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Abstract

Specimens of earlywood and latewood of Pinus taeda L. were excised so that length along the grain was 3 inches and thickness was 0.1 inch. These specimens were cut orthogonally-as with a carpenter's plane-in the three major directions. Cutting velocity was 2 inches per minute.

When cutting was in the planing (90-O) direction, thin chips, intermediate to high moisture content, rake angles of 5 and 15° favored formation of the Franz Type II chip and accompanying good surfaces.

In the O-90 direction, a knife with 70° rake angle cut the best veneer; wood cut saturated yielded the highest proportion of continuous veneer, although saturated earlywood developed some compression tearing.

When cutting was across the grain (90-90 direction), McKenzie Type I chips were formed and the best surfaces were achieved with a knife having 45° rake angle cutting saturated wood; earlywood was more difficult to surface smoothly than latewood.

For each cutting direction, regression equations were developed to state average cutting forces (normal and parallel) in terms of rake angle, depth of cut, specific gravity, and moisture content.

Tool Forces and Chip Formation in Orthogonal Cutting of Loblolly Pine

The objective of the study reported in this paper was to determine chip types and tool forces typical of loblolly pine earlywood and latewood machined orthogonally.

Orthogonal cutting is the machining process in which the cutting edge is perpendicular to the relative motion of tool and workpiece. The surface generated is a plane parallel to the original work surface. A carpenter's plane cuts orthogonally, as does a bandsaw. Rotary peeling of veneer approximates orthogonal cutting. A two-number notation used by McKenzie (1961) is useful in describing the machining situation (fig. 1).

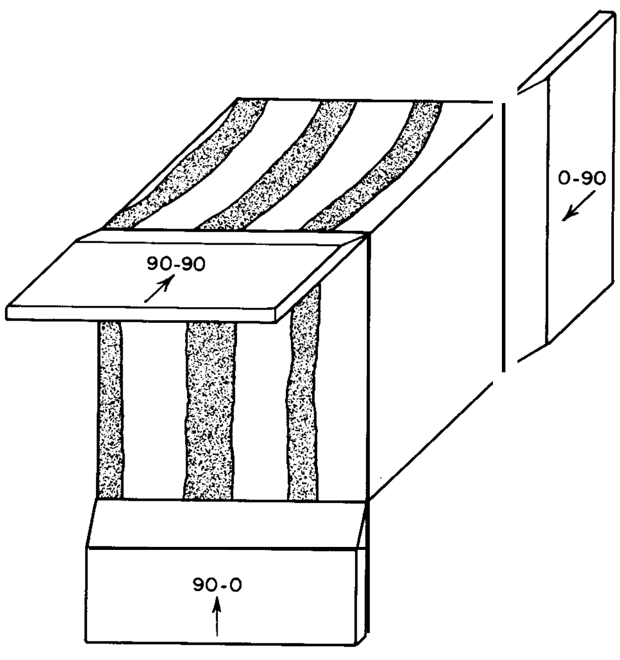


Figure I.-Designation of the three major machining directions. The first number is the angle the cutting edge makes with the grain; the second is the angle between cutter movement and grain.

The world literature on orthogonal cutting is digested in Koch's (1964) text and in the wood-machining reviews by Koch and McMillin (1966a, 1966b) and Koch (1968). The only data specific to southern pine are from studies of veneer cutting. Considerable information on this topic has been issued by the USDA Forest Products Laboratory (Lutz 1964, 1967; Lutz ***et al.*** 1962, 1966, 1967, 1969; Lutz and Patzer 1966; Peters ***et al.*** 1969). Cade and Choong (1969) also have investigated the rotary peeling of southern pine venner.

SCOPE

Because of wide latewood bands, the wood of loblolly pine alternately displays the machining characteristics of two distinct materials, i.e., earlywood and latewood. For this reason, and also because of the difficulty in collecting wholewood specimens statistically representative of the entire species, wood of each cell type was studied separately. Interpolation of data between these extremes should permit estimation of cutting forces in southern pine of intermediate densities, though it should be recognized that small excised specimens of earlywood and latewood may machine differently than the same wood interlayered ***in situ.***

For each of the three primary directions (fig. 1), chip formation was studied and photographed; cutting forces were recorded at a variety of rake angles, depths of cut, and moisture contents. Cutting speed was constant at 2 inches per minute. The main study was factorial with five factors:

Cutting direction

90-O (planing)
O-90 (veneer direction)
90-90 (crosscut)

Rake angle
(clearance angle constant at 15°)

25°
35°

Depth of cut (inch)

0.015
.030
.045
.060

Moisture content (percent)

7
15.5
Saturated

Type of cell

Earlywood
Latewood

Replications: 5

Because the practical range of rake angles differs for each cutting direction, some additional knives were studied:

In the veneer direction (O-90) a special veneer knife with 70° rake angle (20° sharpness angle and no clearance angle) was used in addition to knives with 25, 35, and 45° rakes. Other factors remained the same.

In the crosscut direction (90-90) a knife with 45° rake angle and 15° clearance angle was added.

In the planing direction (90-O) knives with rake angles of 5 and 15° were added.

In all, 1,320 observations were made, of which 720 were in the main experiment (table 1).

Table 1. – ***Number of observations for various cutting directions***

Cutting direction	Cell types	Rake angle	Depth of cut	Moisture content	Replication	Total
O-90	2	4	4	3	5	480
90-90	2	3	4	3	5	360
90-O	2	4	4	3	5	480
						1,320

Figure 2 illustrates nomenclature of orthogonal cutting.

PROCEDURE

Material was obtained from loblolly pine trees cut near Effie, Louisiana, by the Roy 0. Martin Lumber Company. Cross-sectional disks measuring approximately 4 inches along the grain were taken from logs exhibiting fast growth and wide bands of latewood. As an aid to specimen preparation, sampling was limited to logs at least 15 inches in diameter. Compression wood and wood below breast height in the standing tree were avoided. The disks were coated with antistain chemical and conditioned to 9-percent equilibrium moisture content.

Specimens.-Each disk was split into blocks containing the band of earlywood or latewood to be used. The identity of each growth ring was maintained. The bark and all wood between the bark and the selected growth ring were removed with a hand ax and chisel to expose a tangential surface. After trimming, each piece was placed against a belt sander for light sanding. The resulting flat reference surface aided in machining a rectangular block with the growth ring (earlywood or latewood) exposed on one side (fig. 3). Since the block had been split off the disk, it was relatively simple to make specimens with the grain parallel to the sides.

From the master blocks it was possible to prepare specimens for all cutting directions. For veneer cutting, wafers approximately O.l-inch wide were crosscut (fig. 4, O-90). For the planing and crosscutting directions, specimens 0.1 -inch wide were prepared by ripping the earlywood or latewood band off the rectangular block. Specimens were brought to equilibrium moisture content.

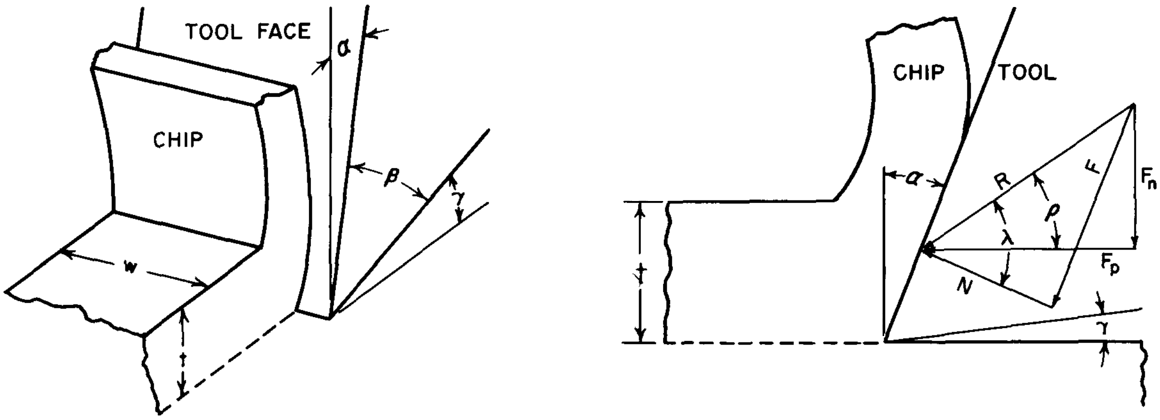


Figure 2.-Nomenclature ***in orthogonal cutting.***

- α – ***Rake angle: angle between the tool face and a plane perpendicular to the direction of tool travel.***
- β – ***Sharpness angle: angle between the tool face and back.***
- γ – ***Clearance angle: angle between the back of the tool and the work surface behind the tool.***
- t – ***Thickness of chip before removal from the workpiece.***
- w – ***Width of undeformed chip.***
- F_n – ***Normal tool force: force component acting perpendicular to parallel tool force and perpendicular to the surface generated.***
- F_p – ***Parallel tool force: force component acting parallel to tool motion in workpiece, i.e., parallel to cut surface.***
- R – ***Resultant tool force: the resultant of normal and parallel tool force components.***
- ρ – ***Angle of tool force resultant: the angle whose tangent is equal to the normal tool force divided by the parallel tool force.***
- F – ***Friction force: force component acting along the interface between tool and chip.***
- N – ***Normal to the friction force: force component acting normal to tool face.***
- λ – ***Angle between resultant tool force and the normal frictional force; the angle whose tangent is equal to the friction force divided by the normal friction force.***

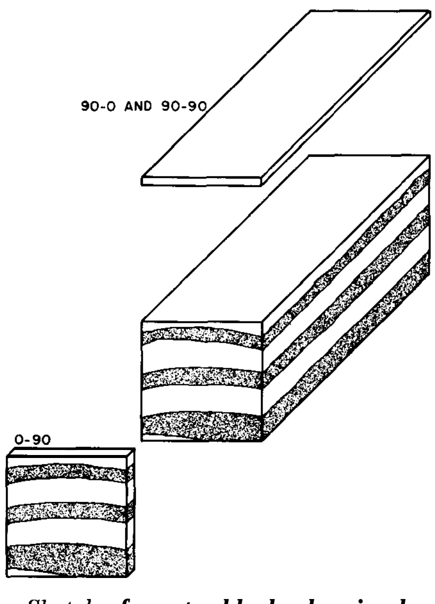


Figure 3.–*Sketch* ***of master block, showing how specimens were prepared.***

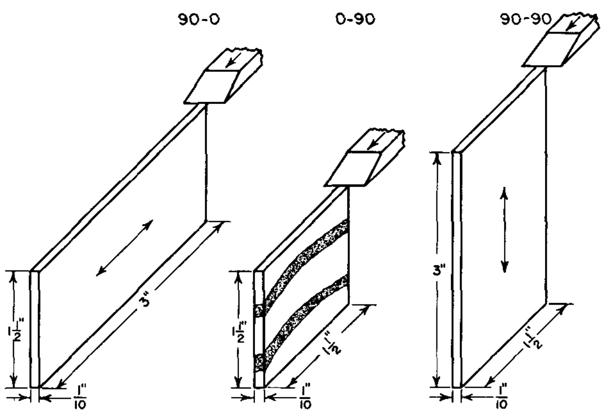


Figure ***4.-Specimens for orthogonal cutting.***

All specimens for a given replication came from the same growth ring and were considered matched, even though they sometimes were from opposite sides of the disk. There were five replications; therefore wood from five different rings was studied.

Specific gravity-on the basis of ovendry weight and ovendry volume-was determined on six specimens randomly selected from each replication. Thus there were 30 determinations for latewood and 30 for earlywood. A mercury volumeter was used for measuring the ovendry volume.

Dynamometer.-A two-component tool dynamometer (Franz 1958) was used (fig. 5) to measure cutting forces. The parallel and normal forces were simultaneously and continuously recorded on a two-channel recorder. Pen deflections on the recorder were calibrated by hanging known weights on the dynamometer-mounted tool point.

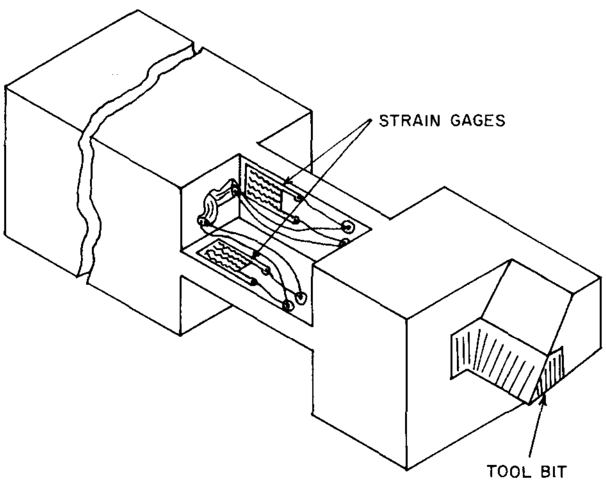


Figure 5. ***-Sketch of two-component tool dynamometer.***

Cutting forces parallel to the surface (F_p) were always positive. The average force and the maximum peak force were recorded for each run. The average force was determined by making areas above and below the average line equal.

Cutting forces normal to the surface (Fn) were sometimes positive (the knife forced the workpiece away) and sometimes negative (the knife tended to lift the workpiece). The average, minimum, and maximum were recorded with appropriate algebraic sign; for example, the minimum force might have been -5 pounds, the maximum -1 pound, and the average (based on areas) intermediate.

Width of each specimen was measured with a micrometer so that cutting forces could be adjusted to a standard O.l-inch width of cut. It is well established that cutting force is directly proportional to width of cut.

Cutting procedures.-Five cutters had rake angles of 5, 15, 25, 35, and 45° (with clearance angle constant at 15°). A sixth knife, used only when cutting veneer, had a rake angle of 70°, with zero clearance angle. The face of each bit was approximately 5/16-inch square; grinding marks were perpendicular to the cutting edge. Edges were examined under a microscope to make sure nicks were absent.

The dynamometer was mounted in a fixture bolted to the bed plate of an Instron testing machine. The workpiece holder was carried in a swivel-mounted traversing vise attached to the crossarm of the Instron. The traversing vise was adjusted for each depth of cut. Crosshead travel determined cutting speed, which was held constant at 2 inches per minute.

Humidity in the testing room was controlled to give an equilibrium moisture content of either 7 or 15.5 percent. The saturated specimens were kept wetted during test.

Specimens were machined in random order. Cutting procedure varied. In the veneer-cutting direction a smoothing cut was first made with the knife having a 70° rake angle, after which (in most cases) a single cut was taken for record; the specimen was then discarded. For 90-0, a smoothing cut was made in the planing direction before the initial cut--and, when roughness made it necessary, before each succeeding cut in the series of four depths; cuts were made in sequence from 0.0 15 to 0.060 inch. In the 90-90 direction an initial smoothing cut was unnecessary, as the sawn end of the block was sufficiently smooth; after each cut, the surface was trimmed smooth again.

Chip formation was viewed through a microscope at 30X magnification. Representative chips were photographed.

Average specific gravity, as determined from ovendry weight and ovendry volume, was found to be:

	Earlywood	Latewood
Average	0.34	0.85
Range	0.29-0.42	0.77-0.96
Standard deviation	0.036	0.046

PARALLEL TO GRAIN: 90-O DIRECTION

As recorded by Koch (1955, p. 261; 1956, p. 397) and enumerated by Franz (1958), three basic chip types are observable when wood is machined parallel to the grain in the 90-O direction.

Type I chips are formed when cutting conditions are such that the wood splits ahead of the tool by cleavage until it fails in bending as a cantilever beam, as illustrated in figure 6a. Machining of saturated specimens of both early-wood and latewood, however, somtimes results in a peeling action rather than an abrupt breaking (fig. 6b). Factors leading to formation of Type I chips are:

Low resistance in cleavage in combination with high stiff-ness and strength in bending.

Deep cuts (Type I chips can form with any depth of cut, depending on the other factors)

Large rake angles (25° and more)

Low coefficient of friction between chip and tool face

Low moisture content in the wood.

The Type I chip leaves a surface that exhibits chipped grain, i.e., the splitting that occurs ahead of the cutting edge frequently runs below the plane generated by the path of the cutting edge. The amount of roughness depends upon the depth to which the cleavage runs into the wood. Power consumed by a knife forming

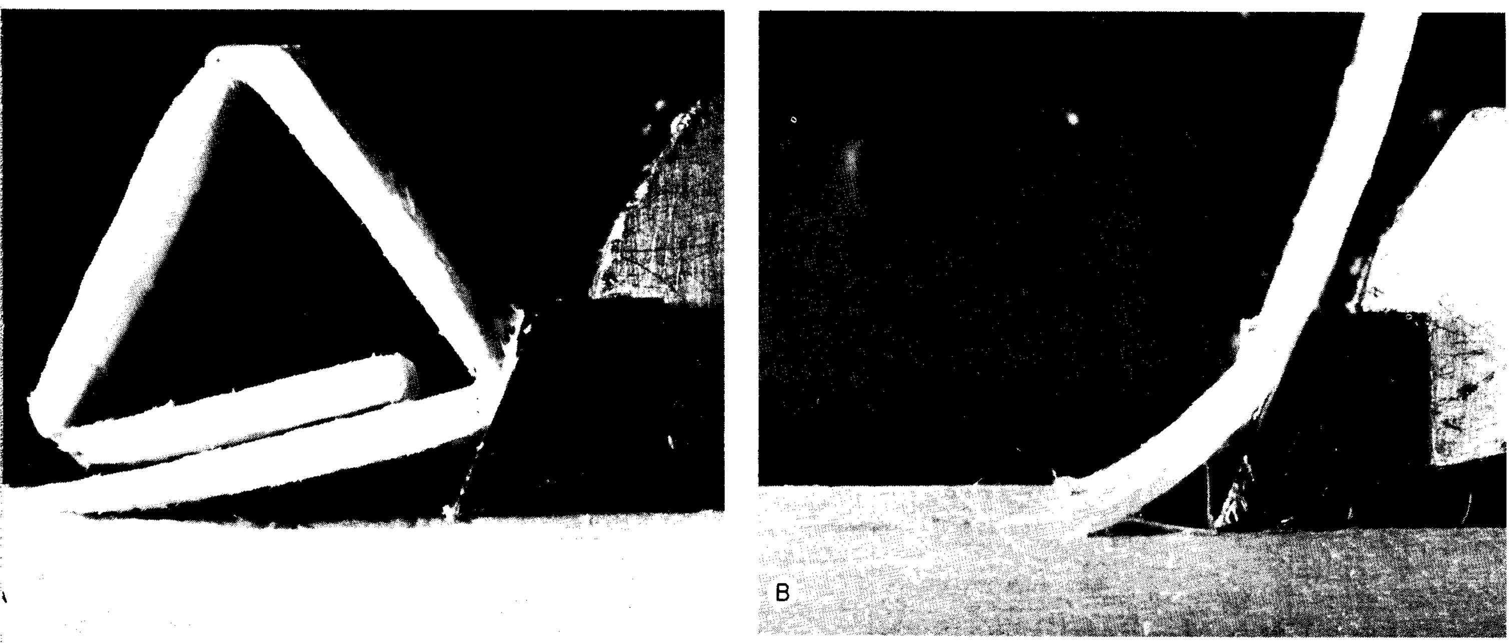


Figure 6.—*Franz* **Type I chips from** *0.045-inch* **cuts in** 90-O ***direction,*** *25°* ***rake angle. A: In loblolly pine earlywood at '/-percent moisture content. B: In saturated loblolly pine latewood.***

Type I chips is low, because wood fails relatively easily in tension perpendicular to the grain, and the knife severs few fibers. Because it is seldom cutting, the knife edge dulls slowly.

With rake angles of 2.5 and 35° the normal cutting force (Fn) was negative at all depths of cut for all moisture contents (fig. 7), and Type I chips were formed.

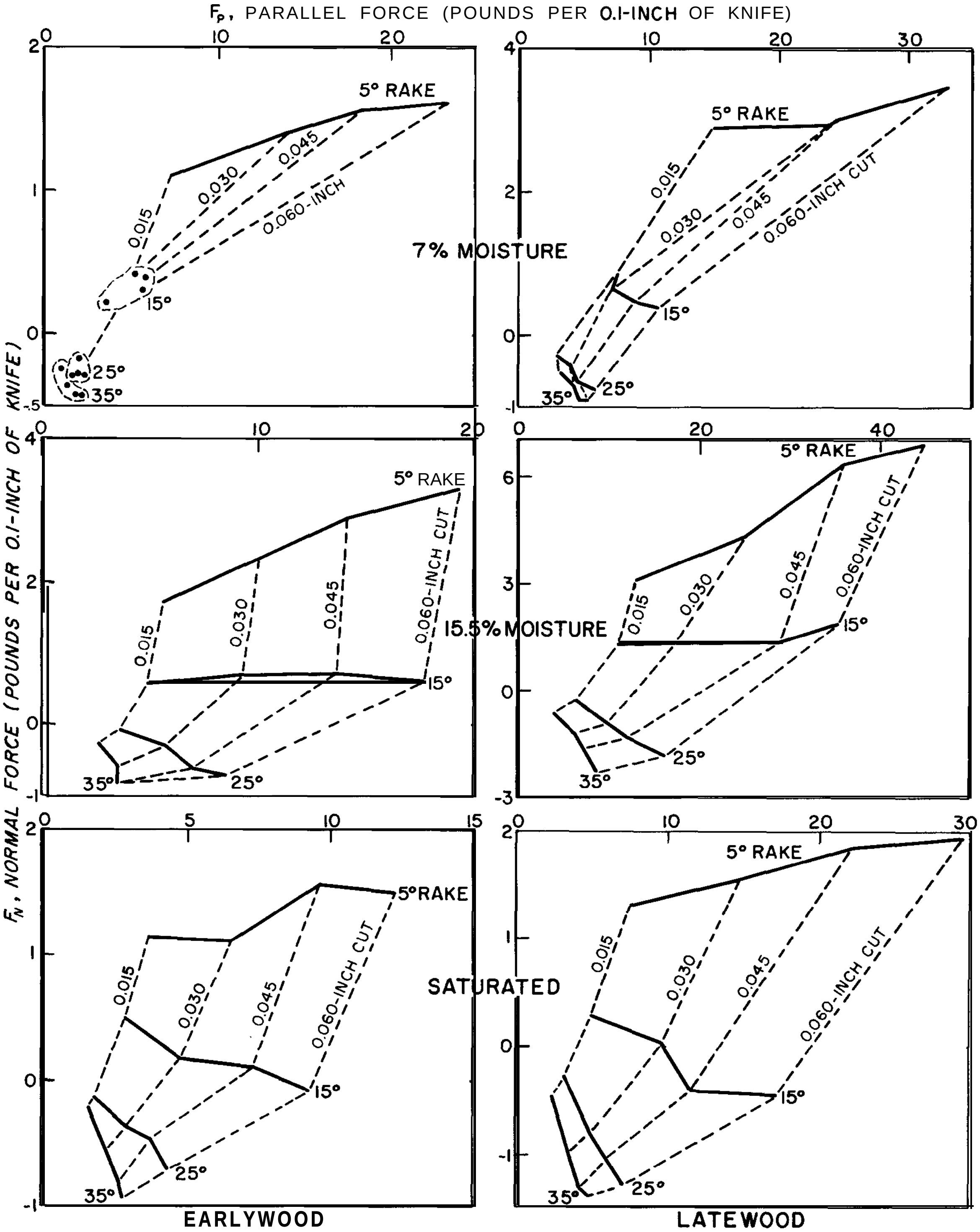


Figure *'T-Effect of depth of cut, rake angle, and moisture content on average cutting forces for earlywood and latewood of southern pine; 90-O cutting direction, orthogonal, 15° clearance angle, 2 inches per minute cutting velocity.*

Type II chips occur under certain conditions; continuous wood failures that extend from the cutting edge to the work surface ahead of the tool must be induced (fig. 8). The movement of the tool strains the wood ahead of the tool in compression parallel to the grain and causes diagonal shearing stresses; the wood fails and a continuous, smooth, spiral chip is formed. The radius of the spiral increases as chip thickness increases. Quite frequently latewood chips display laminae or layers. The resultant surface is excellent. In this study, thin chips, intermediate to high wood moisture contents, and rake angles of 5 to 15° favored formation of the Type II chip. In commercial practice Type II chips may be formed at rake angles somewhat higher than 15°–possibly up to 20°–because the splitting ahead of the knife may be less in the layered earlywood and Iatewood than in these homogeneous samples. The cutting edge is in intimate contact with the wood at all times, and dulling probably is rapid. Power demand is intermediate between that for Type I and Type III chips.

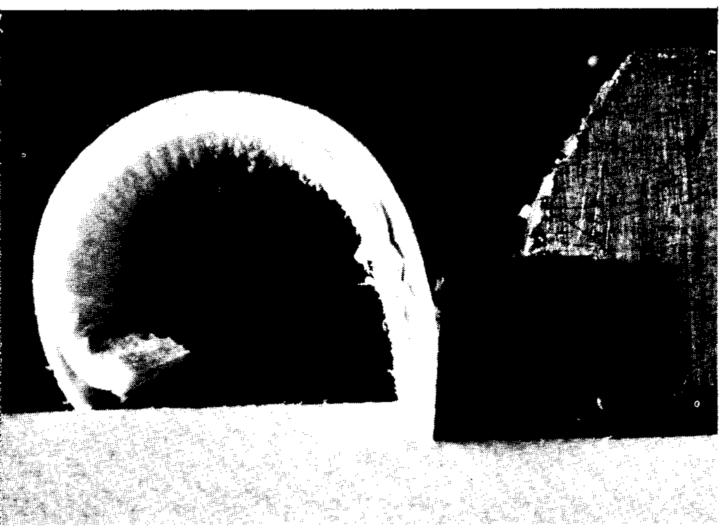


Figure ***B.-Franz Type II chip formed when making an 0.045.inch cut (90-0 direction) in loblolly pine latewood at 7-percent moisture content; 5° rake angle.***

Type III chips tend to form in cycles. Wood ahead of the tool is stressed in compression parallel to the grain. Rupture occurs in shear parallel to the grain and compression parallel to the grain, and is followed by compaction of the deformed wood against the tool face (fig. 9). Stresses are then transferred to undeformed areas that subsequently fail in turn. The chip does not escape freely up the tool face but remains interposed between face and area of continuing wood failure. When the accumulation of compressed material becomes critical, buckling takes place, the chip escapes upward, and the cycle begins again. Factors favorable to the formation of Type III chips include:

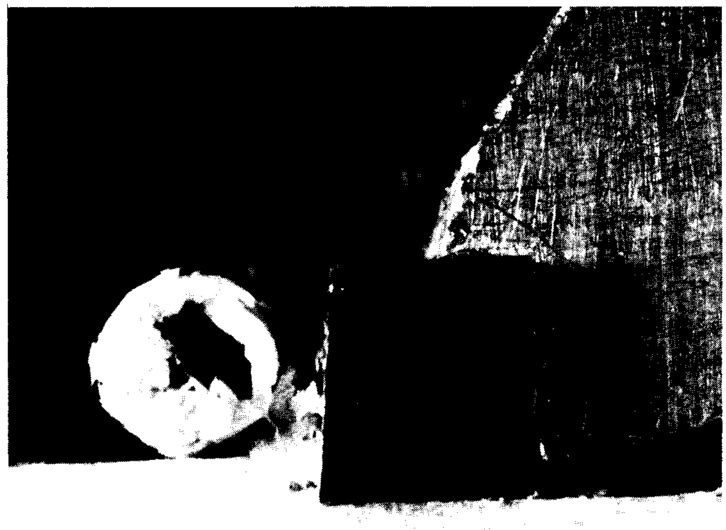


Figure ***9. Franz Type III chip formed when making an 0.045inch cut (90-0 direction) in loblolly pine earlywood at 7-percent moisture content; 5° rake angle.***

Small or negative rake angles

Dull cutting edges (the rounded edge presents a negative rake angle at tool-edge extremity)

High coefficient of friction between chip and tool face.

Wood failures ahead of the tool establish the surface. The failures frequently extend below the plane of the cut, and incompletely severed wood elements remain prominent on the surface. This machining defect is termed fuzzy grain. Power consumption is high and dulling is rapid.

Occurrence of the three chip types in orthogonal cutting of loblolly pine earlywood and latewood is summarized in table 2.

Effects of knife angles.-Rake angle exerted a strong effect on tool forces; forces were

Table 2.-*Typical chip types when orthogonally cutting loblolly pine wood parallel to the grain in the 90-O direction*[1]

Moisture content and rake angle (degrees)	Chip type[2]	
	In earlywood	In latewood
Saturated		
5	II (III)	II
15	II (III)	I (II)
25	I (II)	I
35	I	I
15.5 percent		
5	III (II)	II (III)
15	II (III)	II
25	I (II)	I (II)
35	I	I
7.0 percent		
5	III (I)	II (I)
15	I (III)	I
25	I	I
35	I	I

[1]Depths of cut ranged from 0015 to 0.060 inch. Cutting velocity was 2 inches per minute, clearance angle 15°.

[2]The first number in each entry is major chip type as classified by Franz (1958); a second number in parentheses indicates that a combination of chip types was observed.

Table 3.–*Average* ***tool forces per*** *0.1-inch* ***of knife when orthogonally cutting loblolly pine parallel to the grain in the 90-O direction***

Factor	Parallel force	Normal force[1]
	– –*Pounds* – –	
Cell type		
Earlywood	6.5	0.3
Latewood	12.5	.5
Moisture content, percent		
7	8.3	.4
15.5	12.9	.8
Saturated	7.3	.0
Depth of cut, inch		
0.015	5.2	.5
.030	8.3	.4
.045	10.8	.4
.060	13.7	.4
Rake angle, degrees[2]		
5	18.0	2.6
15	10.9	.5
25	5.4	–.6
35	3.7	–.7

[1]A negative normal force means that the knife tended to lift the workpiece; force was positive when the knife tended to push the workpiece away.

[2]Clearance angle constant at 15°.

negatively correlated with rake angle (fig. 10a and tables 3 through 7). Figure 7 shows the effect of rake angle at the three moisture contents studied.

The sharpness angle strongly affects the rate at which the cutting edge dulls. Minute fracturing of a freshly sharpened and honed knife edge occurs as the first few chips are cut and continues until equilibrium is reached between the cutting edge-which grows thicker and more rigid as the edge dulls-and the cutting forces; from this time wear proceeds at a slower rate. Effective rake angle is decreased as wear proceeds; cutting forces rise and chip formation is altered. In addition, the effective clearance angle is reduced and in fact may become negative; a negative clearance angle increases the cutting forces exerted by the knife and usually affects surface quality by causing raised grain-a roughened condition in which hard latewood is raised above the softer earlywood but not torn loose from it.

Effects of ***depth*** *of cuts.*–In orthogonal cutting, depth of cut is synonymous with thickness of the undeformed chip. As Lubkin (1957) and others have observed, in a given cutting situation two types of parallel-force curves may develop with changing chip thickness. When chips are very thin, the parallel force varies according to a power curve and F_p becomes zero at zero chip thickness.

$$F_p = K t^m w \qquad (1)$$

where

F_p = parallel tool force
K = a constant
t = chip thickness
m = a constant between 1 and 0 (generally observed to be from 0.25 to 0.67)
w = width of chip

Beyond the region of very thin chips it is possible to approximate considerable portions of

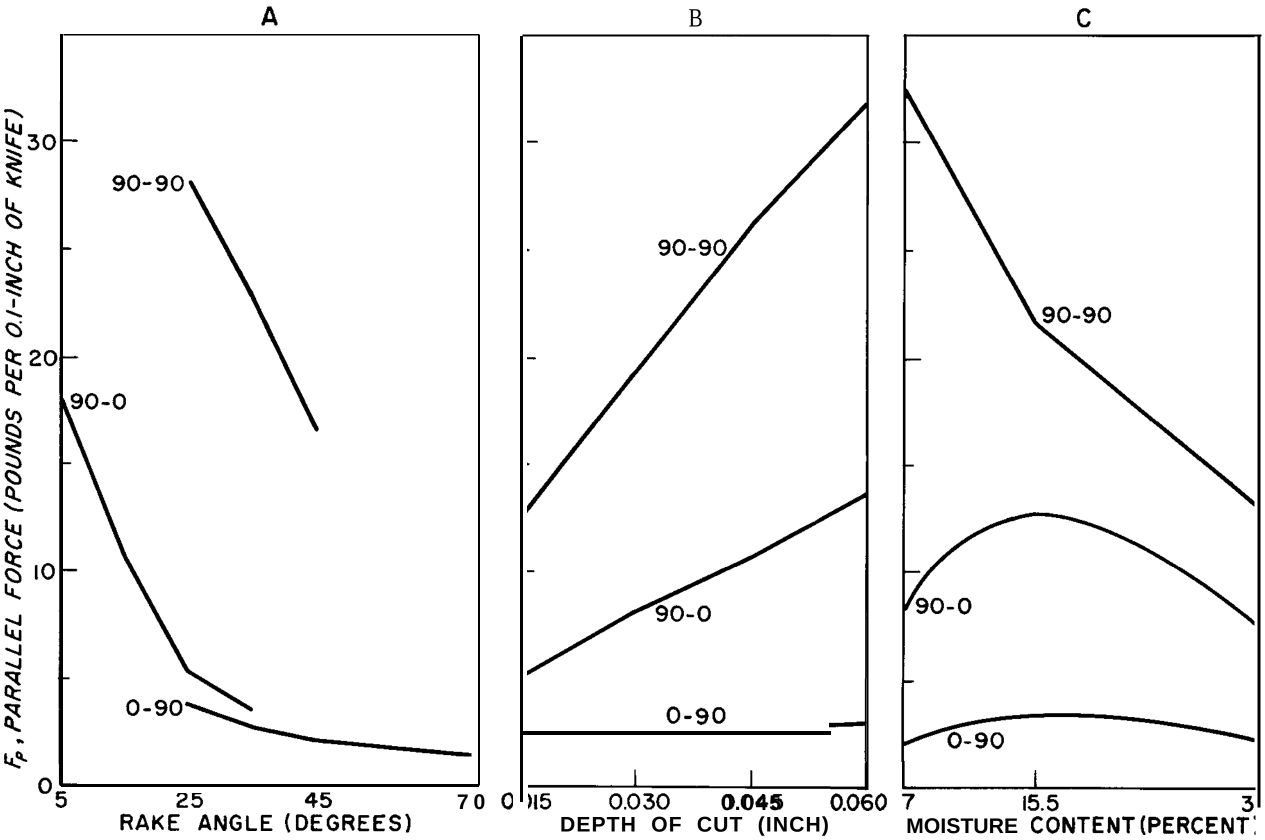


Figure 10. -*Effect* ***of rake angle, depth of cut, and moisture content on average parallel cutting force. For these curves, data were pooled for both earlywood and*** *latewood* ***at a range of rake angles, three moisture contents (saturated, 15.5, and 7 percent), and four depths of cut (0.015, 0,030, 0.045, and 0.060 inch).***

this curve with a straight-line function of t that can be expressed:

$$F_p = (A+Bt)w \qquad (2)$$

if constants A and B are suitably chosen.

In some situations the experimentally determined parallel cutting force defined by equation 1 holds for the entire practical range of chip thicknesses. In other situations, the curve straightens beyond a certain chip thickness and continues linearly as described by equation 2.

If the data on parallel cutting force (tables 4 and 5) are averaged for both earlywood and latewood over all moisture contents and all rake angles, the resultant curves can be approximated by straight lines (fig. 10b). Figure 7 shows in more detail how cutting forces are related to chip thickness.

Effects of wood factors.-The specimens were cut on the radial face (fig. 1, 90-O direction) and it was observed that most Type I chips failed in planes of weakness at ray locations. Had the specimens been machined on the tangential face, i.e., perpendicular to the rays, fewer Type I failures might have developed at the 25° rake angle.

Averaged over all rake angles, all depths of cut, and all moisture contents, latewood required much more cutting force per O.l-inch width than earlywood:

Cell type	Specific gravity	F_p	F_n
		— — ***Pounds*** — —	
Latewood	0.85	12.5	0.5
Earlywood	.34	6.5	.3

Table 4.–*Parallel* ***tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine latewood parallel to the grain in the 90-O direction*** [1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	5		15		25		35	
	Pounds							
0.015 inch								
7	14.4	(26.6)	7.6	(22.5)	3.0	(16.7)	3.3	(11.3)
15.5	13.0	(17.1)	11.1	(15.7)	6.3	(11.0)	4.0	(6.4)
Saturated	7.4	(11.1)	5.0	(7.8)	3.0	(5.3)	2.4	(3.7)
0.030 inch								
7	23.9	(49.2)	7.1	(39.9)	4.1	(22.3)	4.4	(15.7)
15.5	25.0	(32.7)	17.5	(28.7)	9.9	(16.9)	6.4	(10.3)
Saturated	14.8	(19.2)	9.6	(13.9)	5.0	(8.1)	3.5	(6.5)
0.045 inch								
7	24.4	(62.4)	8.8	(46.0)	4.5	(31.6)	4.8	(16.6)
15.5	36.1	(46.0)	28.8	(38.0)	11.8	(26.2)	7.1	(12.9)
Saturated	22.3	(28.0)	11.5	(19.5)	5.9	(10.7)	4.2	(7.8)
0.060 inch								
7	33.2	(87.3)	10.3	(52.6)	6.0	(31.0)	5.2	(21.6)
15.5	44.8	(57.6)	35.5	(51.8)	16.3	(34.9)	9.2	(15.3)
Saturated	29.6	(35.8)	17.3	(27.9)	7.1	(14.5)	4.7	(7.9)

[1] The first number in each entry is the average cutting force; the number following in parentheses is the average of the maximum forces observed in the five replications.

[2] Clearance angle 15°; cutting velocity 2 inches per minute.

Table S.-***Parallel tool forces per 0.1 inch of knife when*** *orthogonally* ***cutting loblolly pine earlywood parallel to the grain in the 90-O direction*** [1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	5		15		25		35	
	Pounds							
0.015 inch								
7	7.3	(10.6)	5.8	(9.2)	2.0	(6.2)	1.3	(5.2)
15.5	5.5	(7.4)	4.9	(6.2)	3.7	(5.3)	2.5	(3.5)
Saturated	3.8	(5.2)	2.9	(4-O)	2.0	(3.0)	1.6	(2-4)
0.030 inch								
7	14.2	(18.8)	5.9	(16.5)	1.8	(9.8)	1.8	(7.3)
15.5	10.0	(12.6)	9.3	(11.1)	5.7	(8.4)	3.5	(5.8)
Saturated	6.6	(8.7)	5.0	(6.3)	2.9	(4.5)	2.2	(3.8)
0.045 inch								
7	18.5	(25.8)	3.7	(20.6)	2.0	(10.9)	2.2	(9-1)
15.5	14.0	(16.9)	13.6	(15.7)	6.9	(11.9)	3.6	(8.5)
Saturated	9.7	(11.9)	7.4	(9.5)	3.8	(5.7)	2.6	(4.3)
0.060 inch								
7	23.4	(33.9)	5.2	(25.7)	2.2	(13.4)	1.9	(10.9)
15.5	18.3	(22.7)	17.5	(20.2)	8.5	(14.5)	3.6	(10.7)
Saturated	12.4	(14.5)	9.3	(11.5)	4.3	(7.1)	2.9	(5.3)

[1] The first number in each entry is the average cutting force; the number following in parentheses is the average of the maximum forces observed in the five replications.

[2] Clearance angle 15°; cutting velocity 2 inches per minute.

Table *6.-Normal tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine latewood parallel to the grain in the 90-O direction* [1,2,3]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	5		15		25		35	
				Pounds				
0.015 inch								
7	**2.8**	**(0.4** to 5.6)	0.8	(-0.3 to 2.5)	-0.3	(-1.8 to 0.5)	-0.5	(-2.5 to **0.4)**
15.5	3.1	(1.6 to 4.5)	1.3	(–.4 to 2.6)	–.3	(-1.0 to .5)	–.6	**(-1.3** to .1)
Saturated	1.3	(.5 to 2.5)	.3	(–.4 to 1.1)	–.3	(–.8 to .4)	–.4	(-1.0 to .2)
0.030 inch								
7	2.9	(.4 to 6.1)	.7	(-1.1 to 2.7)	–.4	(-3.2 to .7)	–.7	(-3.9 to .4)
15.5	4.6	(2.6 to 7.7)	1.4	(–.2 to 3.0)	–.9	(-2.3 to .1)	–1.2	**(-2.2** to –.2)
Saturated	1.6	(.6 to 2.9)	.0	(-1.0 to 1.1)	–.8	(-1.7 to .0)	-1 .o	**(-2.0** to .1)
0.045 inch								
7	**3.0**	(.6 to 7.7)	.4	(-1.8 to 2.5)	–.6	(-4.7 to .7)	–.9	(-4.3 to .5)
15.5	6.7	(4.7 to 9.6)	1.4	(–.7 to 3.1)	-1.3	(-3.2 to .0)	-1.5	(-3.1 to –.3)
Saturated	1.8	(.8 to 3.4)	–.4	(-1.8 to .5)	-1.0	(-2.2 to .0)	-1.3	(-2.8 to .O)
0.060 inch								
7	3.4	(.5 to 9.1)	.4	(-2.0 to 2.3)	–.8	(-5.6 to .6)	–.9	(-5.9 to .4)
15.5	7.0	(3.8 to 11.1)	1.7	(–.7 to 4.1)	-1.8	(-4.4 to .0)	–2.4	**(-4.1** to –.6)
Saturated	2.0	(.6 to 3.7)	–.4	(-1.7 to .7)	-1.3	(-3.2 to –.1)	-1.4	(-3.1 to –.1)

[1] The first number in each entry is the average cutting force. the numbers following in parentheses are minimum and maximum forcer (average of five replications).
[2] Clearance angle IS" cutting velocity 2 inches per minute
[3] A negative normal force means that the knife tended to lift the workpiece: force was positive when the knife tended to push the workpiece away.

Table *7.-Normal tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine earlywood parallel to the grain in the 90-O direction* [1,2,3]

Depth of cut and moisture content (percent)	**Rake angle, degrees**							
	5		**15**		***25***		***35***	
				Pounds				
0.0 15 inch								
7	1.1	(0.4 to 1.9)	0.3	(-0.1 to **0.9)**	**-0.2**	(-0.9 to 0.4)	-0.2	(-1.3 to 0.2)
15.5	1.7	(.7 to 2.7)	.6	(.1 to **1.4)**	**.o**	(–.4 to .3)	–.3	(–.7 to .0)
Saturated	1.2	(.5 to 2.1)	.5	(.1 to 1.0)	–.1	(–.4 to .3)	–.2	(–.5 to .2)
0.030 inch								
7	**1.4**	(.3 to 2.6)	.4	(–.6 to 1.1)	–.3	(-1.7 to .4)	*–.3*	**(-2.3** to .2)
15.5	**2.3**	**(1.1** to 4.1)	.7	(.3 to 1.3)	–.3	(-1.0 to .3)	*–.6*	**(-1.5** to .0)
Saturated	1.1	(.7 to 2.2)	.2	(–.1 to .7)	–.4	(–.7 to .0)	*–.6*	(-1.1 to –.1)
0.045 inch								
7	1.6	(.4 to 3.0)	.2	(-1.2 to 1.2)	–.3	(-2.2 to .4)	*–.4*	(-3.1 to .2)
15.5	2.9	(1.8 to 4.6)	.6	(.1 to 1.3)	–.6	(-1.7 to .2)	*–.8*	(-2.3 to .1)
Saturated	1.6	(1.0 to2.9)	.1	(–.3 to .6)	–.5	(-1.0 to .1)	*–.8*	(-1.5 to –.2)
0.060 inch								
7	1.6	(.4 to 3.5)	.4	(-1.6 to 1.4)	–.3	(-2.9 to .3)	*–.4*	(-3.6 to .3)
15.5	3.3	(1.8 to 5.1)	.6	(.0 to 1.5)	–.7	(-2.4 to .2)	*–.8*	(-2.9 to .2)
Saturated	1.5	(.9 to 2.2)	–.1	(–.5 to .7)	–.7	(-1.5 to .1)	*–.9*	(-2.0 to .1)

[1] The first number in each entry is the average cutting force: the numbers following in parentheses are minimum and maximum forces (average of five replications)
[2] Clearance angle 15°; cutting velocity 2 inches per minute.
[3] A negative normal force means that the knife tended to lift the workpiece; force was positive when the knife tended to push the workpiece away.

Maximum parallel cutting force per 0.1-inch of width was inversely proportional to moisture content when averaged over all rake angles, all depths of cut, and both cell types:

Moisture content (percent)	F_p
	Lbs.
7	***24.6***
15.5	18.8
Saturated	10.5

Average parallel cutting force was positively correlated with moisture content when cutting in the 90-O direction at the lower moisture contents (fig. 10c, tables 4 and 5). When dry wood is cut, the forming chip fails as a cantilever beam and there are intervals when no force is required; hence the average is low even though the maximum force is high.

To summarize the effects of the principal factors in 90-O cutting, earlywood and latewood data were pooled and multiple regression equations were developed to relate depth of cut (inch), rake angle (degrees), moisture content (decimal fraction of ovendry weight), and specific gravity (ovendry volume and weight) to average parallel (F_p) and normal (Fn) cutting forces (pounds) per 0.1 -inch width of specimen.

$$F_p = -6.996 + 2{,}178.193\left[\frac{\text{(specific gravity)(depth of cut)}}{\sqrt{\text{rake angle}}}\right] - 274.182\,\text{(specific gravity)(depth of cut)} - 409.777\,\text{(moisture content)}^2 + 147.362\,\text{(moisture content)} \quad (3)$$

Within the stated limits of the factors, equation 3 accounted for 75 percent of the variation with a standard error of the estimate of 4.7 pounds.

$$F_n = -0.659 - 6.610\,\text{(moisture content)}^2 + 4.751\left[\frac{1}{\sqrt{\text{rake angle}}}\right] - 87.518\,\text{(specific gravity)(depth of cut)} + 336.975\left[\frac{\text{(specific gravity)(depth of cut)}}{\sqrt{\text{rake angle}}}\right] \quad (4)$$

Equation 4 accounted for 71 percent of the variation with a standard error of the estimate of 0.93 pound.

PERPENDICULAR TO GRAIN: O-90 DIRECTION

In commercial practice, veneer is cut in the O-90 direction from heated logs with a knife having a rake angle of approximately 70° and a clearance angle of close to 0°. The knife is used in conjunction with a nosebar to compress the wood ahead of the cutting edge. The compression reduces the severity of checks in the forming veneer. This paper reports on orthogonal cutting of room-temperature wood without a nosebar and at a variety of rake angles.

Chip formation.-For O-90 cutting, McMillin (1958) has accounted for the formation of various chip types in terms of the mechanical properties of the wood; the explanation will not be duplicated here.

As defined by Leney (1960), continuous veneer is formed in an unbroken sheet in which the original wood structure is essentially unchanged by the cutting process. With a suitably sharp knife, and a thin cut, this can be accomplished so that the veneer has relatively unbroken surfaces on both sides (fig. 11).

Following initial incision, the cells above the cutting edge move upward along the face of the knife. They are restrained by the wood above them and therefore are compressed. As the compression increases, a force normal to the knife face is developed, together with a frictional force along the face of the knife. As the cut proceeds, the forces reach a maximum when the veneer begins to rotate or bend as a cantilever beam. This bending creates a zone of maximum tension above the cutting edge and causes compression on the top or face of the forming veneer.

As depth of cut is increased, rake angle decreased, or cutting edge dulled, critical zones of stress develop, as depicted in figure 12. In Zone 1 maximum tension due to bending develops close to the cutting edge and at right angles to the long axis of the zone as drawn; failure occurs as a tension check. In Zone 2 the frictional force along the face of the knife may create a more or less horizontal shear plane between the compressed cells at the knife-chip interface and the resisting wood above them. In Zone 3 the cutting edge deflects the wood elements into a slight bulge preceding the edge, and the somewhat compacted cell walls may eventually fail in tension either above or below the cutting plane (compression tearing).

In this study compression tearing was prominent in earlywood when rake angles were between 25 and 70°. The degree of tearing ranged from moderate (fig. 13a) to severe (fig. 13c); in the latter case, the earlywood was simply pushed off the underlying latewood.

With rake angles of 45° and lower, latewood failed as a cantilever beam at all moisture contents (fig. 14). The knife with 70° rake and 0° clearance cut continuous veneer from saturated latewood with only an occasional failure as a cantilever beam (fig. 1 lc). With all knives (rake angles 25, 35, 45, and 709 both earlywood and latewood developed deep tension checks when cut at 7-percent moisture content (figs. 14,15).

The knife with 70° rake cut the best veneer; saturated wood yielded the highest proportion of continuous veneer, although there was some compression tearing in earlywood. Generally, tension checks occurred when veneer was cut from wood dried to a mositure content of 15.5 or 7 percent. In studying figures 11, 13, 14, 15,

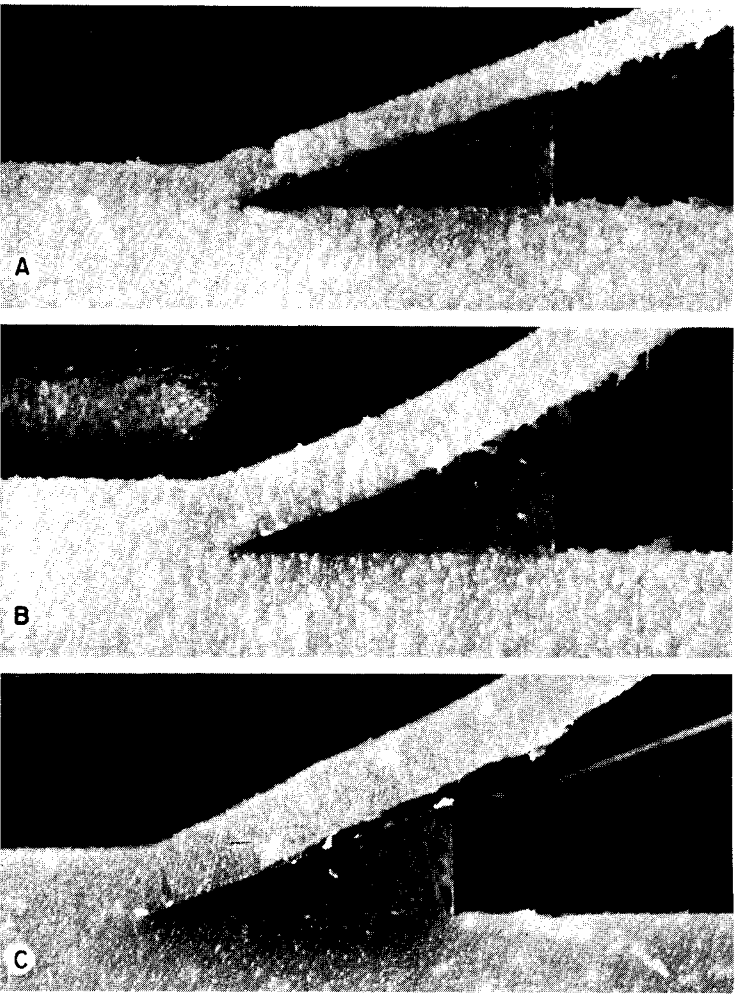


Figure 1 1.—*Continuous **veneer cut from saturated** lob-lolly **pine in*** O-90 ***direction;*** *70°* ***rake angle and*** *20°* ***sharpness angle (zero clearance angle).***

A. ***Earlywood,*** *0.030-inch* ***cut.***

B. Earlywood, *0.060-inch* ***cut.***

C. Latewood, *0.060-inch* ***cut.***

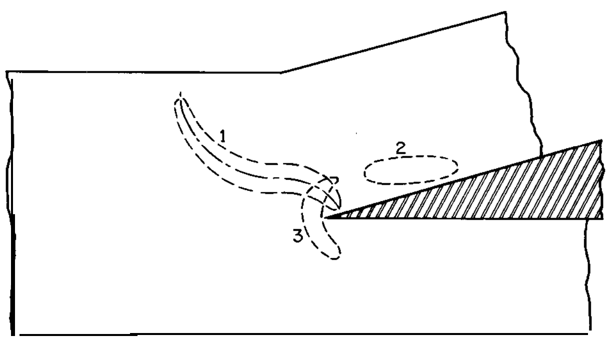


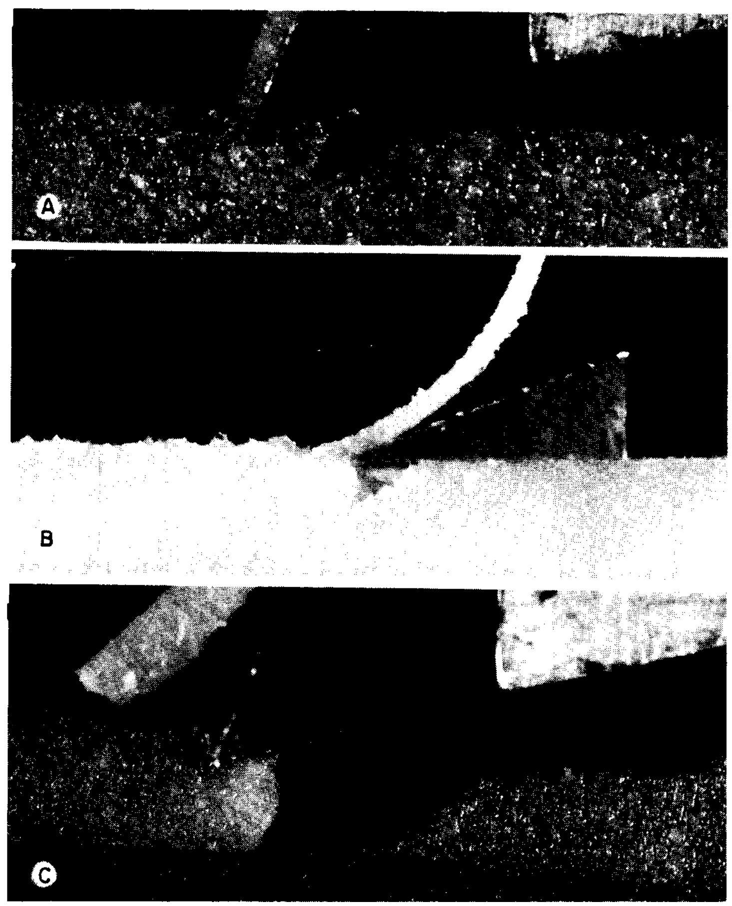
Figure ***12.-Critical zones of stress in veneer cutting without a** nosebar: **(1) tension, (2) shear, (3) compression tearing.***

Figure 13.—*Compression* ***tearing in veneer cut in the O-90 direction from saturated loblolly pine earlywood.***

A. ***Rake angle** 25°**, depth of cut 0.030 inch.***

B. ***Rake angle** 70°**, depth of cut 0.015 inch.***

C. Rake angle** 25°**, depth of cut 0.045 inch.



it should be remembered that the specimens were very narrow and that chip formation in wide specimens of mixed earlywood and latewood might develop somewhat differently.

Cutting forces.-Cutting forces were strongly affected by cell type, moisture content, depth of cut, and rake angle (table 8).

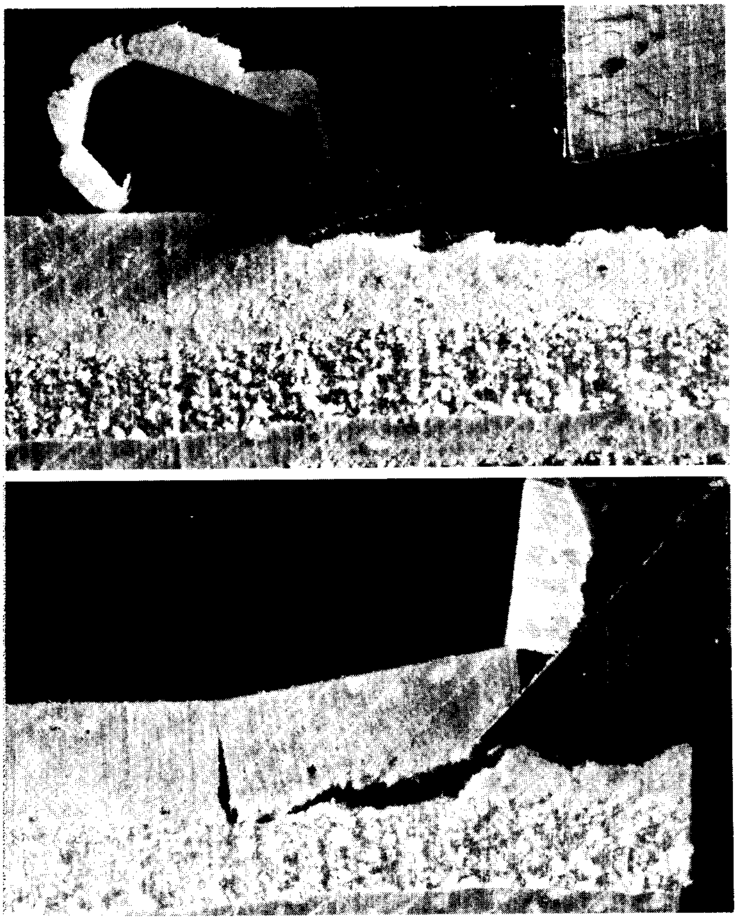


Figure 14.–*Veneer* ***fails as a cantilever beam when cut in O-90 direction from loblolly pine*** *latewood* ***at*** *7-percent* ***moisture content with a rake angle of*** *45°* ***and clearance angle of*** *15°*. ***Veneer is*** *0.030-inch* ***thick in top photo and 0.045 in bottom***

Figure 15.–*Tension* ***checks in*** *0.060-inch* ***veneer cut in O-90 direction from loblolly pine earlywood at 7 percent moisture content. Rake angle*** *70°*. ***Sharpness angle*** *20°*.

Table ***8.-Average tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine veneer in the O-90 direction***

Factor	Parallel force	Normal force[1]
	– – *Pounds* – –	
Cell type		
Earlywood	2.6	0.1
Latewood	2.7	–.8
Moisture content, percent		
7	2.2	–.5
15.5	3.5	–.4
Saturated	2.2	–.2
Depth of cut, inch		
0.015	2.2	–.1
.030	2.5	–.3
.045	2.7	–.4
.060	3.0	–.6
Rake angle, degrees[2]		
25	3.9	.1
35	2.8	–.3
45	2.2	–.6
70	1.6	–.6

[1] A negative normal force means that the knife tended to lift the workpiece; force was positive when the knife tended to push the workpiece away

[2] Clearance angle 15°, except that knife with 70° rake had zero clearance

Moisture content was negatively correlated with maximum parallel cutting force per O.l-inch of width (but not with maximum normal force) when averaged over all rake angles, all depths of cut, and both cell types.

Moisture content (percent)	F_p
	Lbs.
7	*9.8*
15.5	*8.2*
Saturated	4.7

Average parallel cutting force, however, was relatively independent of moisture content when data on all rake angles, all depths of cut, and both cell types were pooled (fig. 10c, O-90). Figure 16 and tables 9 and 10 give a more detailed view of the interactions with moisture content. When veneer is cut from dry wood, the forming chip fails as a cantilever beam and there are intervals when no force is required; hence the average is low. In wet wood, however, continuous veneer is formed and the average parallel force is high.

Table 9.-*Parallel tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine latewood veneer in the O-90 direction*[1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	25		35		45		70	
	Pounds							
0.015 inch								
7	2.9	(14.7)	2.0	(12.3)	2.1	(8.8)	2.0	(4.3)
15.5	4.3	(8.7)	4.0	(6.6)	2.9	(4.7)	2.3	(3.7)
Saturated	2.3	(4.5)	2.1	(3.6)	1.7	(2.8)	1.4	(1.9)
0.030 inch								
7	3.0	(20.7)	2.5	(15.2)	1.8	(11.4)	2.0	(5.0)
15.5	5.9	(14.8)	3.9	(10.0)	2.3	(7.2)	2.4	(5.0)
Saturated	2.6	(6.9)	2.3	(6.1)	1.6	(4.1)	1.5	(2.5)
0.045 inch								
7	3.1	(25.6)	1.9	(16.1)	2.2	(15.9)	1.7	(5.3)
15.5	5.5	(17.7)	3.9	(14.8)	2.5	(9.2)	2.3	(5.6)
Saturated	3.5	(10.0)	2.2	(7.8)	1.5	(5.9)	1.6	(2.9)
0.060 inch								
7	2.6	(26.9)	1.7	(18.2)	2.8	(17.9)	1.5	(5.3)
15.5	6.6	(21.5)	4.0	(16.3)	3.3	(11.7)	2.9	(7.1)
Saturated	3.7	(12.7)	2.7	(10.3)	1.7	(6.8)	1.7	(3.7)

[1] The first number in each entry is the average cutting force; the number following in parentheses is the average of the maximum forces observed in the five replications.

[2] Clearance angle 15°, except that knife with 70° rake had zero clearance. Cutting velocity 2 inches per minute.

Table IO.-*Parallel tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine earlywood veneer in the* O-90 *direction*[1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	25		35		45		70	
	Pounds							
0.015 inch								
7	2.6	(5.5)	2.0	(4.8)	1.7	(4.1)	1.0	(1.8)
15.5	3.3	(5.1)	2.8	(4.1)	1.8	(3.7)	1.0	(1.9)
Saturated	2.2	(2.9)	1.8	(2.6)	1.5	(2.2)	1.3	(1.9)
0.030 inch								
7	3.4	(8.2)	1.9	(6.3)	1.9	(5.6)	1.1	(2.2)
15.5	4.7	(6.8)	3.6	(6.7)	2.5	(5.6)	1.4	(2.8)
Saturated	3.0	(4.5)	2.2	(3.5)	1.9	(3.2)	1.2	(1.9)
0.045 inch								
7	3.5	(10.1)	2.4	(7.5)	1.8	(6.0)	1.1	(2.2)
15.5	6.7	(10.1)	4.9	(8.8)	2.5	(6.1)	1.6	(3.0)
Saturated	3.6	(5.4)	2.6	(4.7)	2.1	(3.8)	1.2	(1.9)
0.060 inch								
7	3.4	(9.6)	2.3	(8.1)	2.0	(5.6)	1.1	(2.4)
15.5	7.6	(13.0)	5.1	(10.2)	3.0	(7.0)	1.4	(2.6)
Saturated	4.0	(6.0)	3.3	(5.5)	2.8	(4.7)	1.3	(2.0)

[1] The first number in each entry is the average cutting force; the number following in parentheses is the average of the maximum forces observed in the five replications.

[2] Clearance angle 15°, except that knife with 70° rake had zero clearance. Cutting velocity 2 inches per minute.

Parallel cutting force was negatively correlated with rake angle. With the rake angles evaluated, the average normal force was always negative in latewood. With earlywood, however, the 25 and 35° rake angles generally caused a positive normal force, i.e., the tool pushed on the workpiece (fig. 16 and tables 11 and 12).

Depth of cut had a relatively small effect on the average parallel cutting force; figure 10b (O-90) shows data averaged over all rake angles, all moisture contents, and both cell types. Figure 16 and tables 9 through 12 show the interactions for both normal and parallel forces.

To summarize the effects of the major factors in O-90 veneer cutting, earlywood and latewood data were pooled and multiple regression equations were developed to relate depth of cut (inch), rake angle (degrees), moisture content (expressed as a decimal fraction), and specific gravity (ovendry volume and weight) to average parallel and normal cutting forces (pounds) per 0. l-inch width of specimen,

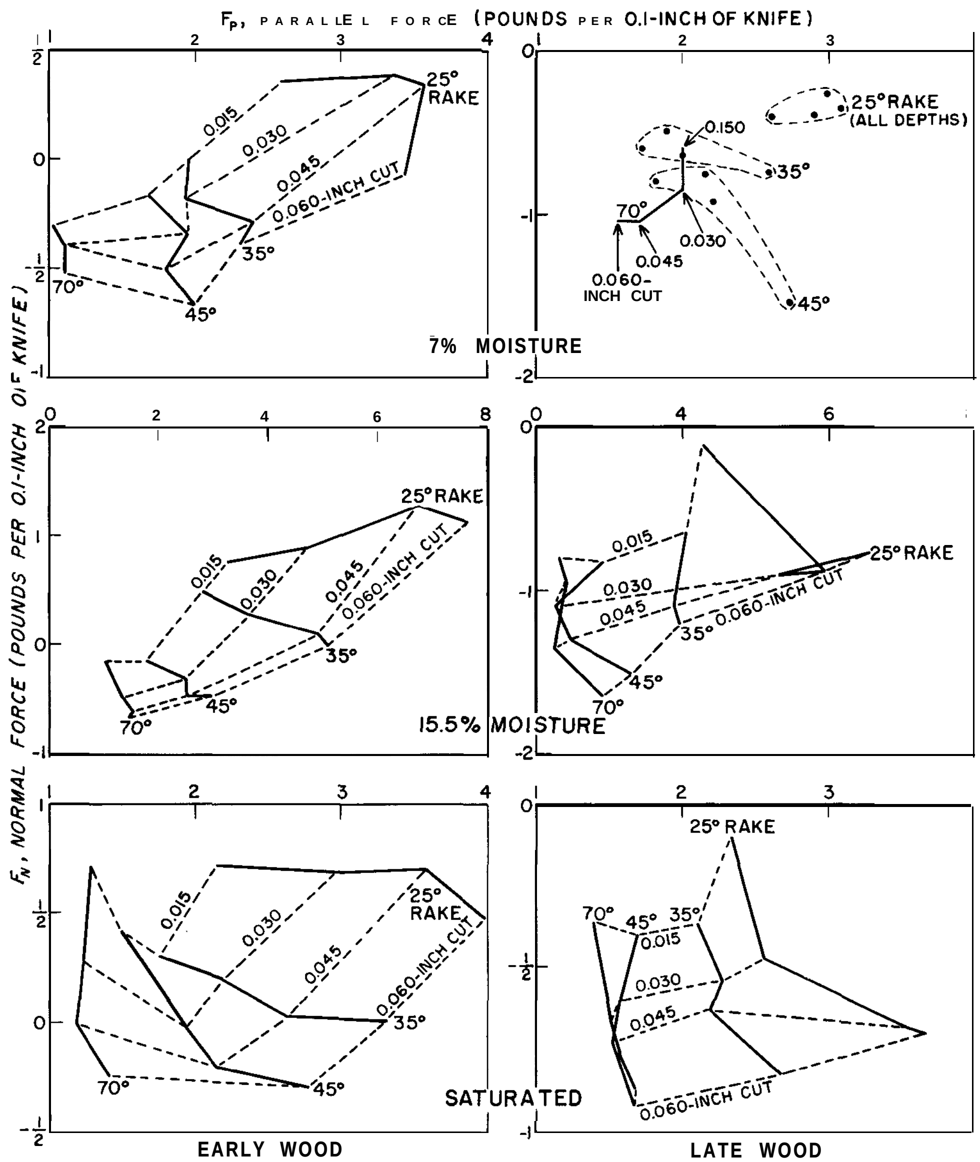


Figure 16.–*Effect* ***of depth of cut, rake angle, and moisture content on average cutting forces for earlywood and latewood of southern pine; O-90 cutting direction, orthogonal, 15° clearance angle, 2 inches per minute cutting velocity.***

Table 11.-Normal tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine latewood veneer in the O-90 direction[1,2,3]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	25		35		45		70	
	Pounds							
0.015 inch								
7	-0.4	(-2.3 to 1.3)	-0.7	(-3.5 to 0.5)	-0.7	(-3.5 to 0.6)	-0.6	(-1.6 to 0.5)
15.5	-.1	(-1.4 to .6)	-.6	(-1.8 to .4)	-.8	(-1.9 to .O)	-.8	(-1.6 to .1)
Saturated	-.1	(-.6 to .4)	-.3	(-1.1 to .3)	-.4	(-1.2 to .4)	-.4	(-.8 to .2)
0.030 inch								
7	-.3	(-4.0 to 1.5)	-.7	(-5.0 to .3)	-.8	(-5.8 to .5)	-.9	(-2.3 to .4)
15.5	-.9	(-3.0 to .8)	-1.0	(-3.1 to .5)	-1.1	(-3.6 to .3)	-.9	(-2.2 to .0)
Saturated	-.5	(-1.5 to .5)	-.5	(-2.2 to .4)	-.6	(-2.2 to .5)	-.7	(-1.5 to .3)
0.045 inch								
7	-.3	(-4.7 to 1.2)	-.5	(-5.4 to .2)	-.9	(-7.0 to .5)	-1.0	(-2.9 to .4)
15.5	-.9	(-3.9 to 1.1)	-1.1	(-5.4 to .3)	-1.3	(-5.5 to .1)	-1.3	(-2.8 to .0)
Saturated	-.7	(-2.3 to .6)	-.6	(-2.9 to .3)	-.7	(-3.4 to .6)	-.8	(-2.0 to .4)
0.060 inch								
7	-.4	(-4.7 to .5)	-.6	(-7.4 to .8)	-1.6	(-9.5 to .6)	-1.0	(-3.4 to .5)
15.5	-.8	(-4.7 to 1.7)	-1.2	(-5.8 to .7)	-1.5	(-6.4 to .2)	-1.6	(-3.3 to .2)
Saturated	-.7	(-3.0 to .5)	-.8	(-4.1 to .3)	-.9	(-3.9 to .4)	-.9	(-2.9 to .6)

[1] The first number in each entry is the average cutting force; the numbers following in parentheses are minimum and maximum forces (average of five replications)
[2] Clearance angle 15°, except that knife with 70° rake had zero clearance. Cutting velocity 2 inches per minute.
[3] A negative normal force means that the knife tended to lift the wood; force was positive when the knife tended to push the workpiece away.

Table 12.-*Normal tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine earlywood veneer in the O-90 direction*[1,2,3]

Depth of cut and moisture content (percent)	Rake angle, degrees							
	25		35		45		70	
	Pounds							
0.015 inch								
7	0.4	(-0.5 to 2.4)	0.0	(-0.5 to 1.3)	-0.2	(-0.9 to 0.6)	-0.3	(-0.7 to 0.2)
15.5	.8	(-.2 to 2.1)	.5	(-.3 to 1.3)	-.1	(-.7 to 1.0)	-.1	(-.5 to .3)
Saturated	.7	(.2 to 1.4)	.3	(-.1 to .9)	-.4	(.0 to 1.1)	-.7	(.2 to 1.2)
0.030 inch								
7	.4	(-.7 to 2.7)	-.2	(-1.0 to 1.4)	-.3	(-1.3 to .8)	-.4	(-1.2 to .2)
15.5	.9	(-.4 to 2.5)	.3	(-.9 to 1.9)	-.3	(-1.3 to .6)	-.5	(-1.0 to .1)
Saturated	.7	(-.1 to 1.9)	.2	(-.3 to 1.0)	-.1	(-.4 to .8)	-.3	(-.1 to .7)
0.045 inch								
7	.3	(-1.1 to 2.5)	-.3	(-1.4 to 1.0)	-.5	(-2.1 to .6)	-.4	(-1.6 to .4)
15.5	1.3	(-.5 to 3.6)	.1	(-1.4 to 2.6)	-.5	(-1.6 to .3)	-.6	(-1.3 to .2)
Saturated	.7	(.O to 1.8)	.0	(-.7 to .9)	-.2	(-.7 to .5)	.o	(-.4 to .6)
0.060 inch								
7	-.1	(-1.4 to 1.9)	-.4	(-2.0 to .9)	-.7	(-2.6 to .7)	-.5	(-1.8 to .5)
15.5	1.1	(-1.0 to4.3)	.o	(-1.9 to 2.3)	-.4	(-2.0 to .7)	-.6	(-1.4 to .1)
Saturated	.5	(-.4 to 1.7)	.o	(-.7 to .8)	-.3	(-.8 to .6)	-.2	(-.6 to .3)

[1] The first number in each entry is the average cutting force; the numbers following in parentheses are minimum and maximum forces (average of five replications).
[2] Clearance angle 15°, except that knife with 70° rake had zero clearance. Cutting velocity 2 inches per minute.
[3] A negative normal force means that the knife tended to lift the wood; force was positive when the knife tended to push the workpiece away.

$$F_p = -5.902 + 63.565\left(\frac{1}{\text{rake angle}}\right) + 747.561\left(\frac{\text{depth of cut}}{\text{rake angle}}\right) - 0.0338\left(\frac{1}{\text{moisture content}^2}\right) + 3.318\left(\frac{1}{\sqrt{\text{moisture content}}}\right) \quad (5)$$

Equation 5 accounts for 64 percent of the variation with a standard error of the estimate of 0.85 pound.

$$F_n = -2.241 - 3.572\left(\sqrt{\text{depth of cut}}\right) + 694.063\left(\frac{1}{\text{rake angle}^2}\right) + 1.296\left(\frac{1}{\sqrt{\text{specific gravity}}}\right) + 0.0305\,(\text{moisture content})(\text{rake angle}) \quad (6)$$

Equation 6 accounts for 69 percent of the variation with a standard error of the estimate of 0.36 pound.

Tool forces when cutting in the O-90 direction are influenced by the strength of wood in tension perpendicular to the grain, shear perpendicular to the grain, and compression perpendicular to the grain. Because wood is relatively weak when so stressed, tool forces are substantially less in this mode than in the 90-O or 90-90 directions.

PERPENDICULAR TO GRAIN: 90-90 DIRECTION

McKenzie (196 1) recognized two chip types when cutting a variety of softwoods and hardwoods perpendicular to the grain. The same general types were observed in this study of loblolly pine. Average cutting forces are relatively constant during formation of Type I chips. Below the cutting plane, splits occur parallel to the grain. The splits may be minute and virtually invisible, in which case the surface is quite good (fig. 17a), or they may be fairly frequent and deep, in which case the surface is poor (fig. 17c). Each subchip above the cutting plane is formed by shear along the grain.

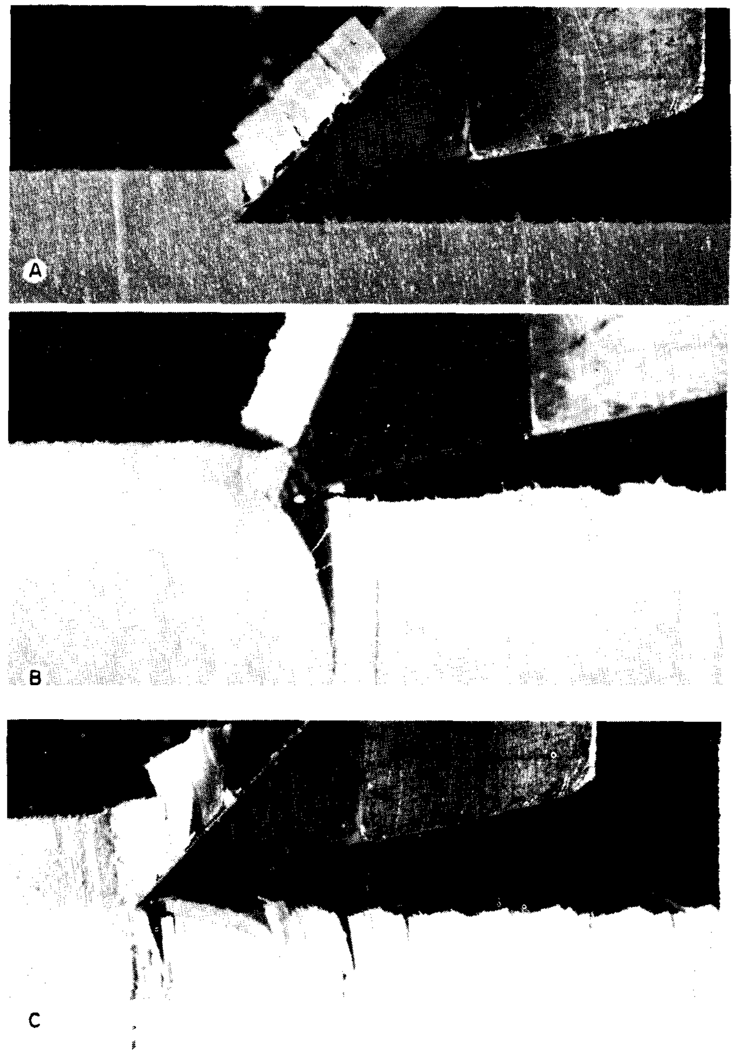


Figure 17.-*McKenzie Type I chips formed when orthogonally cutting 0.060-inch deep across the grain of loblolly pine in the 90-90 direction.*
A. *Latewood, saturated, rake angle 45°.*
B. *Earlywood, saturated, rake angle 25°.*
C. *Latewood at 7-percent moisture content, rake angle 45°.*

Cyclic variation of average cutting forces with successive cuts is usual when Type II chips are *formed. Failures occur perpendicular to the grain and at a variable distance below the cutting plane (fig. 18). After the initial cut, therefore, the knife edge may not be engaged in all portions of its path. The mechanics of these two chip formations are explained in McKenzie (1961) or Koch (1964, pp. 93-109).

Type I chips and good surfaces can be achieved by cutting the wood at relatively high

Figure 18.—*McKenzie* ***Type II chips formed when orthogonally cutting loblolly pine earlywood of 7-percent moisture content across the grain in the 90-90 direction.***
A. ***Rake angle*** *45°, 0.060-inch* ***cut.***
B. Rake angle *25°, 0.045-inch* ***cut.***

moisture content with a very sharp knife having a high rake angle, e.g., 45° (fig. 17a). Although supporting data are not at hand, it is probable that high cutting velocities, e.g., 10,000 feet per minute, are conducive to formation of Type I chips. Figure 19 suggests the idea that a high-velocity cutter might be resisted by the inertia of the fibers, and therefore could accomplish clean severance and a Type I chip. It is more difficult to cut a Type I chip in earlywood than in latewood, particularly in wood of low moisture content. Type II chips are most frequent in wood of low moisture content (table 13).

Cutting *forces.*—Cutting forces were strongly affected by cell type, moisture content, depth of cut, and rake angle (table 14).

When averaged over all rake angles, all depths of cut, and both cell types, maximum cutting forces per 0.1 inch of specimen width were negatively correlated with wood moisture content.

Table 13.—*Typical* ***chip types when orthogonally cutting loblolly pine across the grain in the 90-90 direction***[1]

Moisture content and rake angle (degrees)	Chip type[2]	
	In earlywood	In latewood
Saturated		
25	I	I
3.5	I	I
45	I	I
15.5 percent		
25	II (I)	I
35	II	I
45	II (I)	I
7 percent		
25	II	II (I)
35	II	II (I)
45	II	II (I)

[1]Depths of cut ranged from 0.015 to 0.060 inch. Cutting velocity was 2 inches per minute, clearance angle 15°.
[2]The first number in each entry is major chip type as classified by McKenzie (1961); a second number in parentheses indicates that a combination of chip types was observed.

Table 14.—*Average* ***tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine across the grain in the 90-90 direction***

Factor	Parallel force	Normal force[1]
	- - - Pounds - - -	
Cell type		
Earlywood	11.4	2.4
Latewood	33.6	-8.8
Moisture content, percent		
7	32.5	-2.1
15.5	21.9	-3.6
Saturated	13.1	-3.9
Depth of cut, inch		
0.015	12.4	-1.3
.030	19.5	-2.5
.045	26.2	-3.7
.060	31.9	-5.3
Rake angle, degrees[2]		
25	28.2	—.7
35	22.8	-3.6
45	16.6	-5.4

[1]A negative normal force means that the knife tended to lift the workpiece; force war positive when the knife tended to push the workpiece away
[2]All knives had a 15° clearance angle. cutting velocity 2 inches per minute

Moisture content (percent)	F_p	F_n
	Lbs.	*Lbs.*
7	43.3	6.8
15.5	29.0	1.6
Saturated	16.6	-1.7

Average cutting forces displayed a similar negative correlation. Figure 20 and tables 15 through 18 give a detailed view of interactions with moisture content. From figure 20 it is seen that the normal force was positive only in dry earlywood.

Rake angle was negatively correlated with parallel (tables 15 and 16) and normal tool forces (tables 14, 17, 18).

Depth of cut had a positive linear correlation with parallel cutting force when data for earlywood and latewood were pooled over all moisture contents and rake angles (fig. 10b). Figure 20 illustrates an interaction; normal force was unaffected by depth of cut only when dry earlywood was cut with a knife having a 45° rake angle.

To summarize the effects of the major factors in 90-90 cutting, earlywood and latewood data were pooled and a multiple regression

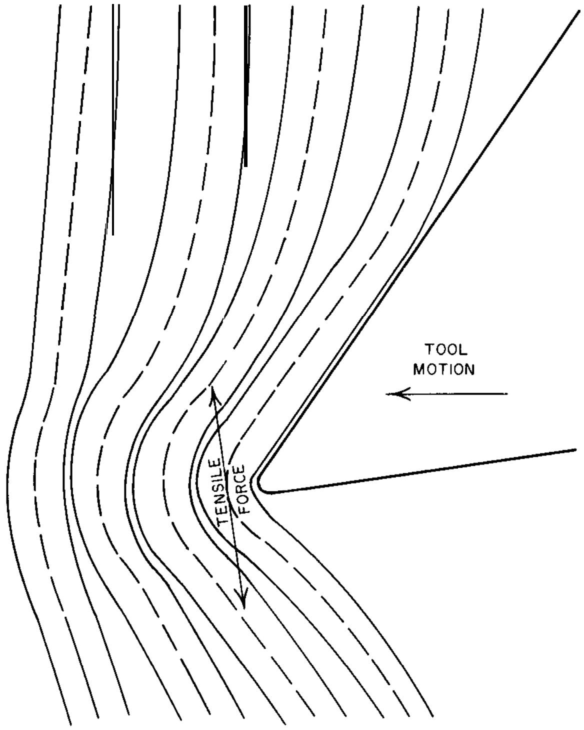


Figure *19.-In the 90-90 mode, failure at the cutting edge is due to tension across the cutting plane.*

Table 15.–*Parallel tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine latewood across the grain in the 90-90 direction*[1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees		
	25	35	45
	Pounds		
0.015 inch			
7	32.4 (42.8)	29.1 (39.6)	21.7 (31.7)
15.5	22.8 (27.7)	18.2 (22.9)	13.5 (17.7)
Saturated	11.8 (14.8)	11.7 (14.3)	6.2 (7.8)
0.030 inch			
7	56.6 (73.5)	42.1 (62.3)	33.6 (51.8)
15.5	37.9 (45.5)	24.5 (32.2)	i7.6 (24.7)
Saturated	20.2 (24.4)	20.4 (24.9)	10.0 (13.5)
0.045 inch			
7	71.9 (81.7)	52.2 (80.5)	46.1 (66.7)
15.5	53.7 (66.0)	33.8 (43.7)	24.3 (34.2)
Saturated	26.3 (31.8)	27.3 (32.4)	14.0 (18.9)
0.060 inch			
7	85.9 (119.7)	65.7 (99.7)	59.1 (87.1)
15.5	68 .O (80.5)	38.4 (53.4)	28 .1 (40.7)
Saturated	31.8 (37.4)	35.6 (42.0)	17.5 (24.1)

[1] The first number in each entry is the average cutting force. the number following in parentheses is the average of the maximum forces observed in the five replications.

[2] Clearance angle 15° cutting velocity 2 inches per minute.

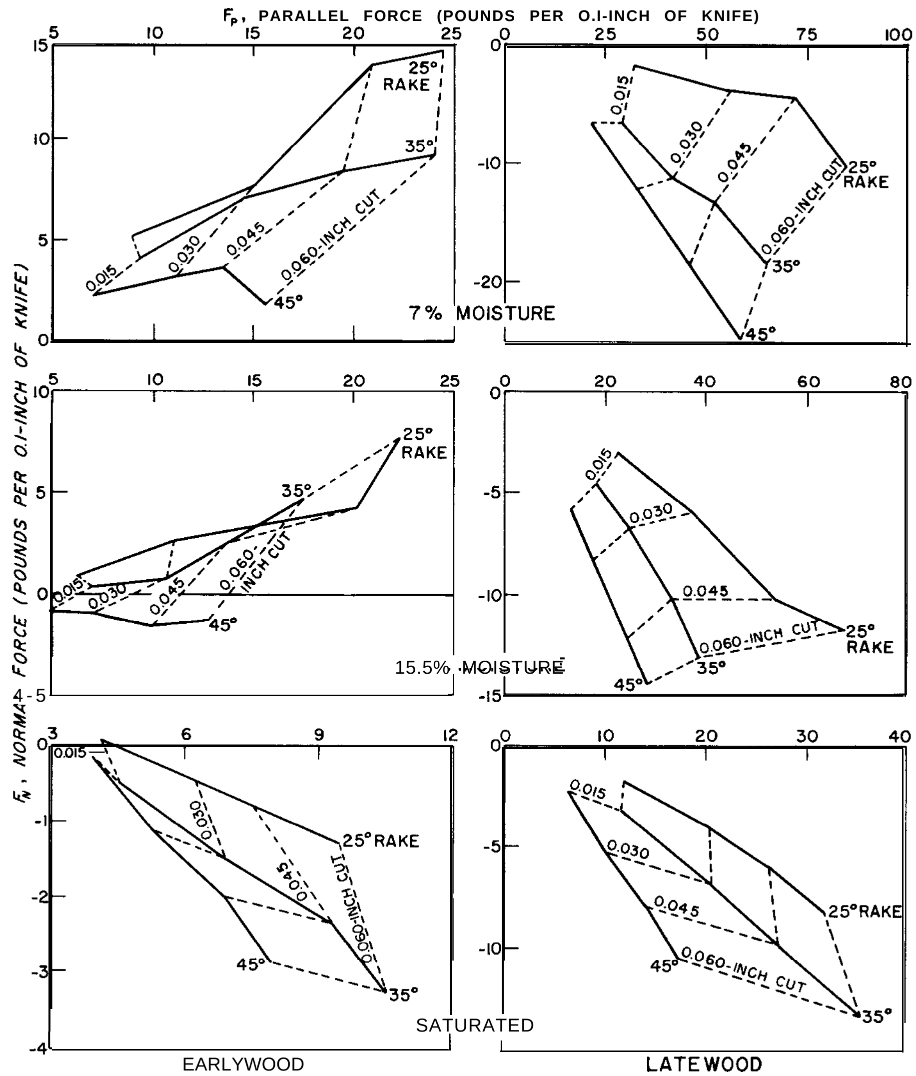


Figure 20.—*Effect* ***of depth of cut, rake angle, and moisture content on average cutting forces for earlywood and latewood of southern pine; 90-90 cutting direction, orthogonal, 15° clearance angle, 2 inches per minute cutting velocity.***

analysis was made to relate depth of cut (inch), rake angle (degrees), moisture content (expressed as a decimal fraction), and specific gravity (ovendry volume and weight) to average parallel and normal cutting forces per 0.1-inch width of specimen.

$$F_p = +1.964 + 561.346\left(\frac{\text{specific gravity}}{\text{rake angle}}\right) + 2{,}650.962\left[\frac{(\text{specific gravity})(\text{depth of cut})}{(\text{rake angle})(\text{moisture content})}\right] \quad (7)$$

Equation 7 accounts for 87 percent of the variation with a standard error of the estimate of 6.8 pounds.

$$F_n = -0.285 - 180.253\,(\text{specific gravity})(\text{depth of cut}) + 6.699\left(\frac{\text{depth of cut}}{\text{moisture content}}\right) \quad 50.615\left[\frac{(\text{specific gravity})(\text{depth of cut})}{\text{moisture content}}\right] + 894.843\left[\frac{\text{depth of cut}}{(\text{moisture content})(\text{rake angle})}\right] \quad (8)$$

Equation 8 accounts for 82 percent of the variation with a standard error of the estimate of 3.4 pounds.

Table 16.—*Parallel* ***tool force per 0.1 inch of knife when orthogonally cutting loblolly pine earlywood across the grain in the 90-90 direction*** [1,2]

Depth of cut and moisure content (percent)	Rake angle, degrees					
	25		35		45	
	– – *Pounds* – – – – – – – – – –					
0.015 inch						
7	8.9	(11.0)	9.3	(11.9)	7.1	(10.2)
15.5	6.2	(9.7)	7.0	(9.2)	4.9	(7.4)
Saturated	4.1	(5.5)	4.5	(5.5)	4.0	(4.9)
0.030 inch						
7	15.0	(19.5)	14.0	(19.5)	11.0	(14.8)
15.5	11.2	(15.8)	10.8	(14.9)	7.1	(10.6)
Saturated	6.1	(8.2)	6.9	(9.3)	5.3	(6.6)
0.045 inch						
7	21.8	(27.5)	19.6	(27.3)	13.4	(18.6)
15.5	20.3	(25.2)	13.9	(18.8)	9.9	(14.6)
Saturated	7.6	(10.6)	9.3	(13.4)	6.8	(9.2)
0.060 inch						
7	24.4	(34.1)	24.0	(32.5)	15.5	(24.8)
15.5	22.4	(3 1.4)	17.6	(26.9)	12.8	(22.8)
Saturated	9.5	(13.0)	10.6	(15.4)	7.8	(10.8)

[1] The first number in each entry is the average cutting force, the number following in parentheses is the average of the maximum forces observed in the five replications

[2] Clearance angle 15°; cuttmg velocity 2 inches per minute.

Table 17.—*Normal* ***tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine*** *latewood* ***across the grain in the 90-90 direction*** [1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees					
	25		35		45	
	– – – – – – – – – – – – – – – – – – – *Pounds* – – – – – – – – – – – – – – – – – –					
0.015 inch						
7	-1.7	(-6.6 to 3.8)	-6.7	(-12.0 to -1.6)	-6.7	(-12.3 to -1.3)
15.5	-3.1	(-4.9 to –.9)	-4.5	(-6.4 to -1.4)	-5.7	(-8.1 to -2.6)
Saturated	-1.6	(-2.7 to –.5)	-3.1	(-4.2 to -1.4)	-2.3	(-3.6 to -1 .O)
0.030 inch						
7	-3.7	(-11.6 to 4.3)	-11.2	(-19.4 to -2.4)	-12.0	(-20.6 to -2.2)
15.5	-6.0	(-8.6 to -2.9)	-6.7	(-10.3 to -2.5)	-8.4	(-12.2 to -3.0)
Saturated	-3.9	(-5.6 to -2.1)	-6.7	(-8.7 to -3.7)	-5.1	(-7.9 to -2.0)
0.045 inch						
7	-4.4	(-15.5 to 8.7)	-13.2	(-27.8 to -2.2)	-18.4	(-31 .1 to -2.5)
15.5	-10.1	(-13.7 to -4.7)	-10.2	(-14.4 to -3.6)	-12.1	(-16.6 to -3.7)
Saturated	-5.7	(-7.9 to -3.2)	-9.8	(-12.5 to -4.5)	-7.9	(-11.1 to -3.1)
0.060 inch						
7	-10.4	(-24.4 to 1.9)	-18.4	(-35.9 to -4.2)	-25.0	(-40.6 to -4.4)
15.5	-11.7	(-16.1 to -4.5)	-13.0	(-18.7 to -4.4)	-14.5	(-21.9 to -4.7)
Saturated	-8.1	(-10.1 to -4.4)	-13.4	(-16.7 to -7.5)	-10.5	(-14.8 to -3.6)

[1] The first number in each entry is the average cuttmg force. the numbers following in parentheses are minimum and maximum forces (average of five replications)

[2] Clearance angle 15°; cutting velocity 2 inches per minute.

Table 18.–*Normal tool forces per 0.1 inch of knife when orthogonally cutting loblolly pine earlywood across the grain in the 90-90 direction*[1,2]

Depth of cut and moisture content (percent)	Rake angle, degrees					
	25		35		45	
			– – Pounds – – – – – – – – – –			
0.015 inch						
7	5.3	(1.5 to 8.9)	4.1	(0.4 to 7.7)	2.2	(-1 .O to 6.3)
15.5	.8	(–.8 to 2.4)	.4	(-1.3 to 2.3)	–.9	(-2.1 to .4)
Saturated	.0	(–.4 to .6)	–.5	(-1.1 to .1)	–.1	(–.6 to .3)
0.030 inch						
7	8.8	(1.9 to 16.2)	7.4	(.5 to 14.9)	3.0	(-1.6 to 8.4)
15.5	2.7	(-1 .0 to 6.5)	.7	(-3.0 to 4.8)	–.9	(-3.9 to 2.6)
Saturated	–.5	(-1.3 to .3)	-1.5	(-2.6 to –.5)	–1.1	(-1.8 to –.3)
0.045 inch						
7	13.2	(2.7 to 20.7)	8.7	(.3 to 17.1)	3.8	(-2.4 to 10.0)
15.5	4.2	(-2.7 to 10.9)	2.5	(-2.8 to 8.7)	-1.5	(-5.8 to 4.2)
Saturated	–.8	(-1.9 to .2)	-2.4	(-4.2 to .9)	-2.0	(-3.5 to –.6)
0.060 inch						
7	14.6	(2.8 to 28.7)	9.5	(–.2 to 18.7)	1.9	(-4.5 to 8.6)
15.5	7.7	(-1.2 to 18.1)	-4.7	(-3.2 to 13.1)	-1.4	(-6.9 to 4.5)
Saturated	-1.4	(-2.7 to .O)	-3.2	(-5.2 to -1.3)	-2.8	(-4.7 to -1 .1)

[1]The first number in each entry is the average cutting force; the numbers following in parentheses are minimum and maximum forces (average of five replications).
[2]Clearance angle 15°; cutting velocity 2 inches per minute.

FORCE COMPARISON FOR THREE CUTTING DIRECTIONS

Because chip formation when cutting in the 90-90 direction requires wood to be failed in tension parallel to the grain (fig. 19), parallel cutting forces are much higher than in the O-90 and 90-O directions. While the data in table 19 are restricted to a rake angle of 35° and one depth of cut, the trends shown are valid for cuts from 0.015 to 0.060 inch deep and also for a rake angle of 25°.

The data on maximum and minimum cutting forces reveal some figures of interest to machine designers.

In the 90-O (planing) direction, forces were greatest (per O.l-inch of knife) for 0.060-inch cuts in latewood:

F_p was maximum at 87.3 pounds when cutting with 5° rake angle in wood at I-/-percent moisture content

F_n was maximum at 11.1 pounds when cutting with 5° rake angle in wood at 15.5-percent moisture content

F_n was minimum at -5.9 pounds when cutting with 35° rake angle in wood at 7-percent moisture content.

In the O-90 (veneer) direction, forces were greatest (per O.l-inch of knife) when cutting 0.060-inch deep :

F_p was maximum at 26.9 pounds when cutting with 25° rake angle in latewood at 7-percent moisture content

F_n was maximum at 4.3 pounds when cutting with 25° rake angle in early wood at 15.5-percent moisture content

Fn was minimum at -9.5 pounds when cutting with 45° rake angle in latewood at 7-percent moisture content.

In the 90-90 (crosscut) direction, forces (per 0.1-inch of knife) were greatest when cutting 0.060-inch chips at 7-percent moisture content:

FP was maximum at 119.7 pounds when cutting with 25° rake angle in latewood

Fn was maximum at 28.7 pounds when cutting with 25° rake angle in earlywood

Fn was minimum at -40.6 pounds when cutting with 45° rake angle in latewood.

Table 19.–*Average* ***parallel tool force per 0.1 inch of knife where orthogonally cutting*** *loblolly* ***pine in the three*** *major* ***directions*** *with* ***a rake angle of*** *35°*; ***depth of cut 0.030*** *inch*[1]

Moisture content (percent)	Cell type	0-90	90-0	90-90
		Pounds		
7	Earlywood	1.9	1.8	14.0
	Latewood	2.5	4.4	42.1
15.5	Earlywood	3.6	3.5	10.8
	Latewood	3.9	6.4	24.5
Saturated	Earlywood	2.2	2.2	6.9
	Latewood	2.3	3.5	20.4

[1]Clearance angle, 15°; cutting velocity 2 inches per minute.

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