahogany	80	Sweetgum	51
Ash	75	Blackgum	48
Hackberry	74	Soft maple	41
Chestnut	74	Elm	33
Yellowpoplar	70	Sycamore	22
Magnolia	65	Cottonwood	21
Basswood	64		
Birch	63	Average	61



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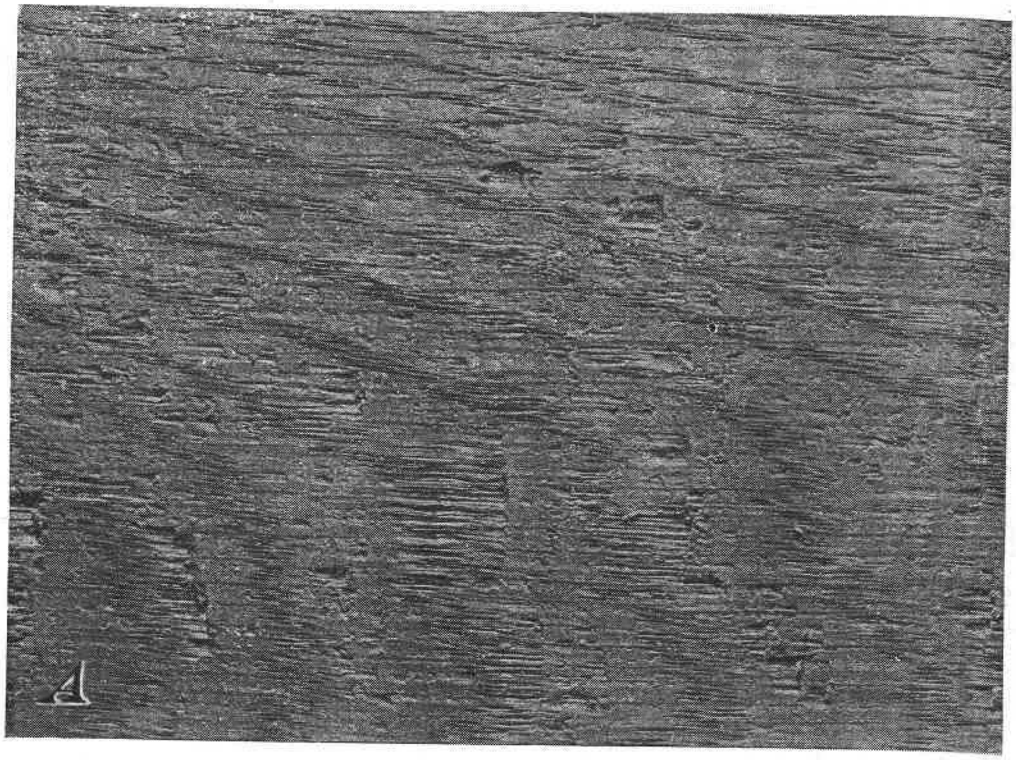
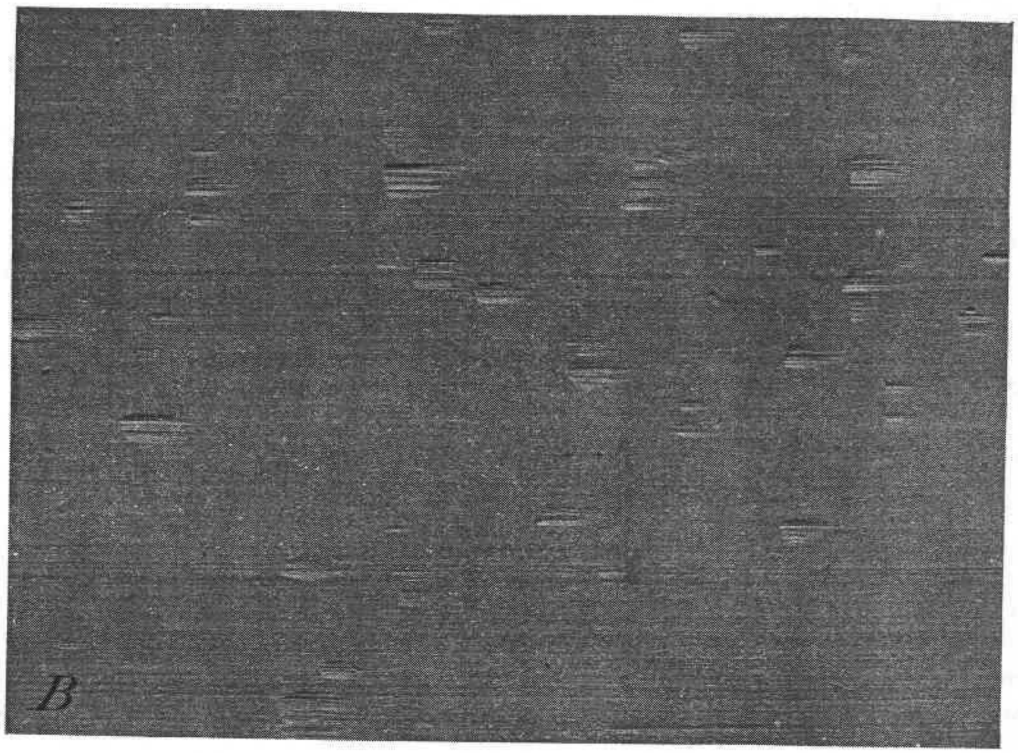
Results of planing: *A*, Raised grain; *B*, fuzzy grain.





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Results of planing: *A*, Chipped grain; *B*, chip marks.

FACTORS AFFECTING RESULTS

Cutting Angle.—Of the many factors affecting planing, probably cutting angle (fig. 1) is the most important. Cutting angle may be altered by changing cutter heads or by grinding a "back bevel" on the knife edge. Results of experiments with six different cutting angles are shown in table 2.

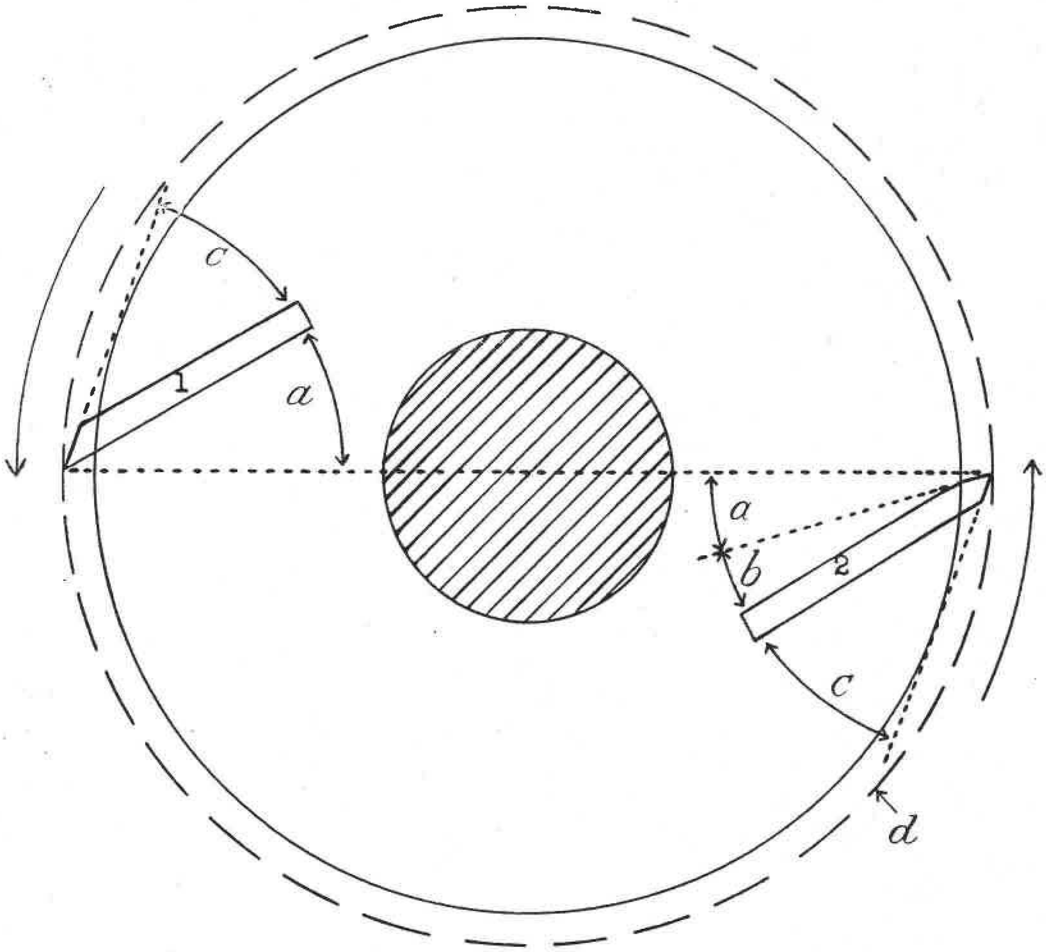


FIGURE 1.—Terms used in connection with planer knives: *a*, Cutting angle; *b*, cutting bevel; *c*, clearance bevel; *d*, cutting circle; 1 and 2, planer knives.

Most woods showed considerable variation in quality of work at different cutting angles, hackberry being an extreme example. However, there are a few, like mahogany, that were relatively unaffected.

The oaks gave good results over a wide range of cutting angles, but most other woods were considerably more exacting in this respect.

Feed and Speed.—Feed is the rate in feet per minute at which the lumber passes through the machine. Speed is the number of revolutions per minute made by the cutter-head. For each of the feed-speed combinations tried, the number of knife cuts per inch is the same; but with the faster (54 feet; 5,400 r. p. m., or about as fast as cabinet planers often operate), the output is one-third greater and the results are consistently better (table 3). Basswood was the only exception among the 17 woods tested. The other woods were affected in different degrees; in the oaks, for instance, the difference was negligible, while in the maples it was apparently significant. The better showing made by the higher feed-speed combination was largely

TABLE 2.—*Planing: Effect of cutting angle on quality of work* [1]

Kind of wood	Defect-free pieces at cutting angle of—					
	5°	10°	15°	20°	25°	30°
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Ash	69	70	72	73	79	53
Basswood			52	65	68	65
Birch			71	63	55	
Chestnut			81	76	65	34
Cottonwood	40	37	25	27	12	31
Elm, soft	24	24	48	33	19	18
Blackgum	42	52	47	53	43	37
Hackberry	37	47	75	93	54	20
Magnolia	87	78	78	56	62	61
Mahogany	77	88	76	77	87	
Hard maple			56	56	51	17
Soft maple	43	61	57	33	34	18
Red oak	66	96	95	92	87	65
White oak	74	98	95	93	74	37
Pecan	78	82	76	92	95	57
Sweetgum	35	66	54	51	49	44
Sycamore	25	39	26	23	18	18
Black walnut			64	73	50	
Willow	32	46	50	59	46	10
Yellowpoplar	66	75	75	67	67	48

[1] For each cutting angle shown the test pieces were planed under two different conditions: (1) At 36 feet per minute feed and 3,600 r. p. m. and (2) on the opposite side at 54 feet feed and 5,400 r. p. m. The moisture content was 6 percent for this entire series of tests.

TABLE 3.—*Planing: Effect of feed and speed on quality of work, in defect-free pieces* [1]

Kind of wood	36-feet feed; 3,600 r. p. m.	54-feet feed; 5,400 r. p. m.	Kind of wood	36-feet feed; 3,600 r. p. m.	54-feet feed; 5,400 r. p. m.
	Percent	*Percent*		*Percent*	*Percent*
Ash	52	64	Soft maple	19	37
Basswood	53	43	Red oak	72	74
Chestnut	47	65	White oak	60	60
Cottonwood	17	23	Pecan	54	69
Elm	17	26	Yellowpoplar	50	54
Blackgum	37	45	Sycamore	16	22
Sweetgum	41	49	Willow	28	38
Hackberry	39	46			
Magnolia	50	72	Average	40	49
Hard maple	24	43			

[1] Based on 4 cutting angles (15°, 20°, 25°, and 30°) and 6 percent moisture content for each feed-speed combination.

due to a decrease in the number of chip marks. Chipped grain and raised grain were not greatly affected, and the slower conditions proved somewhat better for decreasing the amount of fuzzy grain.

Moisture Content.—In general, lumber at 6 percent moisture content gave the best results, 12 percent lumber intermediate, and 20 percent the poorest (table 4). Some woods, like basswood and yellowpoplar, showed a wide variation in results between 6 percent and 20 percent, whereas the maples were not greatly affected. Birch, chestnut, and willow were exceptions in that the material planed at 20-percent moisture content was better than that at 6 percent. Chipped, raised, and fuzzy grain were much more prevalent at 20 percent moisture content than at 6 percent, but the reverse was true of chip marks.

TABLE 4.—*Planing: Effect of moisture content on quality of work* [1]

Kind of wood	Defect-free pieces at moisture content of—			Kind of wood	Defect-free pieces at moisture content of—		
	6 percent	12 percent	20 percent		6 percent	12 percent	20 percent
	Percent	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
Ash	53	39	35	Hard maple	17	17	15
Basswood	65	44	2	Soft maple	17	12	15
Beech	40	30	22	Chestnut oak	64	52	43
Birch	10	5	15	Red oak	65	54	48
Chestnut	34	29	52	White oak	37	37	26
Cottonwood	29	14	14	Pecan	56	28	21
Elm	18	5	6	Yellowpoplar	47	37	20
Blackgum	36	40	30	Sycamore	18	18	12
Sweetgum	46	38	36	Willow	10	13	19
Hackberry	20	8	7				
Hickory	35	27	16	Average	37	29	24
Magnolia	61	61	53				

[1] Based on 30° knife angle only; 36 feet per minute feed, at 3,600 r. p. m. and 54 feet per minute feed at 5,400 r. p. m.

Amount of Jointing.—In modern cabinet planers the knives are ground in place in the machine. Frequently one of them projects just a trifle farther than the others which means that this knife does all the cutting and the resulting work has only one knife cut per revolution instead of four (pl. 3, *A*), assuming a four-knife cutter head. Jointing is then resorted to as an equalizing operation. With the cutter head revolving, a sharpening stone in a carrier is lowered until it barely touches the projecting knife edge and then is mechanically passed back and forth along the length of all knives until their projections are equalized. Each knife then makes one cut in each revolution of the cutter head (pl. 3, *B*). As the knives become dull, jointing is repeated as a sharpening process. Each successive jointing makes a slightly thicker cutting edge, and this affects the planing somewhat.

Tests of the effect on planing of different degrees of jointing were made on seven woods—ash, birch, sweetgum, magnolia, red oak, white oak, and yellowpoplar. The results were consistent and strongly indicate the desirability of jointing, but jointing only lightly. Considerably less sanding would be required with the four-knife work of the jointed knives than with the one-knife work of the freshly ground unjointed knives. As the jointing operation was repeated, however, and the cutting edge became thicker, the quality of planing deteriorated, showing that jointing should not be repeated too many times between grindings.

Depth of Cut.—A series of tests was made with four different depths of cut: 1/32, 2/32, 3/32, and 4/32-inch. The shallowest cut gave much the best results with progressively poorer work as deeper cuts were made (table 5). The difference between 1/32 inch and 2/32 inch was much greater than between any other two successive cuts. As usual the different woods behaved in different ways. For example, beech and hickory were greatly affected by depth of cut as compared with elm and willow. At times the operator has little choice as to depth of cut, but where a preliminary roughing cut is practical, results can often be substantially improved by taking this factor into account.

TABLE 5.—*Planing: Effect of depth of cut on quality of work*[1]

Kind of wood	Defect-free pieces at depth of cut of—			
	1/32 inch	2/32 inch	3/32 inch	4/32 inch
	Percent	*Percent*	*Percent*	*Percent*
Ash	58	38	32	26
Beech	76	40	34	24
Cottonwood	38	12	20	6
Elm	6	4	0	0
Blackgum	62	38	40	34
Sweetgum	36	22	14	16
Hackberry	28	10	6	4
Hickory	46	6	14	6
Magnolia	78	50	52	48
Soft maple	40	28	30	14
Red oak	74	56	36	28
White oak	58	34	22	24
Pecan	50	28	26	30
Yellowpoplar	64	36	44	34
Sycamore	22	8	2	4
Willow	30	16	20	20
Average	48	27	25	20

[1] Based on 30° knife angle only, 36-foot feed per minute at 3,600 r. p. m., and 6 percent moisture content.

SHAPING

The distinctive use of the shaper is to cut a pattern on a curved edge like that of an oval table top. The machine has cutter heads that revolve on vertical spindles. Typically these heads are much smaller in diameter than planer heads, but operate at higher speeds. Shaping is a less important operation than planing in the average woodworking plant because it is employed less often.

Like other woodworking machines, shapers come in numerous sizes and types. The one used in these tests was a double spindle type, electric drive, operated at 7,200 r. p. m. and fed by hand.

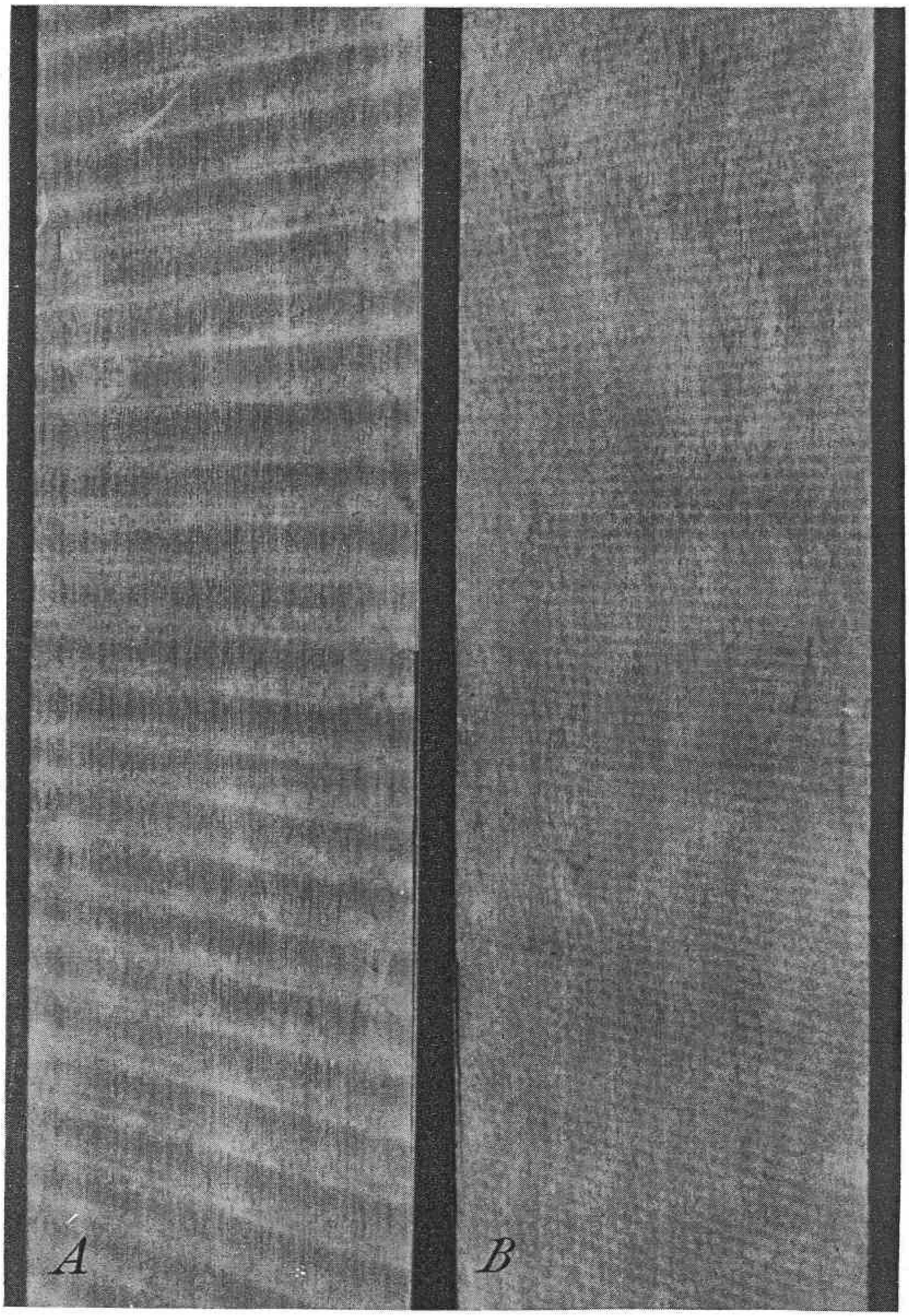
The primary object of the work was to compare and measure the shaping qualities of the various hardwoods under conditions that were uniform and fairly typical. Some additional data were obtained on certain factors involved, but these were merely incidental.

METHOD

Before the actual shaping operation the test samples were band sawed to a curved outline (pl. 4, *A*). Woodworking machines, like hand tools, differ in the way that they cut wood at different angles to the grain, and the outline chosen required cuts varying from right angles to parallel to the grain. The actual shaping was done by an experienced operator, the samples being fastened to a form and fed past the cutters by hand.

Two separate runs were made (after a preliminary roughing cut), one with the samples at 6-percent moisture content and the other after conditioning the samples to 12 percent. The two spindles of the shaper revolved in opposite directions and enabled all cutting, except the right-angle cut, to be done with the grain regardless of the curves of the pattern.

Following each run the samples were graded on the basis of such defects as raised, fuzzy, chipped, and torn grain. For all practical purposes the most defective place on a shaping determines its grade, that is, the worst place indicates the amount of smoothing that will be necessary to make it commercially acceptable.



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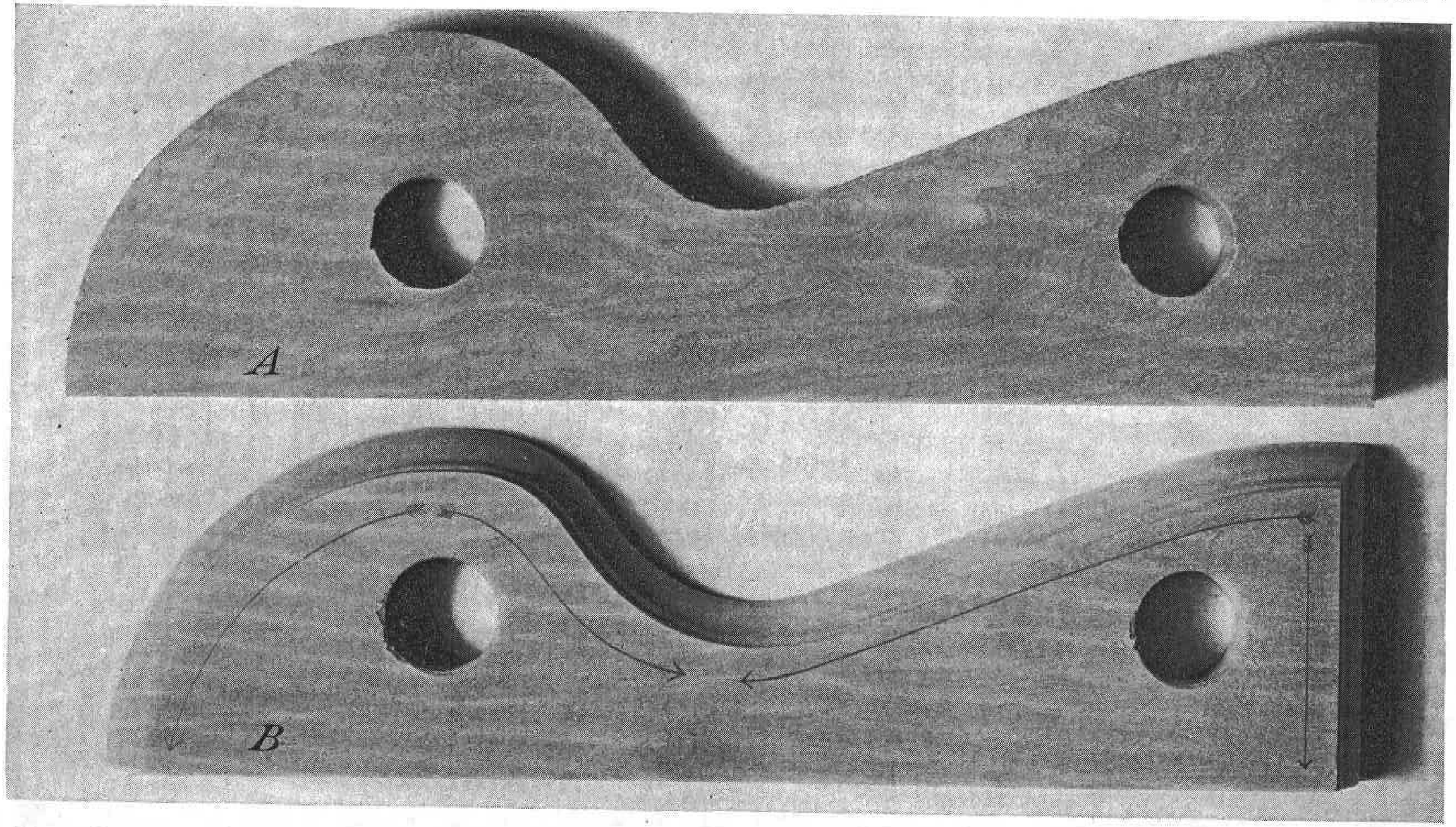
Effects of jointing: *A*, Before jointing one knife projects beyond the others, does all the cutting, and produces one knife mark for each revolution of the cutter head; *B*, after jointing the projection of all four knives has been equalized and each knife makes one cut each revolution.



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Type of test sample used for shaping: *A*, The blank; *B*, finished sample with arrows showing the direction of the different cuts.

RESULTS

The best shaping woods, like mahogany and hard maple, produced about two-thirds of samples that were good to excellent (pl. 4, *B*), whereas the poorest, like willow and cottonwood, yielded very few samples of equal quality (table 6).

TABLE 6.—*Shaping: Relative working quality of hardwoods* [1]

Kind of wood	Good to excellent shapings	Kind of wood	Good to excellent shapings
	Percent		*Percent*
Mahogany	68	Beech	21
Maple, hard	62	Sweetgum	21
Birch	53	Hickory	19
Ash	51	Yellowpoplar	12
Tupelo	43	Elm	11
Walnut	34	Hackberry	10
Pecan	31	Basswood	9
Oak, white	28	Sycamore	8
Magnolia	25	Buckeye	6
Chestnut	24	Willow	5
Oak, chestnut	23	Cottonwood	3
Blackgum	23		
Maple, soft	22	Average	25
Oak, red	21		

[1] Results for 6-percent and for 12-percent moisture content averaged.

Cuts made in a direction parallel to the grain or in a diagonal direction were consistently and noticeably better than cuts at right angles to the grain or thereabouts.

In the parallel and diagonal cuts, raised grain was the worst defect in all the ring-porous woods.[3] A minute roughness that varied considerably in degree in different samples and in different woods was the most serious defect in the diffuse-porous woods.

In cuts at right angles to the grain, surface roughness was the most serious defect in nearly all woods and more pronounced than in cuts at other angles. Examples of torn grain were encountered in several woods, and in tupelo, magnolia, soft maple, and cottonwood this was the worst defect.

FACTORS AFFECTING RESULTS

Moisture Content.—Moisture content did not appear to be an important factor in shaping, at least as between 6 percent and 12 percent. In most woods results differed little at these two moisture contents; with some, 6 percent gave the better results; with others, 12 percent. For these reasons table 6 is based upon an average for both moisture contents.

Pore Arrangement.—The three best shaping woods were all diffuse porous, but so were the five poorest ones. The ring-porous and diffuse-porous woods were mixed in the middle of the list in table 6, failing to show any consistent relationship between pore arrangement and shaping properties.

[3] Those hardwoods are termed ring porous in which the pores are comparatively large at the beginning of each annual ring and decrease in size more or less abruptly toward the outer portion of the ring, forming a distinct inner zone of larger pores known as springwood and an outer zone of smaller pores known as summerwood; in diffuse-porous woods the pores are practically uniform throughout each annual ring or slightly smaller towards the outer border.

Specific Gravity.—The specific gravity of a wood is a measure of its hardness, which is a factor of importance in several machining operations. In general, heavy woods shaped better than light ones. There were, however, some exceptions to this rule. Tupelo, for instance, gave better results than several heavier woods, like red oak and hickory. Where there was any considerable difference in the specific gravity of different pieces of the same wood, it was noticeable that the heavier pieces gave somewhat better results.

Other Factors.—Any complete study of shaping would involve other factors, such as speed of cutter head and angle of knives. The problem of getting satisfactory results in some woods may well depend on these factors, and it is well to recognize their importance.

TURNING

Turned products include tool and implement handles, spools, and bobbins together with certain types of woodenware, sporting goods, chair parts, furniture parts, and many minor items. Although turnings are not among the largest wood uses they are chiefly high-grade products with a value out of proportion to the volume. Naturally there are several different types of lathes adapted to various types of turnings.

METHOD

A milled-to-pattern knife was designed that produced small turnings with considerable detail. The knife was held in a compound rest of the type used for metal turning, enabling the operator to make several hundred identical turnings in the course of a day. The equipment embodied the back-knife principle with modifications to adapt it to a small hand lathe. The turnings (pl. 5) contained a bead, cove, and fillet together with cuts at several different angles with the grain—in fact, most of the common features of turning. They were 5 inches long and ⅜ inch in smallest diameter when finished. Turnings were made at three moisture contents: 6, 12, and 20 percent, and at 3,300 r. p. m. Commercial wood turners with whom the problem was discussed expressed the opinion that this was a more severe test than when turnings are subjected to ordinary manufacture and that it was a good means of comparing the "turnability" of different woods, and of working out the effect of certain factors that affect turning.

Each turning was carefully examined and graded, taking into account sharpness of detail and smoothness of surface. The poorest point in a turning was the controlling factor because that point governs the amount of sanding necessary to make it commercially acceptable. Grading was done on a numerical scale of 5, in which 5 represented a perfect turning and 0 a reject.

RESULTS

Turning qualities of 25 hardwoods were tested (table 7). Although the spread in quality from best to poorest was not nearly so wide as in most machining properties, the poorest woods yield several times as many inferior turnings as the best. Consecutive species were seldom more than 1 or 2 percent apart.

TABLE 7.—*Turning: Relative working quality of hardwoods* [1]

Kind of wood	Ratio of good to excellent turnings	Kind of wood	Ratio of good to excellent turnings
	Percent		*Percent*
Black walnut	91	Magnolia	79
Beech	90	Tupelo	79
Chestnut oak	90	Ash	79
Pecan	89	Hackberry	77
Mahogany	89	Soft maple	76
Chestnut	87	Blackgum	75
Sweetgum	86	Cottonwood	70
White oak	85	Basswood	68
Sycamore	85	Elm	65
Hickory	84	Willow	58
Red oak	84	Buckeye	58
Hard maple	82		
Yellowpoplar	81	Average	79
Birch	80		

[1] Based on average for 6-, 12-, and 20-percent moisture contents.

FACTORS AFFECTING RESULTS

Specific Gravity.—Four of the five poorest turning woods—cottonwood, basswood, willow, and buckeye—were the lightest four woods tested. Aside from this, no consistent relationship between the average specific gravity of a wood and its turning qualities could be traced. Woods of light, medium, and heavy average weight were found in nearly all parts of the list in table 7, which suggests that structure outweighs specific gravity in importance. In general, however, the heavy pieces of a given wood tended to turn better than the light pieces although the difference was not very pronounced.

Moisture Content.—In general the woods tested turned about equally well at 6-percent and at 12-percent moisture content, and both were decidedly better than 20 percent (table 8).

The woods were affected by the moisture content factor in varying degrees. Elm, hackberry, pecan, and mahogany were relatively little affected. At the other extreme is a group of the lightest and softest woods, including basswood, cottonwood, yellowpoplar, and willow, all of which gave much poorer results at 20 percent.

TABLE 8.—*Turning: Influence of moisture content on work* [1]

Kind of wood	Relation of good to excellent turnings, at moisture contents of—			Kind of wood	Relation of good to excellent turnings, at moisture contents of—		
	6 *Percent*	12 *Percent*	20 *Percent*		6 *Percent*	12 *Percent*	20 *Percent*
	Percent	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
Ash	93	98	45	Hard maple	95	87	63
Basswood	88	76	35	Soft maple	96	82	54
Beech	99	92	78	Chestnut oak	100	95	84
Birch	93	82	62	Red oak	90	95	75
Buckeye	100	52	21	White oak	93	92	78
Chestnut	100	99	63	Pecan	92	93	94
Cottonwood	92	75	52	Yellow poplar	98	98	49
Elm	60	70	61	Sycamore	97	98	67
Blackgum	80	86	72	Tupelo	88	94	67
Sweetgum	95	92	77	Black walnut	96	88	90
Hackberry	78	87	78	Willow	79	51	39
Hickory	99	88	83				
Magnolia	69	98	89	Average	90	86	67
Mahogany	89	91	87				

[1] Based on a lathe speed of 3,300 r. p. m.

Breakage of turnings was negligible or lacking at 6-percent and 12-percent moisture content, but appreciable at 20 percent. This breakage was largely because only one knife was used to do all the work, instead of two knives, one for a roughing cut and one for a finishing cut as in commercial back-knife lathes.

Speed of the Lathe.—The best lathe speed depends upon the diameter of the turning regardless of species. Tests made at four speeds ranging from 950 r. p. m. to 3,300 r. p. m. showed that, with test pieces 0.75 inch in diameter, the higher the speed the better the results, and subsequent tests were made at the highest available speed, or 3,300 r. p. m.

Number of Rings per Inch.—Search was made for any relationship that might be found between number of annual growth rings per inch and turning qualities, but without result. The number of rings in itself offered little, if any, indication of turning qualities either as between fast-growing and slow-growing woods or as between fast-growing and slow-growing pieces in the same wood.

Boring

Boring is commonly done wherever dowels, spindles, rungs, and screws are used in making chairs, furniture, and other hardwood products.

The earliest form of boring tool consisted of a stone point set in the end of a round wooden shaft which was rotated between the hands. At the other extreme of precision, speed, and general efficiency are specialized machines like the modern chair-seat borer which bores all holes in both sides of the seat in one operation that lasts only a few seconds. Although it is not one of the most important woodworking operations, the quality of the boring either adds or detracts from the general utility of any wood. The woods tested differed noticeably not only in the smoothness of cut, roundness, and trueness to size of the holes, but also in power consumed and in the rate of dulling of the bit.

There are many types of bits, wood drills, and boring machines, often highly specialized for some one job on a mass production basis. In these tests the equipment used was a general purpose type, such as might be found in nearly any small wood shop.

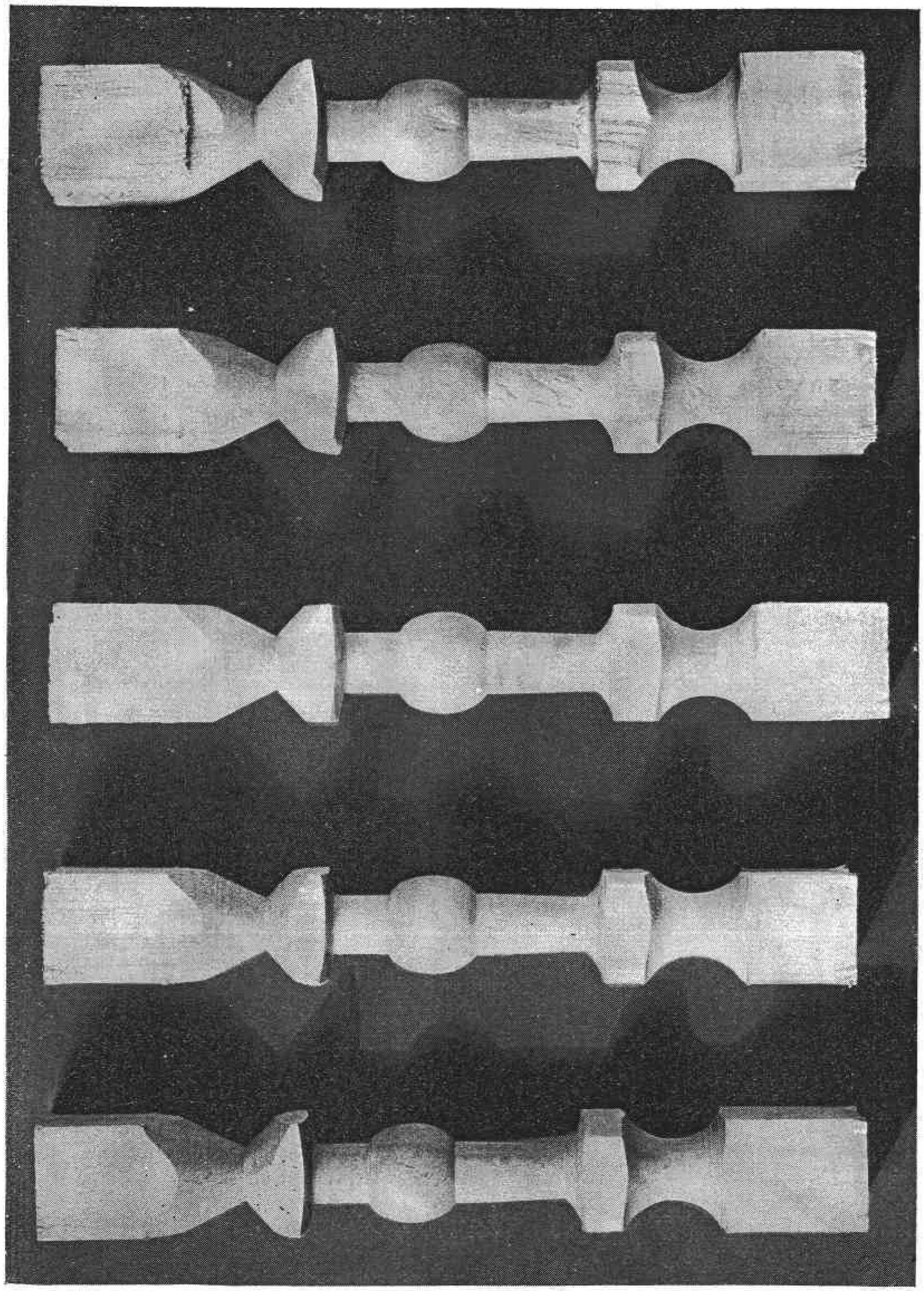
METHOD

A small motor-driven boring machine operating at 2,400 r. p. m. was used. Mechanical means of feeding the bit into the wood at a uniform rate would have been desirable, but the machine permitted only hand feed. The rate, however, was kept uniform by means of a stop watch. The bit itself was the 1-inch size, single-twist, solid-center, brad-point, kept in first-class cutting condition by frequent light sharpenings.

The test samples were commercial flat grain material, three-fourths inch thick and at 6-percent moisture content. They were bored with two 1-inch holes each, making as a rule from 100 to 200 holes for each wood.

RESULTS

Smoothness of Cut.—One criterion of good boring is a clean, smooth cut with a minimum disturbance of the grain on the cut surface. The



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Test samples used in turning showing range in quality of work.

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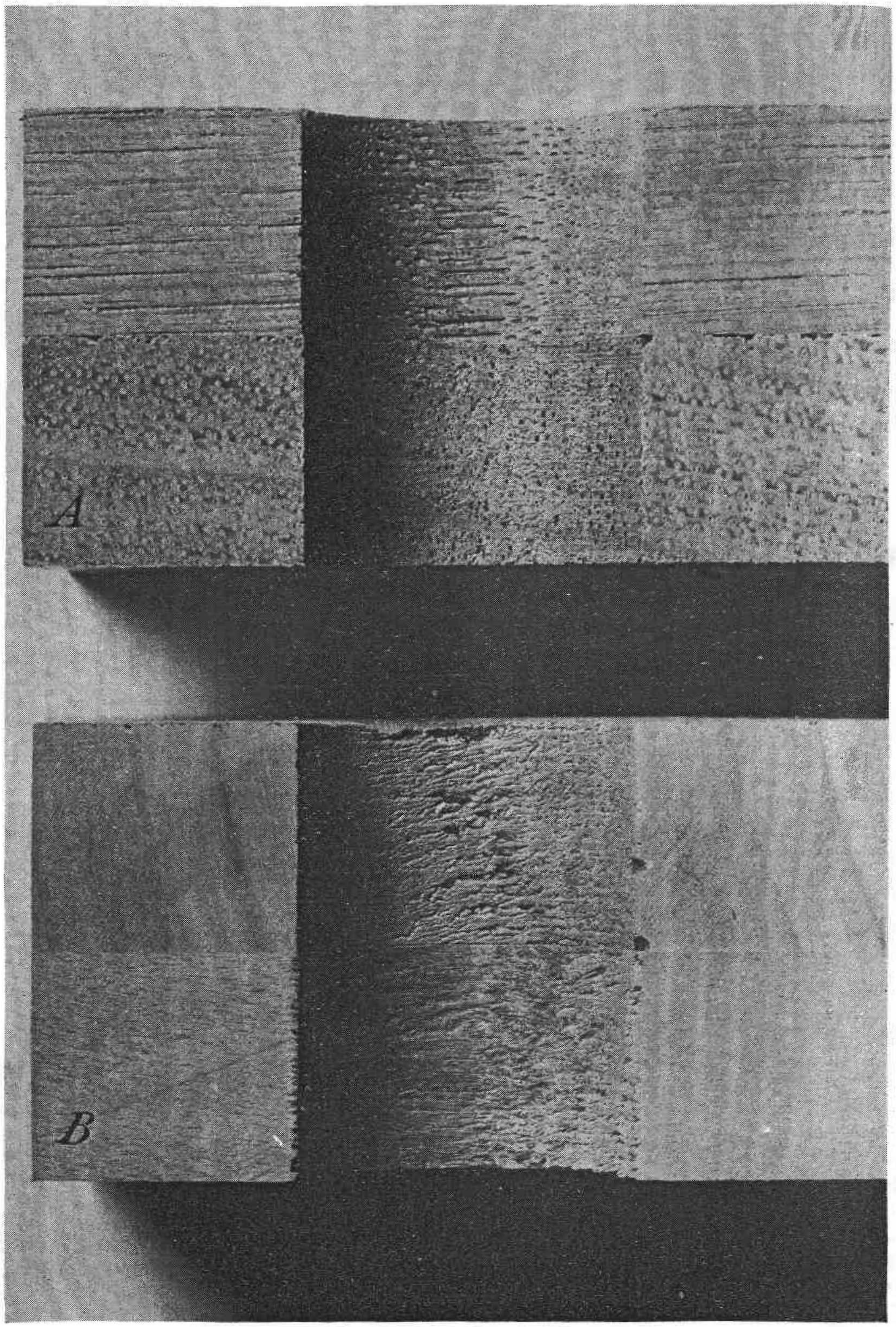

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Differences in smoothness of cut in boring different woods: *A*, Pecan, a smooth-boring wood; *B*, willow, a rough-boring wood.

holes bored were examined and graded for smoothness of cut, and the different kinds of wood were graded according to the percent of holes in each that were good to excellent in this respect (table 9). Results of boring are illustrated in plate 6 by a smooth-boring and a rough-boring wood. The upper half of each sample shows side grain and the lower half, end grain. The wood at each side of the holes has been sanded to show the grain more plainly, but the inside of the holes is just as left by the bit. In pecan the effect of the pressure and the cutting action of the bit produced no distortion of grain. In the willow, however, crushing and tearing of the grain are pronounced.

TABLE 9.—*Boring: Relative smoothness of cut in hardwoods*

Kind of wood	Good to excellent holes	Kind of wood	Good to excellent holes
	Percent		*Percent*
Chestnut oak	100	Sweetgum	92
Pecan	100	Chestnut	91
Hickory	100	Yellowpoplar	87
Mahogany	100	Blackgum	82
Black walnut	100	Soft maple	80
Red oak	99	Buckeye	75
Beech	99	Basswood	75
Hard maple	99	Willow	71
Hackberry	99	Cottonwood	70
Sycamore	98	Magnolia	69
Birch	98	Tupelo	62
White oak	95		
Ash	94	Average	89
Elm	94		

The woods did not differ so widely in boring as they did in many other machining properties. Although the contrast between the best and poorest was fairly wide, most of the woods tested were about on a par with 90 percent or more of the holes that were good to excellent in this respect.

Accuracy of Size.—The holes were measured with a plug gage so designed as to permit measuring to the nearest 0.0015 inch. The flat sides of the gage permitted measurements to be taken both parallel to the grain and across it. The difference in average measurements in the two directions was measurable, and the holes were consistenly larger across the grain than parallel to it.

The bored holes differed from the actual size of the bit by amounts ranging up to about 0.0025 inch (table 10). These figures are averages for 100 to 200 holes for each wood and some individual pieces were found to be as much as 0.006 inch off size.

In several woods, chiefly the harder ones, the holes, which in all species were measured immediately after boring, averaged slightly smaller than the bit. This could hardly be due to anything except recovery of fibers bordering the hole that had been flattened, bent, or compressed during boring and then partially recovered their original position. Oversize, however, was much more common than undersize.

Off-size holes, or different-sized holes in different woods bored with the same bit, help to explain why some woods split considerably more than others when dowelled. By way of contrast, some pieces of beech were 0.002 inch undersize and some pieces of magnolia as much as 0.006 inch oversize, which is enough to make all the difference

TABLE 10.—*Boring: Variation from size of bored holes in hardwoods* [1]

Kind of wood	Amount of off size	Kind of wood	Amount of off size
	Inch		*Inch*
Pecan	0.0001	Chestnut	0.0009
Red oak	.0002	Sycamore	.0009
Hickory	.0003	Beech	.0010
Birch	.0004	Blackgum	.0010
Elm	.0004	Yellowpoplar	.0011
Ash	.0005	Tupelo	.0015
Mahogany	.0005	Basswood	.0020
Sweetgum	.0005	Buckeye	.0022
Willow	.0005	Soft maple	.0022
White oak	.0006	Cottonwood	.0024
Chestnut oak	.0006	Magnolia	.0025
Hard maple	.0006		
Hackberry	.0006	Average	.0010
Black walnut	.0009		

[1] Figures represent off size either across the grain or parallel to it, whichever is greatest.

between a drive fit and a loose fit with an accurately sized dowel. The combination of a dry dowel of a high-shrinkage wood and thin liquid glue might, it would seem, make trouble with one wood and not with another in such instances.

The size of a given hole is not necessarily constant, but changes with changes in moisture content. The tests indicated that the holes increase in size as the moisture content increases. Increase across the grain was more marked than increase parallel to the grain.

Power Consumed in Boring.—The woodworker quickly notices a difference in the effort required to cut different woods with hand-feed machines of any type. This difference is reflected both in the volume of work accomplished and in the amount of power consumed. During the day's work a man will bore fewer holes in hard maple or hickory, for instance, than in basswood, and more power will be consumed in the process (table 11). Even where the feed is mechanical, thus maintaining the daily output, the power consumption factor still remains. Ease of cutting, then, directly affects the all-important matter of costs in wood fabricating and this in turn affects the utility. In testing these woods for the average power consumed in boring a 1-inch hole, it was found that hickory took more than three times as much power as basswood.

TABLE 11.—*Boring: Power consumed in boring a 1-inch hole* [1]

Kind of wood	Power consumed	Kind of wood	Power consumed
	Watts		*Watts*
Basswood	220	Soft maple	460
Willow	270	Blackgum	460
Chestnut	280	Red oak	465
Cottonwood	290	Birch	500
Yellowpoplar	315	Sycamore	500
Sweetgum	380	Hard maple	520
Tupelo	390	Pecan	540
Hackberry	400	Ash	555
White oak	430	Beech	560
Magnolia	440	Hickory	740
Chestnut oak	440		
Elm	450	Average	437

[1] In wood at 6-percent moisture content.

THE SPECIFIC GRAVITY FACTOR

The heavier the wood as a rule the more power was consumed (fig. 2). There were, however, several of the heavier woods, including white oak, chestnut oak, and birch, that took less power than might be expected from weight alone. Another point of interest is that power consumption increased much faster than specific gravity; for instance, ash is about 1½ times as heavy as basswood, but it used about 2½ times as much power in boring.

In plotting similar data for 100 or more holes in a given wood it was found that the heavy pieces consistently used more power than did the light ones, which parallels figure 2. Power consumption has

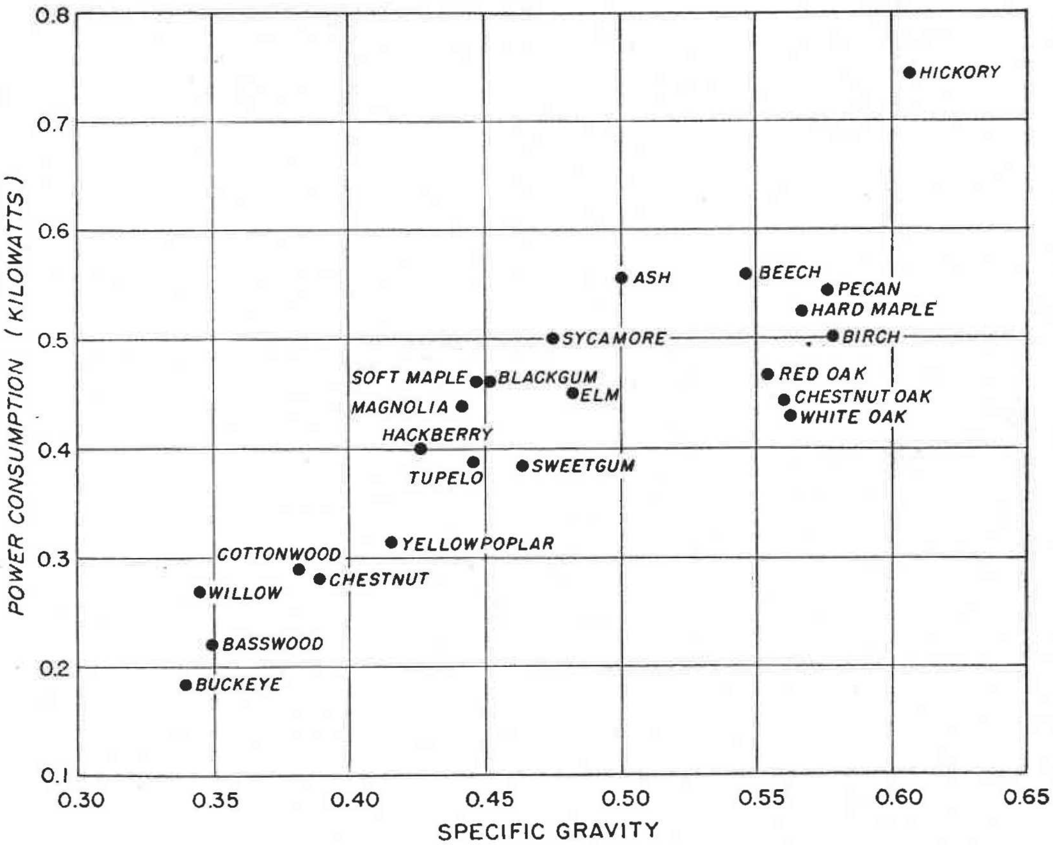


FIGURE 2.—Relationship of specific gravity to power consumption for 23 hardwoods.

received serious consideration in recent European research as one measure of workability. It is, of course, only one of several considerations.

The group of woods that yielded 90 percent or more of good to excellent holes from the smoothness of cut standpoint was composed of medium to heavy woods. The poorer group consisted of light- to medium-weight woods. Mahogany, black walnut, and hackberry were among the medium woods that gave excellent results. On the other hand, magnolia and tupelo represent medium-weight woods that made a poor showing. As a general rule, however, the heavier woods yield more smoothly cut holes than do the light woods.

The heavy woods as a class bored more accurately than the light ones, although there were occasional exceptions. Willow, one of the very lightest, was among the best. Other exceptions are soft maple and magnolia, both of which are moderately heavy but were among the poorest woods in this respect.

MORTISING

The mortise and tenon joint has been used from time immemorial to fasten together the members of wooden products and structures. Today furniture is the commonest hardwood product in which mortise and tenon are used extensively. In the hewn timbers of old colonial buildings, hand tools offered the only means of making mortises, but the modern furniture factory has machines for making them much more quickly and precisely. A less important operation than planing or sanding, mortising is still one of the factors to be considered in appraising the workability of any wood. The tenoning operation is performed on an entirely different machine and is not discussed here.

There are several types of modern mortising machines, and the hollow-chisel mortiser, which is adapted to use on standard boring machines, was the type used here. With this device, which is well known to all woodworkers, the mortise is produced by the action of two separate cutters. First comes the specially designed bit revolving inside the hollow chisel of square cross section. The bit bores a hole slightly in advance of the four edges of the chisel which cut out the corners of the square as they follow the bit. By making several cuts a mortise several times as large as the chisel itself can be produced.

METHOD

The test samples were three-fourth inch thick and had 6-percent moisture content. Two mortises one-half inch square were made in each piece. One set of standard conditions was applied uniformly to all woods. Although the machine used was a hand-feed machine, a relatively uniform rate of feed was obtained by the use of a stop watch. Both the bit and the chisel were sharpened at frequent intervals to prevent progressive dulling of the tool.

The finished mortises were examined and graded for smoothness of cut, and measured with a steel gage for trueness to size. In these respects, as in other machining properties, the different woods varied widely. Although the mortise is largely concealed in the finished product, a smoothly cut, accurately sized mortise obviously makes a better joint than the opposite type.

RESULTS

Smoothness of Cut.—Two of the four sides in each mortise ran across the grain and two parallel to the grain. Cuts parallel to the grain were passably smooth in all woods. Across the grain, however, the woods varied widely, some of them showing considerable crushing and tearing. The position of the different woods in table 12 is determined largely by smoothness of cut across the grain. The figures indicate the percentage of mortises in different woods that were fair to excellent in smoothness of cut, the best woods yielding four or five times as many mortises of that quality range as did the poorest ones.

TABLE 12.—*Mortising: Relative smoothness of cut in hardwoods* [1]

Kind of wood	Fair to excellent mortises	Kind of wood	Fair to excellent mortises
	Percent		*Percent*
Mahogany	100	Yellowpoplar	63
Chestnut oak	100	Ash	62
Red oak	100	Sweetgum	58
White oak	100	Cottonwood	52
Pecan	100	Basswood	51
Hickory	98	Soft maple	36
Black walnut	98	Tupelo	35
Birch	97	Magnolia	32
Sycamore	96	Blackgum	24
Hard maple	95	Willow	24
Beech	93	Buckeye	18
Elm	75		
Chestnut	72	Average	70
Hackberry	70		

[1] Wood at a moisture content of 6 percent.

Plate 7 illustrates a wide contrast in smoothness of cut in different woods. Samples *A*, *B*, and *E* are soft maple from one board and samples *C*, *D*, and *F* are red oak from one board. Samples *A*, *B*, *C*, and *D* are sawed through, so that the character of the inside of the mortises can be plainly seen. Samples *A* and *C* show side grain and sample *B* and *D* end grain. The arrows on samples *A* to *D*, inclusive, indicate the direction of cut of the hollow chisel.

Soft maple is one of the poorest woods for hollow-chisel mortising. Some evidence of crushing, tearing, compression, and general roughness appears on the side grain, but the end grain is much worse. That the great bulk of the distortion of grain and of the damage occurs in the corners where the cutting is done wholly by the chisel is shown by sample *A* and more plainly by sample *B*. By way of contrast, the red oak samples are relatively smooth-cut with distortion of grain negligible. The mark of the bit shows plainly on the red oak, occupying about the central third of the cut.

Samples *E* and *F* have been planned down to half the original thickness to disclose the extent of damage to the wood fiber by the chisel corners. The soft maple sample *E* shows the damage to be much more than superficial, for particles often break out in planing to a depth of one-eighth inch or more back of the chisel cut. A series of successive planer cuts in the soft maple all tell the same story, as fast as one defect is planed out another appears. The red oak sample *F* shows no more than slight traces of this sort of damage. A mortise in red oak, therefore, offers a sounder base for gluing the tenon than a mortise in soft maple. The typical mortise is usually three or four times longer than wide, and hence is more largely side grain than end grain.

Accuracy of Size.—Measurements were taken with a steel gage graduated in thousandths of an inch. In most of the hardwoods tested the mortises were off size, or varied from the actual size of the hollow chisel by amounts up to 0.006 inch parallel to the grain and 0.002 inch across the grain. In addition, the mortises tended to taper slightly towards the side on which the tool entered the wood. The taper was usually about 0.003 inch parallel to the grain and less than

0.001 inch at right angles. The foregoing figures are averages for 100 to 200 mortises in each wood; many individual pieces would necessarily show considerably more off size and taper. However, in view of the rather liberal tolerances allowed in machining wood, the data on off size and taper in mortises are not very significant except as a measure of the ability of different woods to machine to close limits.

Strange as it may seem, the off-size holes were nearly always smaller than the actual size of the hollow chisel, owing in all probability to recovery from compression of the wood fibers. Measured where the off size is most pronounced, that is, parallel to the grain and on the side of the sample where the chisel emerges, the woods tested ranked as given in table 13.

TABLE 13.—*Mortising: Relative degree of off size in hardwoods* [1]

Kind of wood	Off size	Kind of wood	Off size
	Inch		*Inch*
Walnut, black	0.0008	Magnolia	0.0042
Mahogany	.0014	Tupelo	.0043
Hard maple	.0021	Beech	.0044
Pecan	.0025	Sycamore	.0044
Hickory	.0026	Willow	.0045
Birch	.0028	Yellowpoplar	.0046
Hackberry	.0030	Soft maple	.0046
Chestnut	.0031	Sweetgum	.0049
Red oak	.0034	Basswood	.0055
White oak	.0036	Cottonwood	.0059
Chestnut oak	.0036	Buckeye	.0075
Elm	.0039		
Blackgum	.0039	Average	.0038
Ash	.0041		

[1] Wood at a moisture content of 6 percent.

FACTORS AFFECTING RESULTS

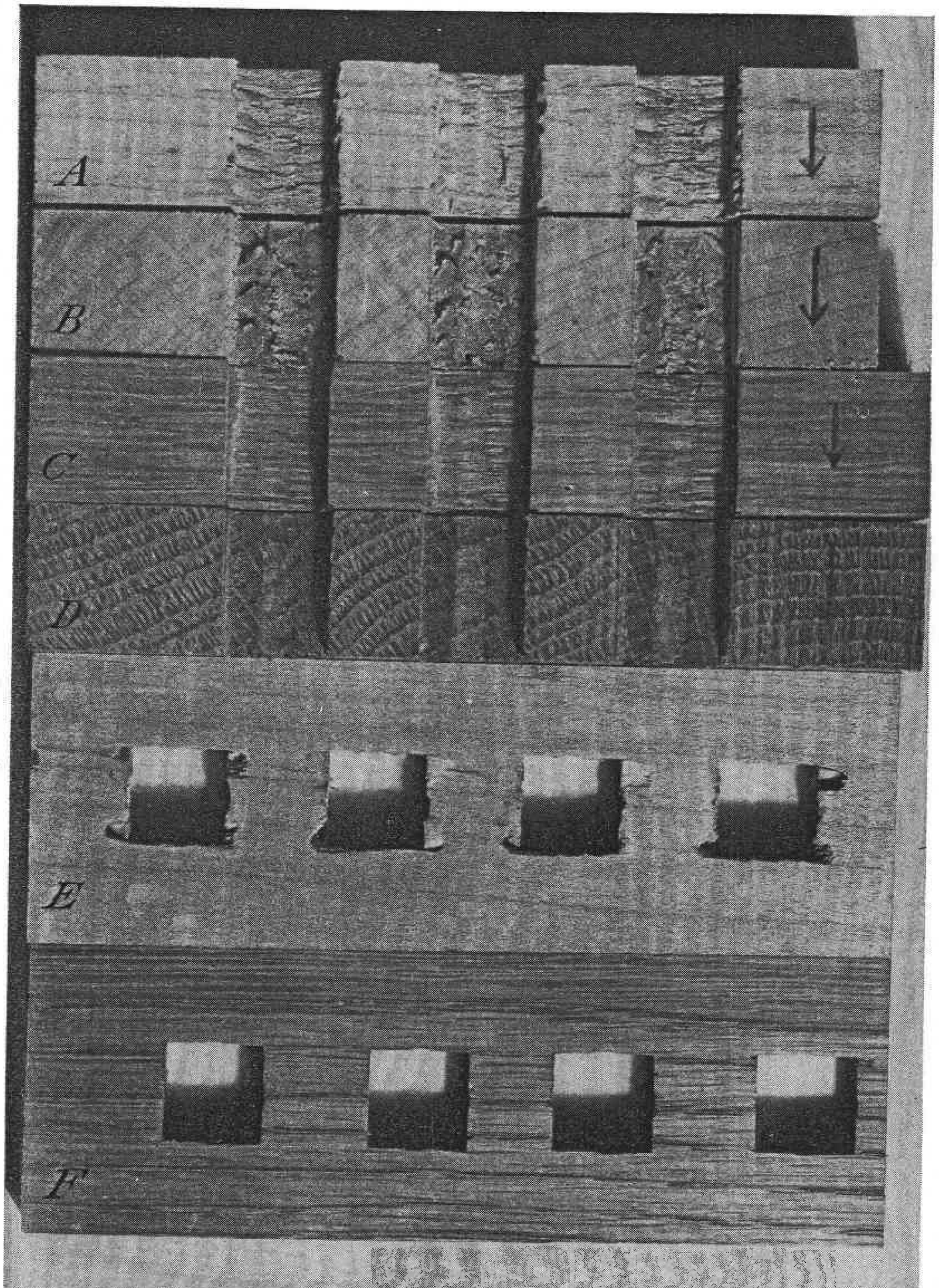
Specific gravity was the principal contributing factor. The heavier woods in general produced more smoothly cut mortises and less off size than did the light woods, but as usual there were exceptions to the rule. Mahogany and black walnut gave better results than their weight alone would indicate, whereas magnolia and blackgum gave poorer results. Among the 50 samples of each wood it was usually noticeable that the heavy pieces were better than the light ones.

Pore arrangement had little influence on the results. It is apparently immaterial whether a wood is ring porous or diffuse porous. Some of the woods in each class were excellent, and others not so good. Fast-growing woods and slow-growing woods did not differ consistently in mortising qualities.

Other factors affecting mortising were chiefly those involved in the operation of the tool itself, such as the speed of the bit in revolutions per minute and the rate at which the chisel is fed into the wood. Study of these factors would no doubt reveal means of improving the performance of the poorest woods, possibly by sacrificing speed of output somewhat.

SANDING

The chief purpose of sanding is to remove small defects in a planed surface and thus prepare it for paint, varnish, or other finish. Such



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Contrast in smoothness of cut in mortising different woods: *A*, *B*, and *E*, soft maple; *C*, *D*, and *F*, red oak; *A* and *C*, side grain; *B* and *D*, end grain. Arrows indicate direction of cut in samples *A* to *D*.

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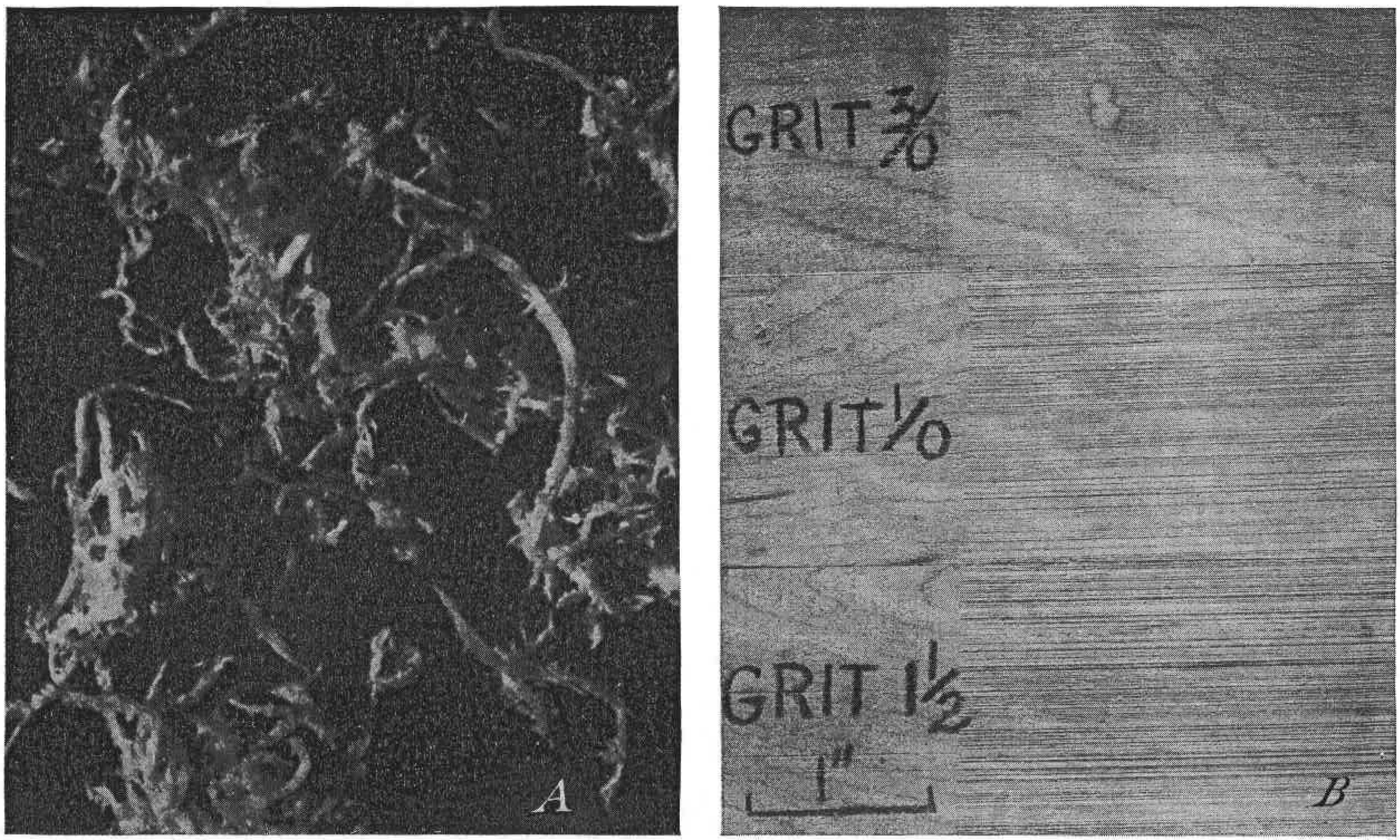


A, Sander dust made by No. 1½ grit and enlarged 20 diameters. *B*, Scratching tendencies of three different sizes of grit on hard maple.

defects include fuzz, raised grain, knife marks, and small scratches or dents. Unless removed by sanding these defects often show even more plainly after applying certain finishes than before, and therefore high quality products, like furniture and case goods, are sanded as standard practice.

Several different abrasives are used for sanding wood. Some occur in nature, others are electric furnace products, but all are of crystalline structure and smooth the wood by the scratching action of innumerable sharp corners and edges. Under the microscope the sander dust produced in machine-sanding is seen to consist largely of relatively long narrow shreds (pl. 8, *A*) rather than of sawdustlike granules. The abrasives, or grits as the woodworking trade terms them, come in a wide variety of sizes, and it is general practice with any given wood to use the coarsest grit that will not make scratches visible to the eye. Some woods of fine texture require grits two sizes finer that that required for oak. The scratching effect of three different sizes of grit on hard maple test samples cut from the same board is shown in plate 8, *B*. These sizes are chosen for illustrative purposes only and are not all the same sizes that were used in the test.

METHOD

Samples were first conditioned to 6-percent moisture content, then sanded on one side by a drum sander and on the other by a belt sander. The three drums carried sizes 1/2, 1/0, and 2/0 grit, and turned at 1,700 1,200, and 1,200 r. p. m., respectively. The belt traveled at 4,200 feet per minute, and carried 2/0 grit, or the same as the last drum. These are typical commercial conditions. The grit itself was garnet, a natural abrasive, and probably the one most commonly used in woodworking. New abrasive paper was put in both machines at the outset of the work, and the amount of material tested was not enough for wear to become a factor.

Following the sanding, the samples were inspected visually for both fuzz and scratches and were graded on a scale of 5, as an indication of the seriousness of the defects when present.

RESULTS

Scratching Tendencies.—The drums of a drum sander oscillate slightly in addition to rotating so that any scratches that may result are wavy, making "snake tracks." With a belt sander, however, the scratches are straight lines. Any wood can be sanded without visible scratches provided a fine enough grit is used. In this test the grit size was 2/0, which is about the coarsest that can be used satisfactorily for any wood. Table 14 shows how the woods compare in their tendency to show scratches under these conditions. A wide range in results may be noted, from soft elm with 70 percent of scratch-free pieces down to hard maple with none. The first seven woods are all ring-porous woods of rather coarse texture, which tends to obscure fine scratches. The last seven are diffuse-porous woods that are moderately hard to hard and fine textured. The intermediate group consists of woods that are either soft or of intermediate texture. The finer the pores the finer abrasive must be used to avoid obvious scratches.

The belt sander gave better results with 12 woods, drum sander with 6, and with 2 woods the results were the same. In only a few instances was the difference in results by the two types of sander substantial, and table 14 is based on an average for both.

TABLE 14.—*Machine sanding: Relative resistance to scratching of hardwoods*[1]

Kind of wood	Scratch-free pieces	Kind of wood	Scratch-free pieces
	Percent		*Percent*
Elm	70	Yellowpoplar	15
Hickory	67	Cottonwood	14
Red oak	66	Beech	13
White oak	66	Tupelo	10
Ash	52	Sweetgum	8
Chestnut oak	50	Soft maple	8
Chestnut	34	Magnolia	4
Willow	25	Blackgum	4
Sycamore	20	Hard maple	0
Basswood	15		
Sweet birch	15	Average	28

[1] Wood at 6-percent moisture content. Drum sanding and belt sanding averaged; 2/0 grit used.

Fuzzing Tendencies.—By fuzz in sanding is meant short bits of wood fiber that are attached to the board at one end and are free at the other. Several woods were practically free from this trouble, while others had more or less fuzz on most of the pieces. Depending on its degree, fuzz may be a serious drawback that can be overcome only through considerable extra work in getting a good finish. Table 15 lists woods according to fuzzing tendencies. Except elm, the ring-porous woods tested were relatively free from fuzz, and the first six woods are all ring porous. The middle group consists of diffuse-porous woods (except elm) that are moderately hard to hard. The diffuse-porous woods cause the most trouble with fuzzing and include the sofest woods and some that are moderately hard. Results from belt sanding and drum sanding were about the same for most of the woods, but for tupelo, birch, sweetgum, blackgum, cottonwood, and yellowpoplar, all of which are at the poorer end of the list, belt sanding was appreciably better.

TABLE 15.—*Machine sanding: Relative freedom from fuzzing in hardwoods* [1]

Kind of wood	Fuzz-free pieces	Kind of wood	Fuzz-free pieces
	Percent		*Percent*
Chestnut oak	100	Tupelo	57
White oak	99	Sweet birch	53
Ash	98	Blackgum	38
Red oak	95	Sweetgum	37
Chestnut	94	Cottonwood	25
Hickory	92	Willow	23
Beech	85	Yellowpoplar	23
Hard maple	76	Sycamore	22
Magnolia	70	Basswood	18
Soft maple	66		
Elm	62	Average	62

[1] Wood at 6-percent moisture content. Drum sanding and belt sanding averaged; 2/0 grit used.

FACTORS AFFECTING RESULTS

Species of wood, moisture content, angle of grain, structure, and several other factors also affect sanding, as do the type of machine, the type and size of the abrasive, and operating conditions, such as the speed of the machine and the pressure on the abrasive.

RELATED PROPERTIES

Steam Bending

Steam bending is employed to some extent in several hardwood-using industries. Bentwood chairs and tennis rackets are common examples of rather extreme bends in the furniture and sporting goods fields. Products with slight curves, like the back post of a dining room chair, may be either sawed or bent. In such cases bent parts have the advantages of being more economical of material and of being stronger because of less cross grain.

Many variables are involved in steam bending, such as the size of the test material, its moisture content, the amount of steaming, radius of the bend, and, of course, all the numerous details connected with the type of equipment used. The test described here was devised as a means of comparing the inherent bending qualities of hardwoods under one uniform set of conditions and the behavior of the run of the species without special selection, etc.

METHOD

The test material consisted of squares ¾ by ¾ by 30 inches long, conditioned to 12 percent moisture content. The squares were clear and sound, but were not selected for rings per inch, density, straightness, or angle of grain.

After a preliminary steaming for 45 minutes at atmospheric pressure, the squares were bent by hand to a 21-inch radius on the form shown in plate 9 and given time to set. Preliminary experiments showed that even the best bending woods produced a few breaks at this radius and that nearly all pieces in the poorer bending woods broke under the same conditions. Because no end pressure was employed and no metal straps were used on the outside of the bend as in the most modern bending equipment, the test was severe in spite of the fact that the radius was not especially short.

RESULTS

The 24 woods tested varied widely in bending qualities from hackberry with 94 percent of unbroken pieces to basswood with 2 percent (table 16). Oak, ash, hickory, elm, and beech are reported to be good bending woods. None but ash has yielded less than 74 percent of unbroken pieces. Excellent results were obtained with hackberry and magnolia, which are relatively little used for bending.

Ring-porous woods as a class gave better results than did diffuse-porous. The best 4 woods are all ring-porous, and 8 of the 10 ring-porous woods were among the best 12 woods.

TABLE 16.—*Steam bending: Relative bending qualities of hardwoods* [1]

Kind of wood	Pieces unbroken	Kind of wood	Pieces unbroken
	Percent		*Percent*
Hackberry	94	Soft maple	59
White oak	91	Yellowpoplar	58
Red oak	86	Hard maple	57
Chestnut oak	85	Chestnut	56
Magnolia	85	Tupelo	46
Pecan	78	Cottonwood	44
Black walnut	78	Blackgum	42
Hickory	76	Mahogany	41
Beech	75	Sycamore	29
Elm	74	Buckeye	9
Willow	73	Basswood	2
Birch	72		
Ash	67	Average	62
Sweetgum	67		

Wood at 12-percent moisture content.

FACTORS AFFECTING RESULTS

Four general causes of failure were observed in this test: Brashness, localized compression, splintering tension, and cross-grain tension. The relative importance of these types varies greatly in different woods as shown in table 17.

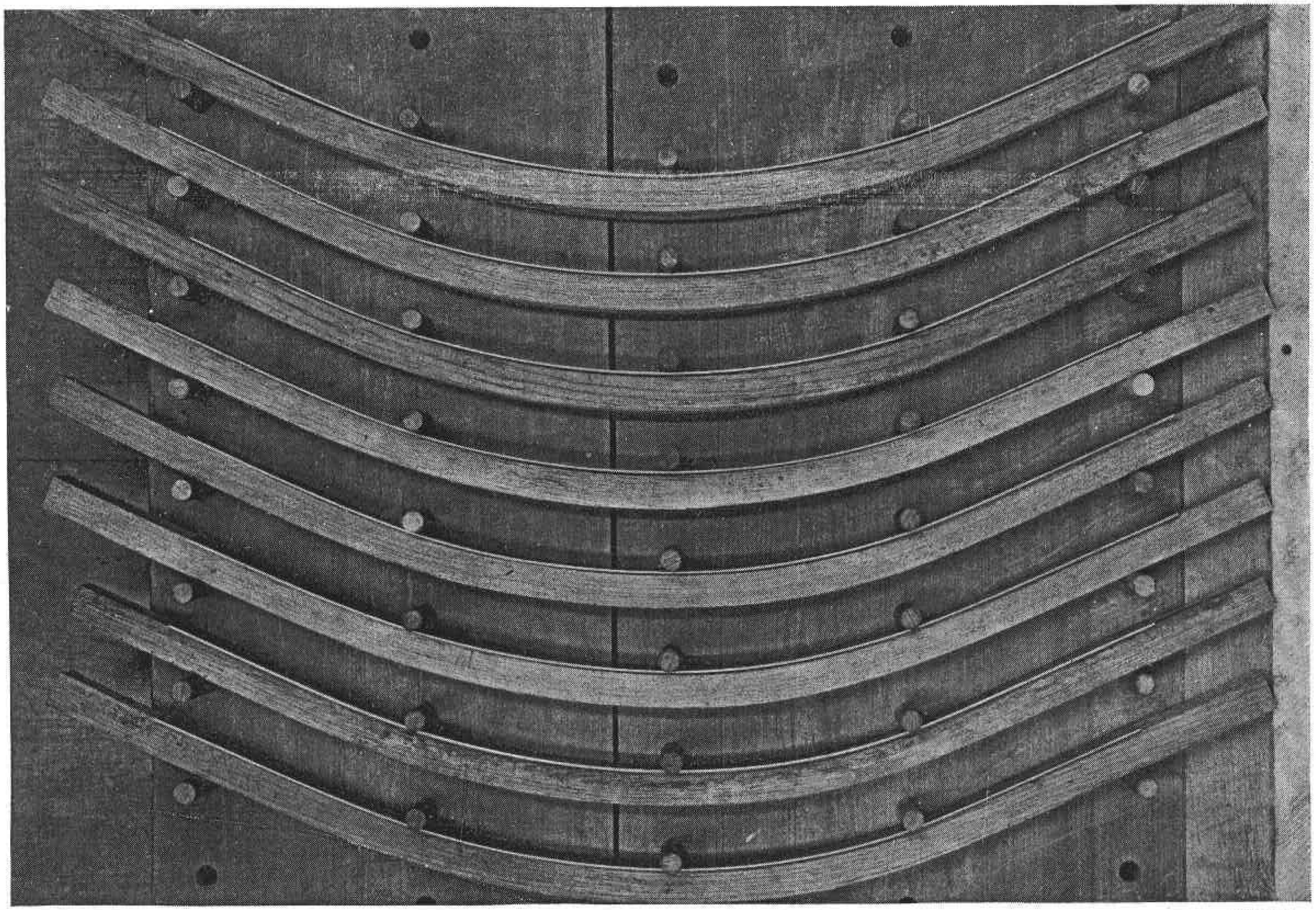
TABLE 17.—*Steam bending: Comparison of causes of failure, in percent of pieces broken* [1]

Kind of wood	Brash tension	Localized compression	Splintering tension	Cross-grain tension
	Percent	*Percent*	*Percent*	*Percent*
Ash	2	0	23	8
Basswood	4	53	32	9
Beech	0	0	18	7
Birch	4	0	18	6
Buckeye	0	45	23	23
Chestnut	4	34	3	3
Cottonwood	5	12	33	6
Elm	4	1	20	1
Sweetgum	0	1	17	15
Blackgum and tupelo	1	1	19	35
Hackberry	4	0	2	0
Magnolia	2	5	7	1
Mahogany	10	8	27	14
Hard maple	1	0	25	17
Soft maple	3	2	27	9
Chestnut oak	2	0	7	6
Red oak	5	0	7	2
White oak	4	0	4	1
Pecan	0	0	15	7
Yellowpoplar	2	15	20	5
Sycamore	10	2	21	38
Black walnut	1	0	6	15
Willow	2	9	8	6
Average	3	8	17	10

[1] Wood at 12-percent moisture content.

Brashness.—Some brash material was found in nearly all the woods, but only in mahogany and sycamore did it amount to more than 5 percent of the pieces tested. Very short breaks characterized brashness failures.

Localized Compression.—Compression failures were most common in basswood, buckeye, and chestnut, while the heavy woods had few,



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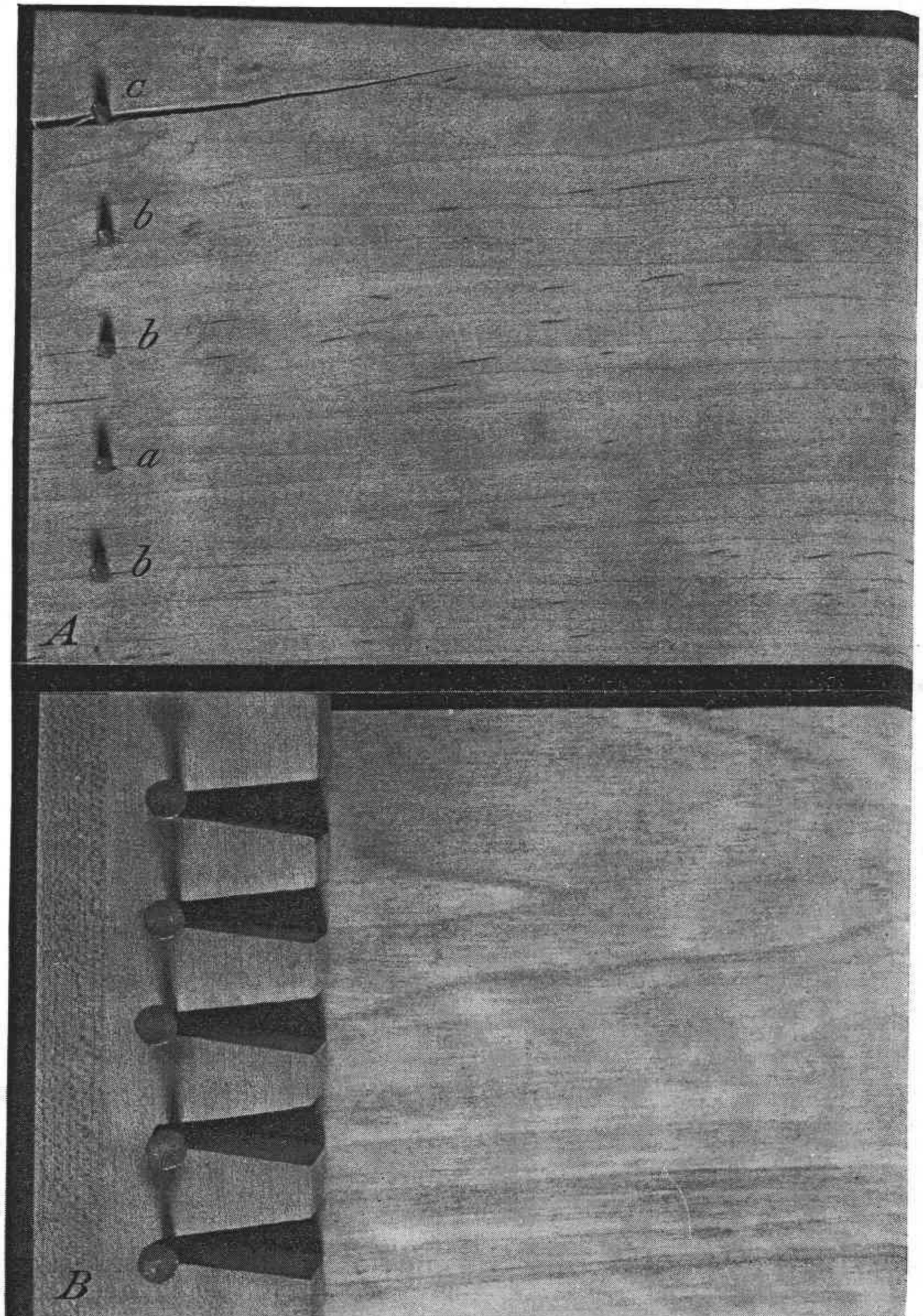
Form used in steambending test.



A, Different degrees of splits, (*a*) barely perceptible, (*b*), intermediate, (*c*), complete; *B*, guide used in driving nails.

if any, of them. This type of failure showed localized wrinkling or buckling on the concave side of the bend.

Splintering Tension.—Splintering-tension failures were not only the most common type of failure but occurred in all the woods. They were evidenced by splintering on the convex side of the bend. Such failures could be greatly reduced by the use of the customary metal straps that give support to the outside of the bend.

Cross-grain Tension.—Although not unmindful of the effect of cross grain on breakage no attempt was made to exclude it from the test samples, the object of the test being to obtain a comparison of bending qualities in different woods based on samples that were unselected other than being clear and sound.

Current specifications for "bending oak" allow cross grain of not more than 1 inch in 15 inches. Such a limitation would exclude some of the lumber tested in most of the woods and in woods having interlocked grain a substantial proportion would be excluded. Naturally the frequent occurrence of cross grain in a pronounced degree is a decided draw-back to the use of any wood for steam bending. Irrespective of other considerations it means that more material must be rejected at the outset in order to keep breakage within due limits. Cross-grain breaks were few or lacking in elm, hackberry, magnolia, red oak, and white oak, probably due more to some peculiarity of structure than to lack of cross grain. At the other extreme more than one-third of the pieces in blackgum and sycamore broke and many of these breaks were obviously due to interlocked grain. Cross-grain breaks, unlike those resulting from compression and tension, were frequently complete or nearly so.

Other Factors.—The average straightness of grain of the different woods gave no reliable indication of their bending qualities except that woods having a considerable amount of extreme interlocked grain, like tupelo and sycamore, were subject to considerable breakage under the conditions of the test.

Specific gravity influenced bending in that the heavy woods bent better than the light woods. In table 16, for instance, all the heavy woods (those with a specific gravity of 0.50 or over), except hard maple, are in the best half, whereas all the light woods (those with a specific gravity of less than 0.40), except willow, are in the poor half. No consistent differences were noted in breakage between light and heavy pieces of the same wood.

Number of rings per inch was found to have no effect on bending properties in different pieces of the same wood. Neither was any relation evident between bending properties and average rate of growth in different species; woods of slow, medium, and fast growth are found all along the quality scale as shown in table 16.

Nail Splitting

Nail-splitting tendencies of hardwoods are of interest because large volumes of both high-grade and low-grade hardwoods are customarily nailed in use. The weakening effect of splits is often greatly overestimated, but since they are unsightly, tend to increase in size with moisture changes, and create an unfavorable impression, it is best to avoid or at least minimize them. This can be done by boring holes in high quality products, by using a blunt-pointed nail, or by reducing the size of nail used. The heavy, strong woods split more readily in nailing than do the relatively light, weak woods, but they have much greater nail-holding power. Consequently, by the use of a small enough nail for the heavy woods it is possible to arrive at less split and still retain nail-holding power. The different woods vary widely in their splitting tendencies when nailed under identical conditions, as in this test, but good nailing practice takes this into account and greater holding power in the woods that split most readily when nailed is a compensating factor.

In any given test sample, nail splitting is affected by many different factors, such as the kind of wood, its moisture content, its specific gravity, its thickness, the size of the nails, the form of the nail point, the distance that they are driven from the end or edge of the sample, the method of driving, and so on. Since it was impractical to make tests with different combinations of these factors, one set of reasonable conditions was applied uniformly to all 24 hardwoods. It is believed that the conditions chosen give a good measure of the splitting tendencies of the woods tested.

METHOD

The nails used were sevenpenny, smooth box nails, 20 to each test sample or from 1,000 to 2,000 for each wood. They were driven by hand through the test pieces, which were commercial flat grain three-eighth inch thick and 15-percent moisture content, into a back of soft pine. A guide, such as shown in plate 10, *B*, was used to locate the nails at a uniform distance from each other and from the end of the board. The number and character of any splits that developed were noted. Splits vary greatly in size and in the damage they do from either the nail-holding or appearance standpoints. The results presented here are based on complete splits only, that is, splits that extend completely through the board from the end back beyond the nail, like (*c*) in plate 10, *A*.

Nails were first driven at ½-inch distance from the end; then, after sawing off the split ends, at ⅜-inch distance. These distances are about right for packing box shooks ⅜ inch thick, considering the probable thickness of box ends or cleats to which the sides, tops, and bottoms would be nailed. As would be expected, splits are more numerous (about one-third) at ⅜ inch from the end than at ½ inch. Aside from this, results obtained at these two distances did not differ significantly, and it seemed best to average the results, which was done. In hand work, different men often get somewhat different results, and to allow for this human factor the above work was duplicated by a second operator working independently. The figures given here are averages for the two workmen.

RESULTS

In the nail-splitting tests under identical nailing conditions (table 18), the woods ranged from willow, the freest from splits, down to hard maple, the poorest. In connection with table 18, the two important considerations already discussed must be borne in mind—that in general the woods most susceptible to splitting have much greater nail-holding power than those least susceptible, and that in commercial practice splitting may be greatly reduced in the woods towards the bottom of the list by the use of smaller nails.

TABLE 18.—*Nail splitting: Relative freedom of hardwoods* [1]

Kind of wood	Samples free from complete splits	Kind of wood	Samples free from complete splits
	Percent		*Percent*
Willow	89	Blackgum	65
Cottonwood	82	Tupelo	64
Elm	80	Hackberry	63
Sycamore	79	Soft maple	58
Basswood	79	Black walnut	50
Yellowpoplar	77	Chestnut oak	49
Magnolia	73	Pecan	47
Sweetgum	69	Beech	42
White oak	69	Hickory	35
Mahogany	68	Birch	32
Chestnut	66	Hard maple	27
Red oak	66		
Ash	65	Average	62

[1] Wood at 15-percent moisture content.

THE SPECIFIC GRAVITY FACTOR

Specific gravity is an important factor in the splitting of wood with nails. As might be expected (fig. 3), the heavier species split more than the light ones, and yet the splitting in different woods is not directly proportional to their specific gravity. Sycamore, soft elm, red oak, and white oak produce appreciably fewer splits than might be expected from specific gravity alone; and on the other hand chestnut, hard maple, and birch split more than might be expected. Just as heavy woods split more than light ones, so heavy pieces of white oak, for instance, split more than light pieces of the same wood.

SCREW SPLITTING

In large woodworking plants screws are usually driven by power tools into bored holes and the heads countersunk. Best practice calls for a hole that fits the shank of the screw snugly, this being the unthreaded part just below the head. For the threaded portion of the screw a smaller hole should be used. For most woods this should be slightly less than the core diameter, which is the diameter at the base of the threads. Among the variables that may affect the screw splitting of a wood sample are its thickness, density, moisture content, ratio of lead-hole diameter to screw diameter, the distance from the end or edge of the piece, and the method of driving the screws.

METHOD

There is no standard test method. About all that can be done in any short-time study aimed at evaluating screw-splitting tendencies of different woods is to adopt a set of reasonable working conditions and apply them uniformly to all woods.

The test materials was ⅜ inch thick and at 15-percent moisture content. Since the object was to evaluate screw-splitting tendencies and not to minimize splitting, a ⅟₁₆-inch leadhole was used with all woods and all screws. The leadholes were bored by machine to insure straightness, after which the screws were driven through and into a soft pine backing using a screw-driver bit in a hand brace. The depth of penetration was uniform with the top of the thread flush with the top of the board. A series of five screws (Nos. 6, 7, 8, 9, and 10) was driven at 0.5 inch from the end of the boards. All were ¾-inch screws. Then after sawing off any splits that developed, a series of three screws (Nos. 8, 9, and 10) was driven 0.75 inch from the end. Nos. 6 and 7 were not used because they were so small as to produce very few splits in

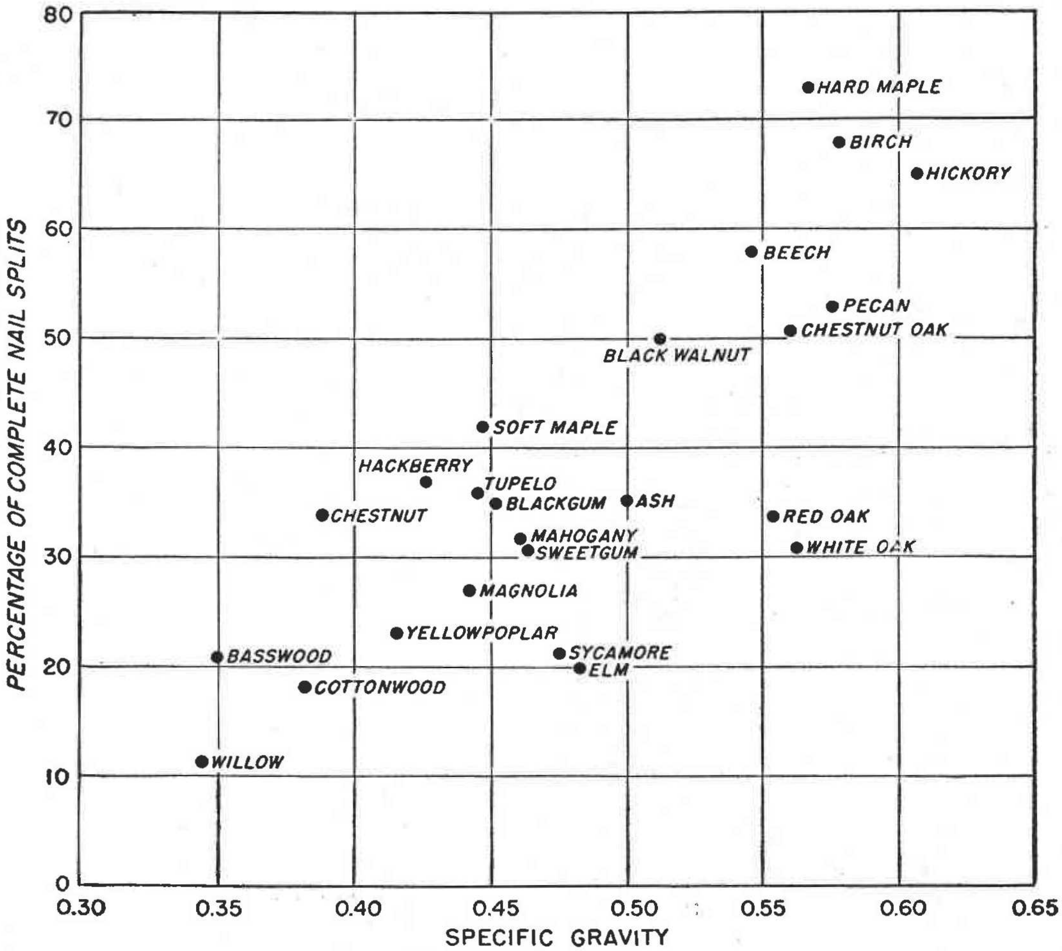
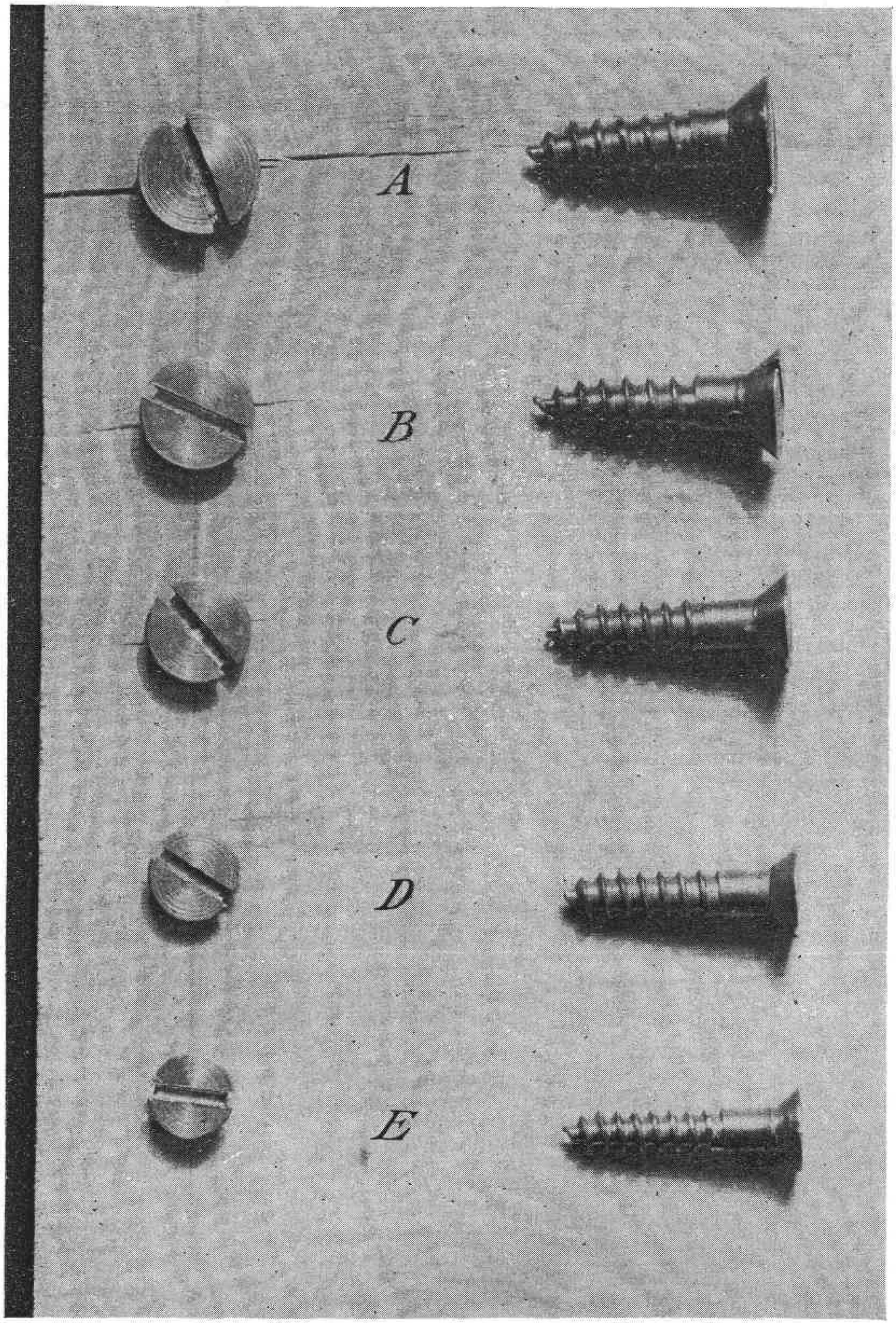


FIGURE 3.—Relation of specific gravity to percent of complete splits for 24 hardwoods.

any wood and none in many of them. As with nails the splits varied greatly in size, and precise evaluation of the damage due to the different-sized screws was impractical. The comparisons that are made here are therefore based on complete splits or splits extending through the end of the board and back beyond the screw, as in plate 11, *A*. Because of operating differences, the figures given here average the results obtained by two different operators working independently.

RESULTS

In the screw-splitting test of 23 hardwoods, birch, the poorest wood in this respect, has nearly 2½ times as many complete splits



Different degrees of splits and different sizes of screws used in screw-splitting test; *A*, No. 10; *B*, No. 9; *C*, No. 8; *D*, No. 7; *E*, No. 6.

as does red oak. The amount of splitting here shown would, of course, be prohibitive in any commercial operation. The lead holes were deliberately made too small in order to produce comparative splits. Some of the woods that made the poorest showing in this test are among the strongest and would give the best service if the screws were properly inserted. These tests serve to emphasize the need for proper use of screws, especially for a proper ratio of lead-hole diameter to screw diameter.

FACTORS AFFECTING RESULTS

Under the conditions of this test no relationship was revealed between the average specific gravity of the different woods and their screw-splitting tendencies. Reference to table 19 shows considerable mixing of heavy and light woods in all parts of the list. Other tests at the Forest Products Laboratory show that dense woods require larger lead holes for maximum efficiency than do light woods, and that large screws require larger lead holes in proportion to their diameter than do small screws.

TABLE 19.—*Screw splitting: Relative freedom of hardwoods* [1]

Kind of wood	Samples free from complete splits	Kind of wood	Samples free from complete splits
	Percent		*Percent*
Red oak	78	Hickory	63
Cottonwood	78	Blackgum	63
Mahogany	78	Tupelo	63
Magnolia	76	Hackberry	63
Elm	74	Willow	62
White oak	74	Soft maple	61
Sycamore	74	Chestnut	60
Ash	71	Black walnut	59
Chestnut oak	70	Beech	58
Sweetgum	69	Hard maple	52
Pecan	69	Birch	48
Basswood	68		
Yellowpoplar	67	Average	67

[1] Wood at 15-percent moisture content.

The percentage of splits increases rapidly with increase in screw size. For example, the Nos. 7, 8, 9, and 10 screws produced, respectively, 1.9, 3.4, 4.5, and 7.3 times as many complete splits as did the No. 6 size when the same size of lead hole was used. This illustrates the necessity for using larger lead holes with larger screws if splits are to be minimized. These figures are an average for all species, and some woods, of course, vary considerably from the averages.

Judging from the sparse data afforded by the two series of screws driven at ¾-inch and ½-inch distance from the end of the test pieces, the chances of producing splits are greatly increased as the screws are driven nearer to the end of the board. The No. 8, 9, and 10 sizes produced on the average twice as many splits at ½-inch as at ¾-inch distance.

Under the typical variations found in the different woods, cross grain had little, if any, influence on screw splitting. Extreme cross grain in individual pieces would perhaps be a factor.

As there is a distinct difference in the action of screws and nails, a given wood will not necessarily behave alike in both screw splitting and nail splitting. In these tests, however, half of the woods fall in about the same part of the list for both nail splitting and screw splitting. The remaining woods may be good in one respect and fair in the other, or fair in one and poor in the other. No wood was found to be good in one and poor in the other.

Variation in Specific Gravity

Machining properties like many others that affect the utility of wood vary with the specific gravity or weight. The heavier woods as a rule yield a smoother finish, and heavy pieces frequently machine better than light pieces in the same wood. On the other hand, heavy wood requires more power, dulls tools more quickly, and tends to split more readily with nails. These matters are dealt with in more detail elsewhere and are cited here merely to evidence the relation between specific gravity and machining.

Different species of wood vary in their average specific gravity largely because of differences in the relative proportions of wood substance and air space. Different pieces of the same wood also vary considerably in specific gravity. Within the same tree, in many species, significant variations in specific gravity will generally be found from the bark to the pith and up the trunk from the base. Again, growth conditions in different localities may vary so widely as to cause marked differences in specific gravity.

METHOD

After soaking in water for several weeks to restore the samples to green volume, they were sawed accurately to uniform size, then oven dried, weighed, and the specific gravity computed on the basis of weight when oven dry and volume when green. Tests showed this method to be accurate within a limit of ± 0.01 when compared with specific gravity values based on volumes determined by displacement.

RESULTS

Average Specific Gravity.—The heaviest of the 25 woods tested, hickory, has nearly twice as high specific gravity as the lightest, buckeye (table 20). Since hardness increases as the 2¼ power of specific gravity, hickory is nearly five times as hard as buckeye. Such differences have a very important effect on machining. In estimating ease of working, however, a sharp distinction should be drawn between measurement by power consumption and the ease with which a smooth surface is obtained suitable for high-grade finish. Cottonwood requires relatively little power consumption, but is difficult to finish smoothly. On the other hand, the oaks are hard and power consumption in machining is rather high, yet a smooth surface is obtained without difficulty.

TABLE 20.—*Average specific gravity of hardwoods* [1]

Kind of wood	States or region of origin	Average specific gravity
Buckeye	Appalachian	0.340
Willow	Mississippi Delta	.345
Basswood	Chiefly Appalachian	.349
Cottonwood	Southern	.382
Chestnut	Appalachian	.388
Yellowpoplar	Southern and Appalachian	.415
Hackberry	Southern	.426
Magnolia	do	.442
Tupelo	do	.445
Soft maple	Southern and Appalachian	.446
Blackgum	Southern	.451
Mahogany	Central America	.460
Sweetgum	Southern	.463
Sycamore	do	.475
Elm	do	.482
Ash	Southern and Appalachian	.500
Black walnut	Central	.512
Beech	Southern and Appalachian	.546
Red oak	do	.553
Chestnut oak	Appalachian	.560
White oak	Southern and Appalachian	.562
Hard maple	Appalachian and Lakes	.567
Pecan	Southern	.576
Birch	Appalachian and Lakes	.577
Hickory	Southern	.607
Average		.475

[1] Based on weight when oven dry and volume when green.

Variability.—Variability in specific gravity differs widely with the different kinds of wood (table 21). In hard maple 90 percent of the samples are within ±9 percent of the average specific gravity of 0.567. At the other extreme are elm and ash with about 2½ times as large a variation. A certain degree of variability is unavoidable, but extreme

TABLE 21.—*Variability in specific gravity of hardwoods,*[1] *arranged in order of increasing variation from the average*

Kind of wood	Range in specific gravity [2]			Variation from average [3]
	Minimum	Average	Maximum	Percent
Hard maple	0.49	0.567	0.66	9
Birch	.50	.577	.68	10
Beech	.45	.546	.64	11
Hackberry	.36	.426	.50	12
Black walnut	.44	.512	.58	12
Sweetgum	.37	.463	.56	13
Sycamore	.39	.475	.58	13
Willow	.28	.345	.42	14
Cottonwood	.31	.382	.48	14
Mahogany	.38	.460	.56	15
Red oak	.42	.553	.66	15
Chestnut oak	.48	.560	.66	15
Hickory	.45	.607	.72	15
Magnolia	.34	.442	.54	16
White oak	.43	.562	.70	17
Pecan	.45	.576	.70	17
Chestnut	.27	.388	.50	19
Basswood	.28	.349	.44	19
Yellowpoplar	.31	.415	.54	19
Tupelo	.27	.445	.56	19
Soft maple	.35	.446	.58	19
Blackgum	.33	.451	.58	20
Elm	.34	.482	.64	23
Ash	.33	.500	.63	23

[1] Based on weight of the oven-dry wood and volume when green.
[2] Range within which 98 percent of the samples fell; 1 percent at each extreme excluded.
[3] Range within which 90 percent of the samples fell; 5 percent at each extreme excluded.

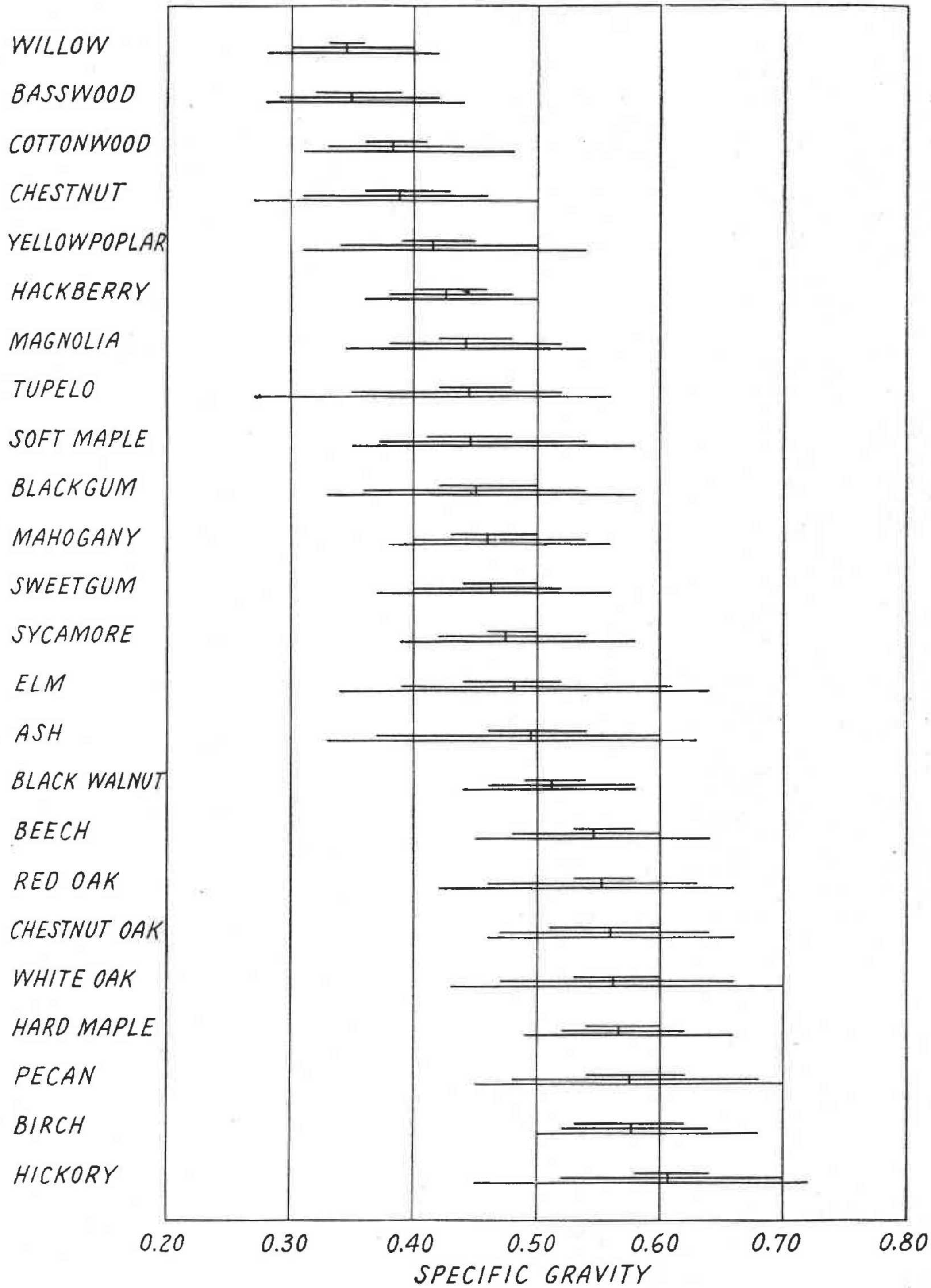


FIGURE 4.—Range of specific gravity of hardwoods. The short, the intermediate, and the long horizontal lines represent, respectively, the specific gravity range within which 50, 90, and 98 percent of the observed samples fell. The vertical line marks the average.

variability is often a drawback because a considerable part of the wood may not be suitable for a given use, and it is these extreme woods that cause the complaints regarding lack of uniformity. Variation may, however, be turned to advantage in that it leaves more room for selection according to use.

These various specific gravity relationships are shown graphically in figure 4. The woods are arranged in order from lightest to heaviest based on averages. For each wood the specific gravity range of the middle 50 percent, 90 percent, and 98 percent of the number of samples is illustrated by the short, intermediate, and long horizontal lines, respectively, and the average is indicated by the short vertical line. Differences in variability, like that between willow and tupelo, stand out plainly. Overlapping in range of specific gravity of light and heavy woods is also evident; the heaviest pieces of cottonwood, for instance, are heavier than the lightest pieces of hickory.

The greater variability in ash and tupelo is due in part to the fact that certain of these trees grow where they are overflowed from time to time by floodwater and therefrom develop an extreme taper at the base which the lumbermen call "swell butt." The wood from the base of these swell-butted trees is abnormally light and tends to give the wood a wide range from minimum to maximum specific gravity. In elm, variability probably results largely from the fact that the commercial elm as marketed contains several botanical species some of which run consistently heavier than others.

Data from collections at 20 mills in the South Atlantic and Gulf States show that the same wood may vary enough in weight to make an appreciable difference in its ease of machining. White oak at the mill, for instance, varied from 0.54 average specific gravity for the lightest timber to 0.64 for the heaviest. The light oak, however, was not all concentrated in one part of the area and the heavy oak in another, but sources of light and heavy oak were scattered throughout. Similar conditions prevailed with other woods. It is evident that growth conditions resulting in light or heavy timber may be quite different at points only a few miles apart or they may be similar at points that are distant from each other. State lines or river drainages cannot be used as indicators of light and heavy timber. The buyer who wishes one type of timber or the other must know his mills.

An exception may be noted, however, with respect to elevation of source. When the collection area is extended to include nine additional mills in the mountain sections of Tennessee, Virginia, and West Virginia, it appears that Appalachian oak averages somewhat lighter than southern oak, and Appalachian ash slightly heavier than southern ash. White oak from the Appalachians and from the deep South averaged 0.53 and 0.58, respectively; red oak 0.53 and 0.56; and ash 0.53 and 0.50.

Even this difference is not entirely consistent, however. Some of the southern mills produce on the average lighter white oak than some Appalachian mills, and there is, of course, a much wider range within each region than between the two regional averages. Actually, such an exception only reemphasizes the need for the buyer to know his mills rather than to depend on geographical divisions.

Number of Annual Rings per Inch

The woodworker is interested in the number of annual rings per inch, because they affect both the "workability" of the wood and its ability to stay in place. The slower and more uniformly growing types are generally preferred, particularly for fine work. If the wood is not naturally uniform, considerable selection may be necessary.

These statements apply more to the ring-porous than to the diffuse-porous woods.

Ring counts were made on a radial line after sanding the end grain to make the rings plainly visible. Rings in excess of 30 per inch, since they are not significant in terms of woodworking, were not counted. Such pieces were recorded as 30+; most of the woods were represented by them, but usually they amounted to less than 10 percent of any one wood.

The ratio between the fastest growing and the slowest growing of the woods (table 22) is about 1 to 3. There appears, however, to be no relation between number of rings per inch and machining properties of the different woods as determined in this investigation.

TABLE 22.—*Average width of rings in hardwoods*

Kind of wood	Rings per inch	Kind of wood	Rings per inch
	Number		*Number*
Cottonwood	7.7	Sweetgum	14.7
Willow	8.9	Hickory	15.1
Black walnut	9.4	Chestnut oak	15.3
Sycamore	9.4	Magnolia	16.1
Red oak	9.9	Basswood	16.5
Chestnut	11.3	Buckeye	16.8
Soft maple	11.9	White oak	16.9
Yellowpoplar	12.5	Hard maple	17.0
Hackberry	12.9	Tupelo	19.4
Ash	13.2	Birch	21.0
Elm	14.3	Blackgum	21.8
Pecan	14.4		
Beech	14.6	Average	14.2

The different woods studied varied considerably in uniformity of rings, the most variable ones having at least twice as wide a range between maximum and minimum number of rings as the least variable. It may be taken as a general rule that the fastest-growing woods are the least variable in number of rings per inch, and that the slowest-growing woods are the most variable.

CROSS GRAIN

Cross grain reduces the strength of wood, adds to difficulty in machining, and may increase warping tendencies. Nearly every piece of lumber contains cross grain in some degree. Where this is slight it need cause little concern, but the more pronounced degrees may prove highly objectionable. In this respect woods differ and individual trees of a given wood differ. Even in woods that are suitable for making split shingles, for instance, most trees are not sufficiently straight grained for this purpose. Three types of cross grain are recognized—diagonal, spiral, and interlocked.

Diagonal grain may result from sawing through a crook or through a swell butt or from sawing parallel to the axis of a log rather than parallel to the bark. This is, as a rule, the least extreme type of cross grain, but is found in all woods. The degree of diagonal grain in lumber can be controlled to some extent by the method of sawing and bucking the logs.

Spiral grain, which was found to some degree in all the woods tested, is caused by fibers that run around the trunk of a tree in a spiral instead of vertically. On the average, spiral grain is more pronounced than diagonal grain, and consequently more detrimental, but, like the other types, it varies in degree. It can usually be reduced in the manufacture of lumber by suitable edging methods. Both spiral and diagonal grain may be found in the same piece of lumber.

Interlocked grain is common in a few hardwoods, rare in others, and lacking in still others. When present, it is usually so extreme as to outweigh in importance any other types of cross grain that may also be present. It is caused by alternate bands of fibers that slope in opposite directions, and is a species characteristic. In the seasoning of lumber interlocked grain and spiral grain tend to cause twist, but this can be minimized by quarter-sawing as much of the lumber as possible.

METHOD

Diagonal grain can be easily measured. The procedure is to select one plainly visible annual ring, follow it from one end of the sample to the point where it reaches the surface, with the ring forming the hypotenuse, make measurements of the height and base of the triangle with a steel scale, and from these compute the percentage of slope. If the grain slopes one-half inch in a length of 10 inches, for instance, the percentage of slope is 5 percent.

Spiral grain cannot be followed by eye as easily as diagonal grain, and hence it is often necessary to split the sample radially and to compute the slope from measurements on the split-off portion.

In interlocked grain the slope is often very extreme and so irregular that no satisfactory method of measurement has been devised. The presence of this type of cross grain can often be detected by visual inspection, but splitting removes all doubt. In the absence of any satisfactory method of measuring interlocked grain, the percentage of pieces containing it was recorded. Interlocked grain, like other types of cross grain, may vary in degree, but the woods in which it is most frequent tend to have the more extreme degrees. In all, about 4,500 samples were tested.

RESULTS

In about two-thirds of the woods no interlocked grain was encountered. In the remaining woods the figures for diagonal and spiral grain apply only to pieces that were free from interlocked grain. In table 23 the 25 woods are arranged in order from the best to the poorest in respect to cross grain.

The order of species in table 23 is believed to be valid for the following reasons: Diagonal grain may be disregarded in comparing the relative seriousness of cross grain in the different woods, because in every species spiral grain had a greater slope, frequently two or three times greater. These are species averages, of course, and some individual pieces would be exceptions. Except for cottonwood and elm, the woods having interlocked grain are among those having the more pronounced degrees of spiral grain as well.

Interlocked grain, when present, probably has a much greater effect on utility than the other types. In steam bending, for example, the four woods with the highest percent of cross-grain breakage were the four with the most interlocked grain. In planing a board having interlocked grain, the knives necessarily revolve against the grain in some part of the board, and this often causes chipping. Twist is the most pronounced form of warp, and the four woods in which interlocked grain is the most common are the woods that twist most in drying. For these reasons, other types of cross grain may be disregarded in woods where interlocked grain is frequent.

TABLE 23.—*Cross grain in hardwoods, arranged in order from the best to the poorest*

Kind of wood	Average slope of grain		Pieces showing interlocked grain	Kind of wood	Average slope of grain		Pieces showing interlocked grain
	Diagonal	Spiral			Diagonal	Spiral	
	Percent	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
Hickory	2.3	3.1	0	Chestnut oak	2.5	7.2	0
Pecan	3.2	4.3	0	Willow	2.8	7.7	0
Basswood	2.3	4.3	0	Hard maple	2.6	7.9	0
Red oak	2.4	4.4	0	Mahogany	2.8	6.2	10
Magnolia	2.7	5.1	0	Buckeye	4.4	6.7	10
Yellowpoplar	1.9	5.2	0	Elm	2.1	4.9	19
White oak	2.3	5.3	0	Cottonwood	1.9	4.3	24
Hackberry	3.0	5.5	0	Sycamore	2.8	7.7	45
Birch	2.7	5.5	0	Sweetgum	2.3	8.2	48
Ash	3.5	5.6	0	Blackgum	2.5	7.5	53
Black walnut	4.1	5.7	0	Tupelo	2.4	8.9	68
Chestnut	2.6	6.2	0				
Soft maple	2.5	6.5	0	Average	2.7	6.0	11
Beech	2.2	6.9	0				

The small size of the test samples (¾ by ¾ by 10 inches) may perhaps cause an underestimate of the occurrence of interlocked grain. For example, interlocked grain may occur in some part of a board and yet be absent in a small sample. The figures given for this type of cross grain should, therefore, be considered minimum.

SHRINKAGE

Since wood swells when it picks up moisture and shrinks when it loses moisture, there is a slight "come and go" or change of dimension with change in moisture content when in use that may cause unsatisfactory results in machining. This may be minimized in two ways—by drying the wood in advance to the approximate moisture content that it will have in use, and by selecting woods of low shrinkage as far as practical. The amount of "come and go" is also influenced by angle of rings, that is, the angle between the annual rings and the surface. Shrinkage parallel to the rings averages about twice as much as at right angles to them. Thus quarter-sawed hardwood lumber shrinks about half as much in width as the more common flat-grained material.

The test samples were small cross sections cut from the ends of 4/4 commercial lumber. The rings were therefore at all angles with the surface. Since many boards were 8 to 10 inches wide, there was often considerable variation in ring angle in different parts of the same test sample. Such samples are believed to represent more accurately the shrinkage that may be expected in typical lumber shipments than will the usual type of shrinkage samples, which are relatively narrow and almost all flat grain or edge grain as the case may be.

Test samples were measured with a gage to the nearest hundredth inch in the green, at 12-percent moisture content, and at 6 percent. Shrinkage is usually computed from green to oven-dry condition, but 6 percent is about as low as wood goes in actual use. Although this is only from 75 to 80 percent of the shrinkage to oven-dry condition, it approximates the maximum that would occur from the tree to any ordinary conditions of use.

The samples were of flat-grained material only, which constituted from 70 to 90 percent of the total volume in different woods. They exhibited (table 24) a wide range from lowest to highest shrinkage. Shrinkage from green to 12-percent moisture content averages more than twice that from 12 to 6 percent. Assuming that hardwood lumber is fabricated into a finished product at 12-percent moisture content and that the finished product comes to equilibrium at 6 percent, then the manufacturer and user are concerned chiefly with the relatively small amounts of shrinkage shown in column 4 of table 24. This represents a ratio of more than 2 to 1 between the highest and lowest shrinkage, but the highest figure is less than 3 percent.

TABLE 24.—*Tangential shrinkage of hardwoods,*[1] *arranged in order of shrinkage*

Kind of wood (1)	Green to 6-percent moisture content (2)	Green to 12-percent moisture content (3)	12-percent to 6-percent moisture content (4)	Kind of wood (1)	Green to 6-percent moisture content (2)	Green to 12-percent moisture content (3)	12-percent to 6-percent moisture content (4)
	Percent	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*
Mahogany	3.4	2.1	1.3	Sycamore	6.9	4.6	2.3
Ash	5.7	3.6	2.1	Basswood	7.2	5.8	1.4
Magnolia	5.9	3.9	2.0	Birch	7.5	5.3	2.2
Soft maple	6.1	4.0	2.1	Elm	7.5	5.1	2.4
Tupelo	6.1	4.2	1.9	Hard maple	7.8	5.5	2.3
Yellowpoplar	6.2	4.3	1.9	Hickory	7.9	5.2	2.7
Willow	6.2	4.4	1.8	Sweetgum	8.4	6.0	2.4
Hackberry	6.5	4.4	2.1	White oak	8.8	6.4	2.4
Chestnut	6.6	4.7	1.9	Beech	8.9	6.1	2.8
Blackgum	6.6	4.3	2.3	Red oak	9.0	6.5	2.5
Pecan	6.6	4.4	2.2	Chestnut oak	9.5	7.4	2.1
Black walnut	6.7	5.0	1.7				
Cottonwood	6.7	4.7	2.0	Average	7.0	4.9	2.1

[1] Flat-grained material only, amounting to 70–90 percent of all woods.

WARP

Warp in lumber has been defined in American lumber standards as "any variation from a true or plane surface." It is one of the characteristics of wood of first importance to the user, because it increases labor and waste in manufacture and often causes trouble subsequently.

Warp includes bow, crook, cup, and twist (fig. 5). The last two are the most serious and the ones to which this discussion is limited. Cup is defined as "a curve across the width of a piece" and twist as "the turning or winding of the edge of a piece so that the four corners of any face are no longer in the same plane." Although some woods naturally warp more than others, proper drying methods will minimize this trouble. The use of badly warped lumber usually involves making it into cuttings that are short or narrow or both.

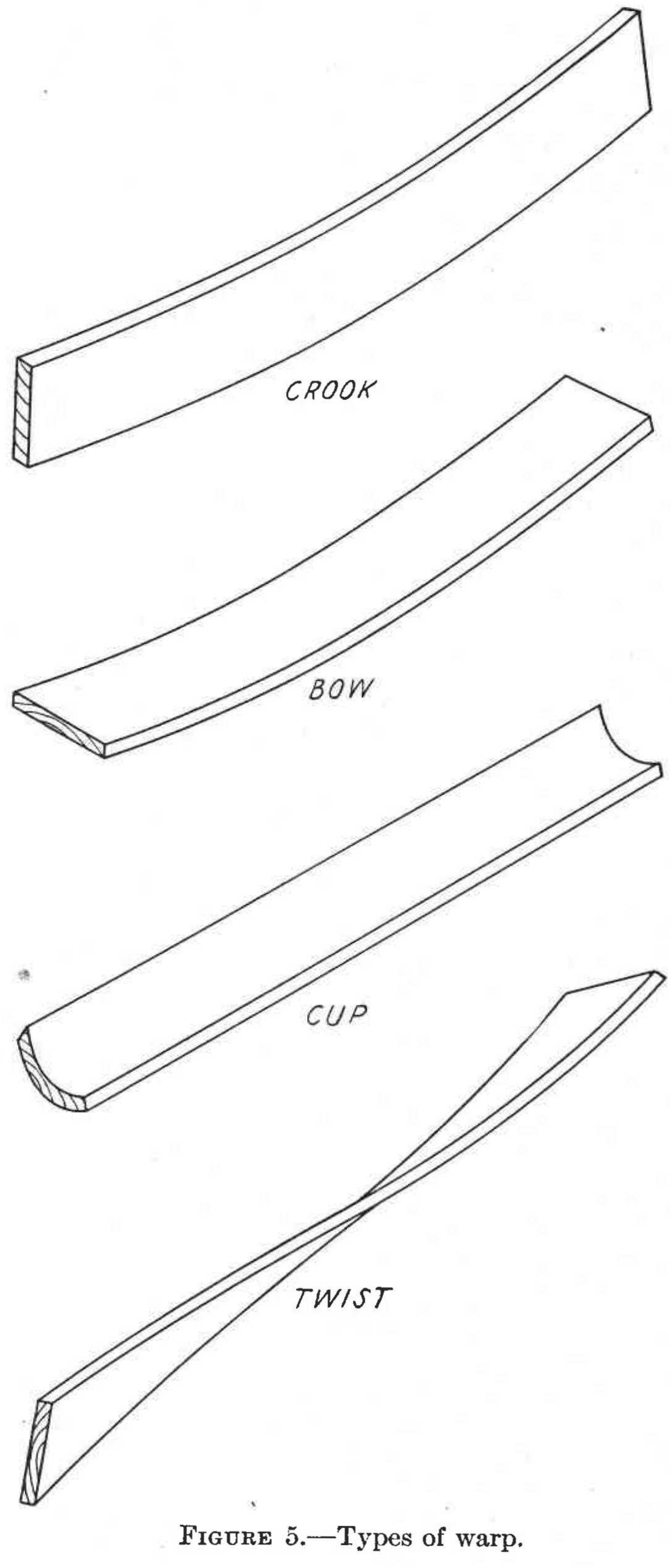


FIGURE 5.—Types of warp.

Four-foot lengths of air-dried lumber from 6 to 10 inches wide were end-piled and dried to room equilibrium at 7 to 8 percent moisture content. This method permitted the test samples to warp without restraint, resulting, it is believed, in an accurate measure of the natural warping tendencies of the different woods. After the drying the boards were placed on a plane surface and measured for warp at each end with a long wedge so tapered and so calibrated that each small division on the hypotenuse represents a vertical distance of 0.01 inch from the adjacent divisions (fig. 6). The amount of warp was then read direct in hundredths of an inch, and the larger of the two measurements was recorded, because the maximum cup in any piece determines the amount of waste in jointing and planing. Warp of 0.02 inch or less was ignored as not significant. Both cup and twist were measured in this manner.

Based on 7-inch widths, twice as much cup was found in the worst wood as in the best, and six times as much twist (table 25). In

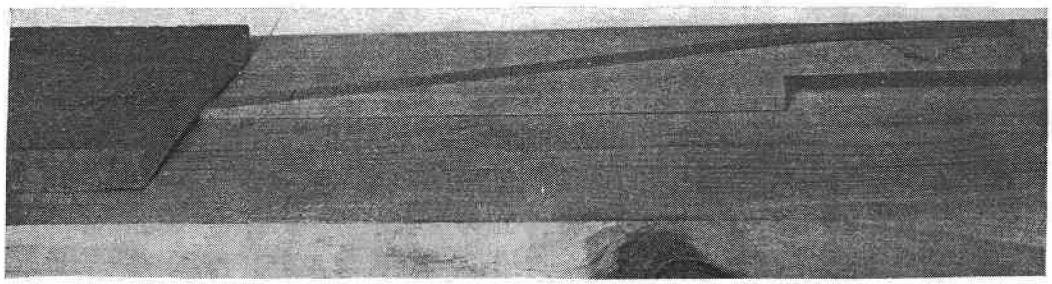


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FIGURE 6.—Method of using calibrated wedge to measure cup warp.

comparing warping tendencies, the twist figures are much more significant because they are nearly two or three times as high as the cup figures in most instances. To some extent, however, twist and cup go together, for the woods having the most twist also tend to have the most cup. Data were obtained on bow, but these proved to be insignificant as compared with cup and twist, and therefore bow is ignored here.

TABLE 25.—*Unrestrained twist and cup in air-dried hardwoods,*[1] *arranged in order from best to worst*

Wood	Twist	Cup	Wood	Twist	Cup
	Inch	*Inch*		*Inch*	*Inch*
Ash	0.107	0.052	Cottonwood	0.224	0.082
White oak	.113	.081	Soft maple	.246	.075
Red oak	.119	.077	Magnolia	.248	.068
Willow	.123	.069	Elm	.281	.079
Hackberry	.131	.086	Beech	.303	.074
Basswood	.168	.075	Sweetgum	.465	.095
Pecan	.187	.054	Sycamore	.534	.089
Hickory	.193	.074	Tupelo	.647	.115
Yellowpoplar	.218	.088	Blackgum	.723	.102

[1] Based on 1- by 7-inch by 4-foot boards.

MINOR IMPERFECTIONS OF HARDWOODS

Hardwood lumber frequently displays various imperfections or irregularities of grain. Their seriousness from the grading standpoint depends largely upon their size, number, and soundness. Frequently they are barred from clear-face cuttings, which must be free of all defects on one side and the other side sound, and admitted in sound cuttings, which must be free from rot, heart center, shake, wane, or other defects that materially impair the strength of the cutting. They are one of the characteristics of wood that should be taken into account because they affect the appearance always and frequently the utility. The term "minor" is used here because the test samples were selected to exclude anything of a more serious character.

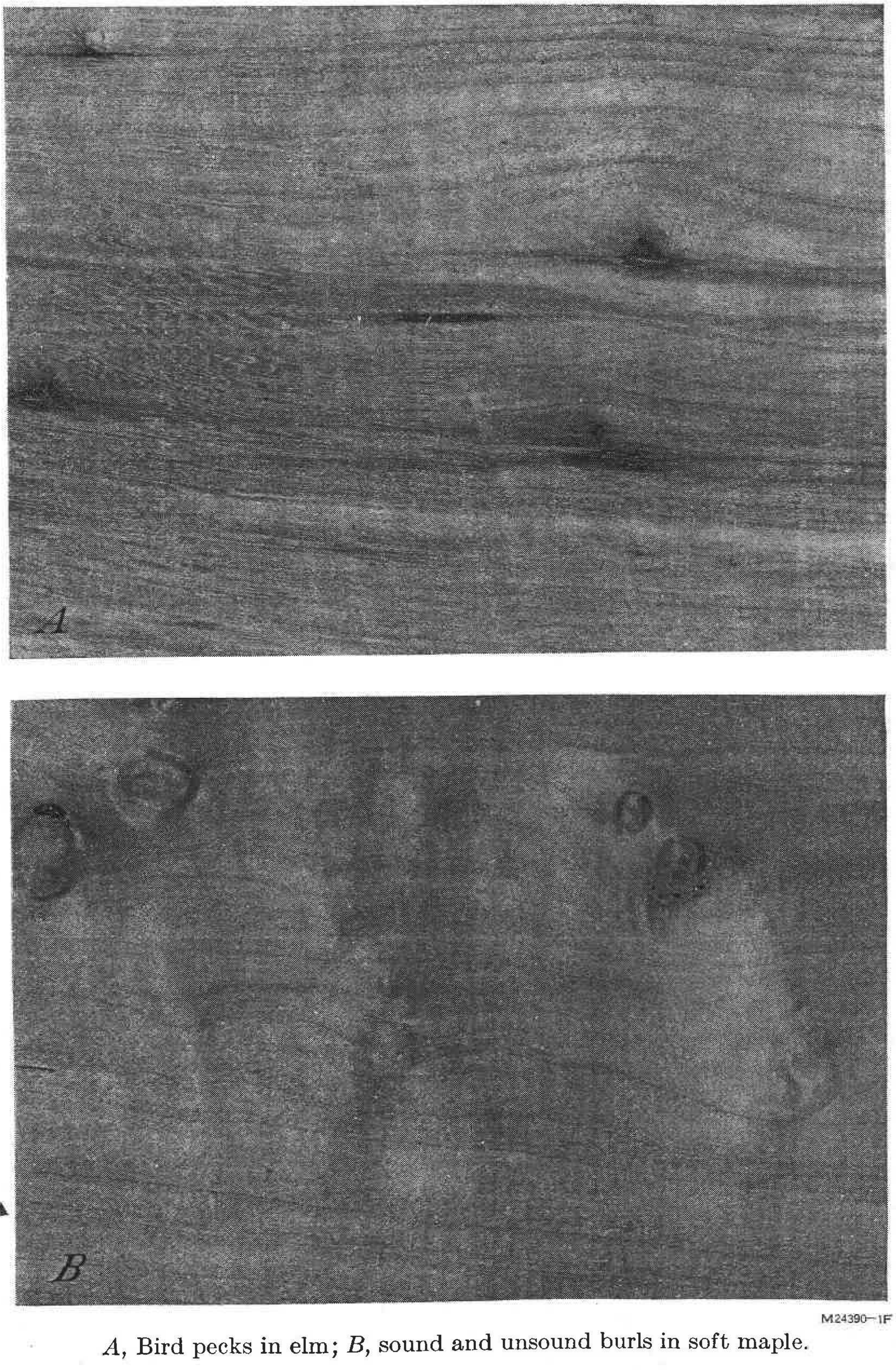
The test samples 4 inches wide by 3 feet long of 23 hardwoods were carefully examined and the occurrence of five of the more common imperfections was recorded (table 26). On these 1-square-foot samples, imperfections would necessarily occur much less frequently than in full-sized boards, but the cuttings nevertheless afforded a good yardstick for obtaining comparable data with respect to these conditions.

Certain special provisions in grading rules for treating some of these things leniently in woods where they are common are pointed out in the following paragraphs.

TABLE 26.—*Occurrence of minor imperfections in hardwood samples*

Wood	Bird pecks	Burls	Pith flecks	Streaks	Worm holes
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Ash	7	12	0	4	4
Basswood	11	18	8	8	0
Beech	5	10	0	2	4
Birch	0	20	0	0	0
Blackgum	11	4	0	0	0
Chestnut	0	6	0	0	34
Cottonwood	6	11	0	0	0
Elm	26	7	0	14	1
Hackberry	17	0	0	7	0
Hickory	25	8	0	10	0
Magnolia	11	13	0	0	1
Maple, soft	16	32	6	6	13
Maple, hard	4	21	12	21	1
Oak, chestnut	7	11	0	2	14
Oak, red	8	2	0	12	3
Oak, white	8	3	0	11	8
Pecan	73	0	0	0	5
Sweetgum	3	29	0	0	0
Sycamore	13	22	0	2	7
Tupelo	16	17	0	1	1
Walnut, black	0	40	0	0	5
Willow	10	25	0	0	0
Yellowpoplar	7	31	0	5	0
Average	12.3	14.9	1.1	4.6	4.4

A bird peck is a small hole or patch of distorted grain resulting from birds pecking through the growing cells of the tree. It usually resembles in shape a carpet tack with the point toward the bark and it is ordinarily accompanied by a distortion extending along the grain and to a smaller extent around the layers of growth. Plate 12, *A*, illustrates bird peck in soft elm. Nearly three-fourths of the pecan samples contained bird pecks; elm and hickory were next, having about one-fourth of the pieces affected. At the other extreme, sweetgum, hard maple, birch, chestnut, and black walnut had few or none. Within reasonable limits, bird pecks are allowable in sound cuttings but are not allowed in clear-face cuttings. In some of the woods most subject to bird peck the grading rules make special allowances; for instance, in hickory, pecan, and soft elm, bird pecks not



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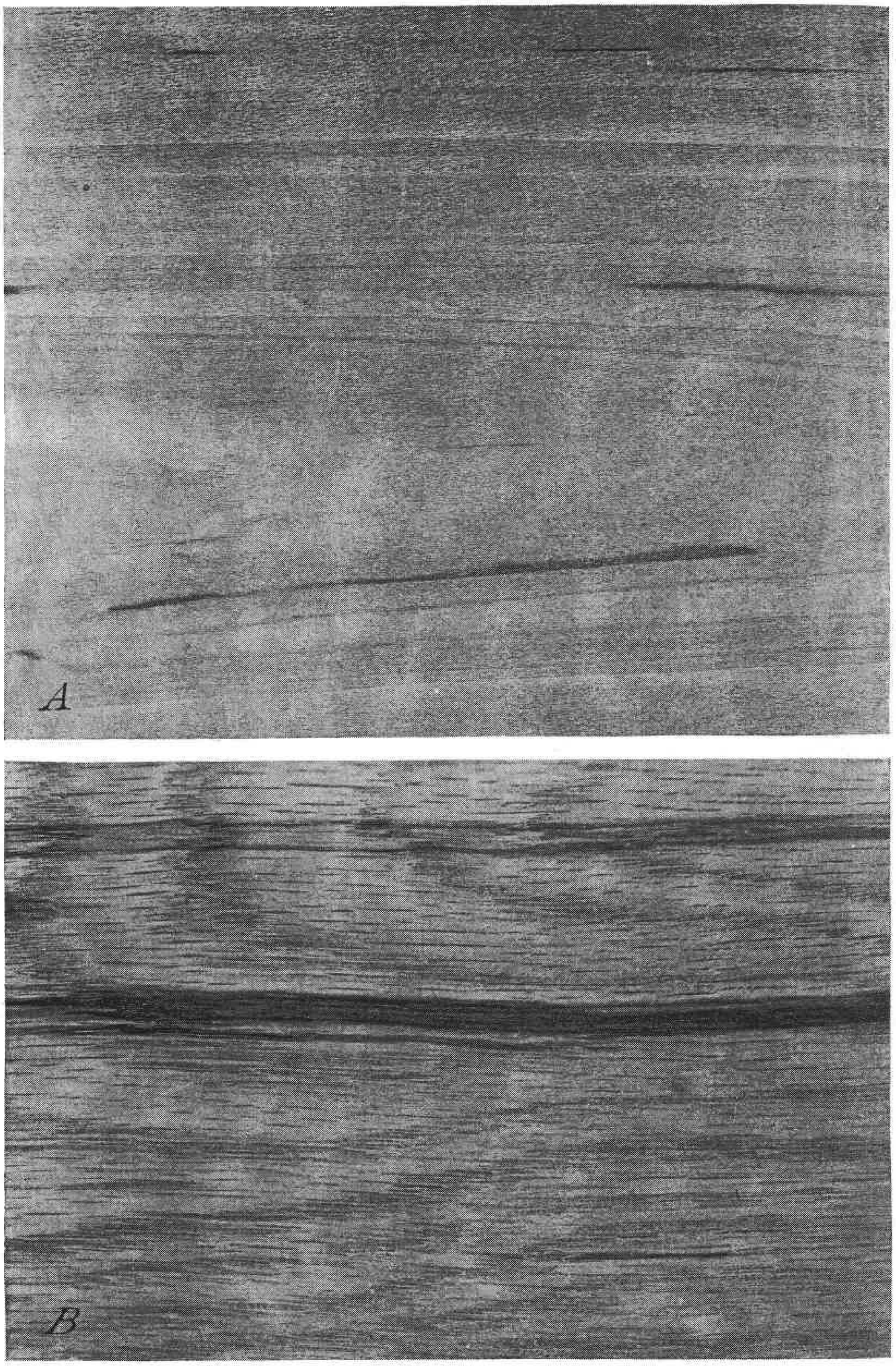
A, Bird pecks in elm; *B*, sound and unsound burls in soft maple.



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A, Pith flecks in basswood; *B*, two streaks of different degree in white oak.

over ⅜-inch average diameter are admitted in the cuttings in Firsts and Seconds and No. 1 Common; but when their aggregate area exceeds one-twelfth of the total area of the required cuttings, they reduce a piece one grade only.

A burl is a distorted grain surrounding the piths of several buds which did not develop (pl. 12, *B*). Sound burls, which contain no knots or unsound centers, are often held to give a more attractive appearance to the lumber by introducing a variation from the normal straight grain. From 25 percent to 40 percent of the samples contained burls in sweetgum, soft maple, yellowpoplar, willow, and black walnut. White oak, red oak, pecan, and hackberry had few if any. The grading rules provide that sound burls shall be admitted in the cuttings.

A pith fleck is a narrow streak resembling pith on the surface of a piece, usually brownish, up to several inches in length, resulting from burrowing of larvae in the growing tissue of the tree (pl. 13, *A*). Pith flecks were found only in the maples and basswood, up to 12 percent of the samples being affected. Badly affected pieces would be allowed only in sound cuttings.

Streaks in hardwoods may be of several distinct kinds, such as gum, decay, or stain streaks, associated with worm holes, mineral streaks, or deep discoloration. In the samples examined, the first three types were negligible, and the fourth is discussed below with worm holes.

Hard maple had 21 percent streak occurrence of the blackish mineral-streak type. Mineral streaks in maple, if dark and large, often develop checks in drying, and constitute a serious defect. Elm, red oak, white oak, and hickory come next with 10 percent to 14 percent occurrences (pl. 13, *B*). Over half of the woods, on the other hand, had few if any streaks.

In red oak and white oak the grading rules provide that mineral streaks, spots and streaks, and spots of similar nature exceeding in aggregate area one-twelfth of the total area of the required cuttings will reduce a piece one grade only. This prevents the grader from dealing with them too severely.

From 13 to 34 percent of the samples in chestnut, chestnut oak, and soft maple had worm holes, while several other woods had occasional occurrences accompanied by dark discolored streaks usually several inches long. "Sound wormy" grades are made in chestnut and the oaks that are characterized by very numerous small worm holes but otherwise sound. The worm holes discussed here were all small, scattered, and of a type that would be admitted in sound cuttings.

Change of Color in Hardwoods

The color of freshly planed wood is subject to change. This change may occur in a very few days of exposure to outdoor sunlight, even if the wood is well dried and protected from the weather. Sunlight streaming through windows will accomplish the same thing. However, such color changes are not wholly due to sunlight, for sheathing boards from old buildings are also considerably darkened. Light-colored woods tend to yellow or brown, and dark woods sometimes bleach noticeably. These changes are only superficial, but they may produce less attractive shades, and in furniture, for example, they sometimes result in complaint after the products have been in use for a time.

METHOD

Tests were made by outdoor exposure of 21 different woods in panels containing 50 pieces each, which were examined at intervals. The panels were laid flat and covered at night and during rainy weather to avoid any moisture effect. Removal of a chip from the surface of each sample with a small gouge permitted close comparison between a fresh surface and the exposed surface.

The proportion of heartwood and sapwood in the different woods tested varies widely. In woods like hard maple that are largely sapwood, the test samples were sapwood; and in woods like willow that are largely heartwood, the test samples were heartwood. Heartwood and sapwood were more evenly balanced in some woods, and in four of these both heartwood and sapwood samples were used (Table 27.)

TABLE 27.—*Degree of change of color of hardwoods in approximately 160 hours of sunlight*

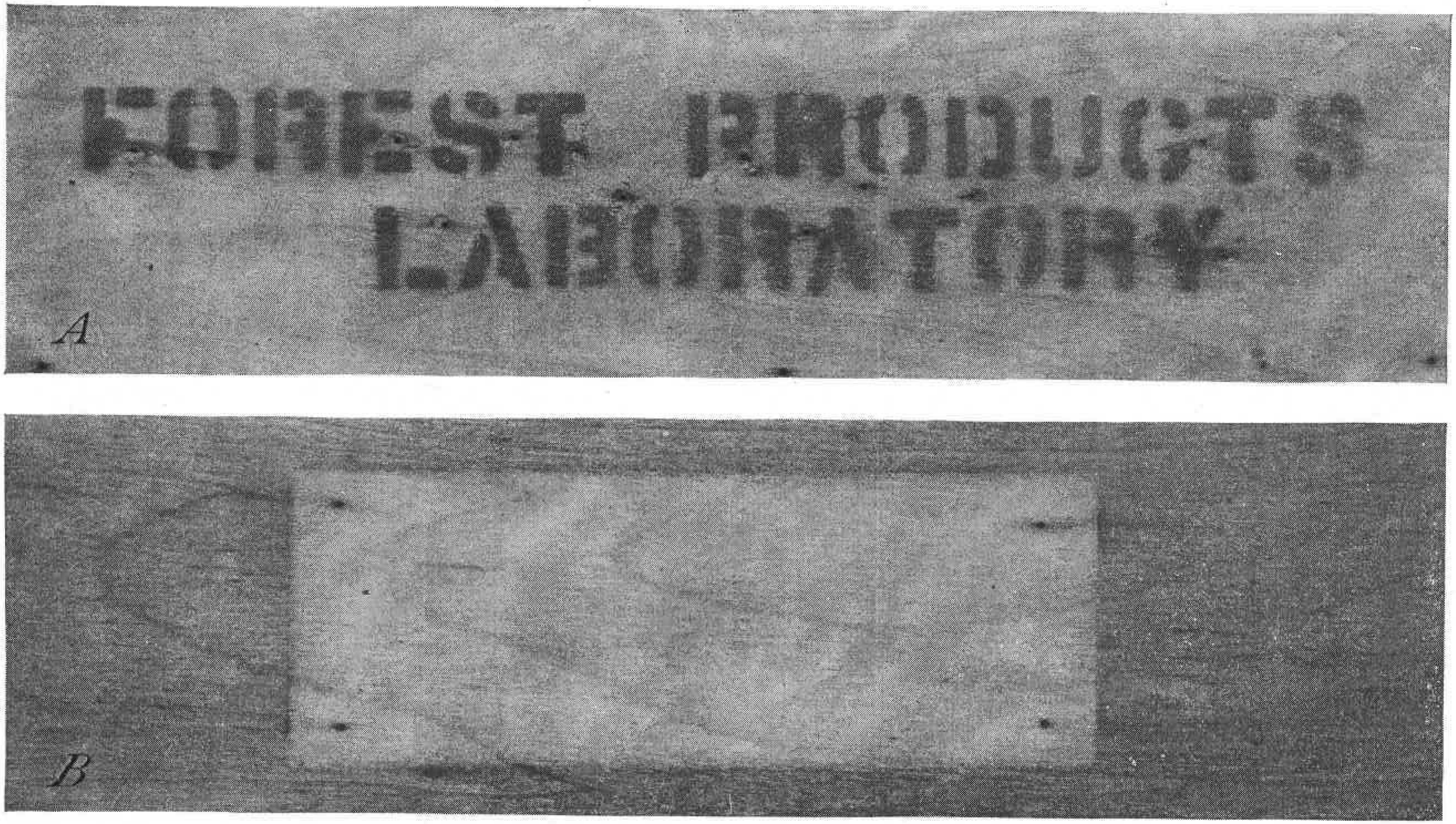
Kind of wood	Heartwood	Sapwood	Degree of color change
Basswood		×	Slight.
Beech	×		
Birch	×	×	
Hackberry		×	
Sweetgum	×		
Sycamore	×		
Blackgum		×	Slight to medium.
Hard maple		×	
Soft maple		×	
White oak	×		Medium.
Black walnut	×		
Cottonwood		×	
Elm		×	
Hickory	×	×	
Willow	×		
Ash		×	Medium to large.
Chestnut	×		
Magnolia		×	
Mahogany	×		
Red oak	×	×	
Yellowpoplar	×	×	

RESULTS

Sixteen of the 21 freshly planed woods tested showed noticeable color changes after only 16 hours' exposure to summer sunlight, or about the interval between sunrise and sunset in June. Earlier examination might have revealed changes sooner in some of them. The woods in which color change appeared doubtful after 16 hours were basswood, white oak, willow, mahogany, and sweetgum. After 32 hours changes could be detected in all woods.

After exposure to 20 days of sun, the 21 woods were classified as to change in color (table 27), affording evidence of relative susceptibility over a short period.

In black walnut and willow heartwood the change consisted of a slight bleaching of the exposed surface. The walnut, for instance, became a dull brown color of a lighter and much less attractive shade than the original. The other 19 woods yellowed or browned in varying degrees. Light-colored woods did not necessarily discolor more than darker ones. Basswood, one of the whitest woods, changed color much less than did chestnut, which had a decided brownish tint at the start. In the same wood, light-colored or sapwood samples generally



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Effect of sunlight on sap yellowpoplar: *A*, Printing produced by sunlight through a stencil; *B*, color contrast between protected area (small rectangle) and unprotected area.

showed a more decided color change after exposure than darker or heartwood samples.

The printed words on the piece in plate 14, *A*, were produced by a stencil tacked on sap yellowpoplar, which let the sunlight darken the area of the letters. The light-colored rectangle shown in plate 14, *B*, was protected from the sun while the surrounding wood was exposed. Yellowpoplar showed as pronounced a color change as any wood upon exposure to sunlight. The time was 20 days.

SUMMARY

Among the important classes of properties that affect the general utility of any wood are its machining properties, which embrace all woodworking operations. In these, as in other classes of properties, different woods vary widely and a given wood may give good results in some operations, fair in others, and poor in still others. The "workability" of any wood therefore cannot be judged by one operation, but depends rather upon the summation of all of them. In any operation there are several factors, both in the wood itself and in the machine, that affect the results, and these results may be good or bad depending upon the conditions under which the work was done. The usability of certain native woods that are somewhat refractory or not familiar to consumers may depend on searching out the optimum machining conditions. Some woods machine well under a relatively wide range of conditions while others are handicapped by the need of exacting techniques if good results are to be obtained.

TABLE 28.—*Some machining and related properties of hardwoods*

Kind of wood	Planing—Perfect pieces	Shaping—Good to excellent pieces	Turning—Good to excellent pieces	Boring—Good to excellent pieces	Mortising—Fair to excellent pieces	Sanding—Good to excellent pieces	Steam bending—Unbroken pieces	Nail splitting—Pieces free from complete splits	Screw splitting—Pieces free from complete splits
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Ash	75	51	79	94	62	75	67	65	71
Basswood	64	9	68	75	51	17	2	79	68
Beech		21	90	99	93	49	75	42	58
Birch	63	53	80	98	97	34	72	32	48
Buckeye		6	58	75	18		9		
Cottonwood	21	3	70	70	52	19	44	82	78
Chestnut	74	24	87	91	72	64	56	66	60
Elm	33	11	65	94	75	66	74	80	74
Gum, black	48	23	75	82	24	21	42	65	63
Hackberry	74	10	77	99	70		94	63	63
Hickory		19	84	100	98	80	76	35	63
Magnolia	65	25	79	69	32	37	85	73	76
Mahogany	80	68	89	100	100		41	68	78
Maple, hard	54	62	82	99	95	38	57	27	52
Maple, soft	41	22	76	80	36	37	59	58	61
Oak, chestnut		23	90	100	100	75	85	49	70
Oak, red	91	21	84	99	100	81	86	66	78
Oak, white	87	28	85	95	100	83	91	69	74
Pecan	88	31	89	100	100		78	47	69
Sweetgum	51	21	86	92	58	23	67	69	69
Sycamore	22	8	85	98	96	21	29	79	74
Tupelo		43	79	62	35	34	46	64	63
Walnut, black	62	34	91	100	98		78	50	59
Willow	52	5	58	71	24	24	73	89	62
Yellowpoplar	70	12	81	87	63	19	58	77	67
Average	61	25	79	89	70	45	62	62	67

Table 28 sums up the results of all the machining tests discussed in this publication. By running down the columns the behavior of the different woods in all tests can be found without referring to the several separate tables. By running across the columns the performance of any given wood in the whole series of tests is shown, giving a bird's-eye view of its general workability. Table 29 similarly sums up certain additional data on hardwood characteristics that were obtained in the study, which affect either the machining or the general utility of the different woods.

TABLE 29.—*Certain characteristics of hardwoods that affect machining*

Kind of wood	Specific gravity average	Rings per inch average	Cross grain		Shrinkage (tangential) in moisture-content reduction)		Warp (per 7-inch widths)—twist
			Slope—spiral grain	Interlocked—pieces	Green to 6 percent	12 to 6 percent	
		Number	*Percent*	*Percent*			*Inch*
Ash	0.50	13	5.6	0	5.7	2.1	0.107
Basswood	.35	16	4.3	0	7.2	1.4	.168
Beech	.55	15	6.9	0	8.9	2.8	.303
Birch	.58	21	5.5	0	7.5	2.2	----
Blackgum	.45	22	7.5	53	6.6	2.3	.723
Cottonwood	.38	8	4.3	24	6.7	2.0	.224
Chestnut	.39	11	6.2	0	6.6	1.9	----
Elm	.48	14	4.9	19	7.5	2.4	.281
Hackberry	.43	13	5.5	0	6.5	2.1	.131
Hickory	.61	15	3.1	0	7.9	2.7	.193
Magnolia	.44	16	5.1	0	5.9	2.0	.248
Mahogany	.46	----	6.2	10	3.4	1.3	----
Maple, hard	.57	17	7.9	0	7.8	2.3	----
Maple, soft	.45	12	6.5	0	6.1	2.1	.246
Oak, chestnut	.56	15	7.2	0	9.5	2.1	----
Oak, red	.55	10	4.4	0	9.0	2.5	.119
Oak, white	.56	17	5.3	0	8.8	2.4	.113
Pecan	.58	14	4.3	0	6.6	2.2	.187
Sweetgum	.46	15	8.2	48	8.4	2.4	.465
Sycamore	.47	9	7.7	45	6.9	2.3	.534
Tupelo	.44	19	8.9	68	6.1	1.9	.647
Walnut, black	.51	9	5.7	0	6.7	1.7	----
Willow	.34	9	7.7	0	6.2	1.8	.123
Yellowpoplar	.41	12	5.2	0	6.2	1.9	.218
Average	.48	14	6.0	11	7.0	2.1	----

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