# Moisture Content of Southern Pine as Related To Thrust, Torque, and Chip Formation in Boring

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## Abstract

Holes 3-1/2 inches deep were bored with a 1-inch spur machine bit in southern pine having specific gravity of 0.53 (ovendry weight and volume at 10.4 percent moisture). The bit was rotated at 2,400 rpm and removed chips 0.020 inch thick. For wood moisture contents ranging from ovendry to saturation, thrust was lower when boring along the grain (average 98 pounds) than across the grain (average 138 pounds), while torque was higher when boring along the grain (average 42 inch-pounds) than across the grain (average 33 inch-pounds). For both boring directions, torque and thrust increased with increasing moisture content to a maximum at about 5 to 10 percent, then decreased to a constant value at about the fiber-saturation point. For the type of bit tested, net power at the spindle required to cut 0.020-inch-thick chips at speeds of 2,400 rpm or less should not exceed 2 hp., regardless of boring direction or moisture content; thrust should not exceed 200 pounds. Chip types resembled those obtained in orthogonal cutting.

Wood moisture content affects tool forces and thus the energy consumed in machining. Moisture also interacts with other factors to influence the process of chip formation and, hence, affects the shape and size of the separated particle. While these subjects have been explored for such operations as peripheral milling and sawing, few specific data are available for machine boring (5, pp. 347-358).

In the research reported here, an analysis was made of the relationship of wood moisture content to the thrust force and torque required to machine-bore southern pine (*Pinus* spp.) in the tangential, radial, and longitudinal directions. Limited consideration was also given to certain aspects of chip formation.

## Procedure

A factorial experiment with three replications was designed with variables as follows:

- Direction of boring: tangential, radial, longitudinal.
- Nominal wood moisture content: 0, 3, 6, 10, 15, 30, 50, and 80 percent.

Held constant were:

- Drill type: spur machine bit.
- Drill diameter: 1 inch.
- Spindle speed: 2,400 rpm
- Chip thickness: 0.020 inch (plunge speed of 1.6 inches per second).
- Wood specific gravity: 0.53 (ovendry weight and volume at 10.4 percent moisture content).

The chip thickness and spindle speed are representative of commercial practice. The spur machine bit was selected because it produces holes of good quality in southern pine; geometrical specifications are given in Figure 1.

New bits were used for each replication and each drilling direction. Except that some minor imperfections were corrected by hand honing, bits were put into test as they came from the manufacturer.

Several hundred board feet of rough-sawn southern pine 4 by 4's were kiln-dried to 12 percent moisture content and accurately surfaced on four sides to 3-1/2 by 3-1/2 inches. They were then crosscut to form 3-1/2-inch cubes; only clear, defect-free wood was accepted. The cubes were placed on stickers (with the end grain exposed) in a room maintained at 60 percent relative humidity and 73°F. Fans assured adequate air circulation throughout the stacks until the samples reached constant weight.

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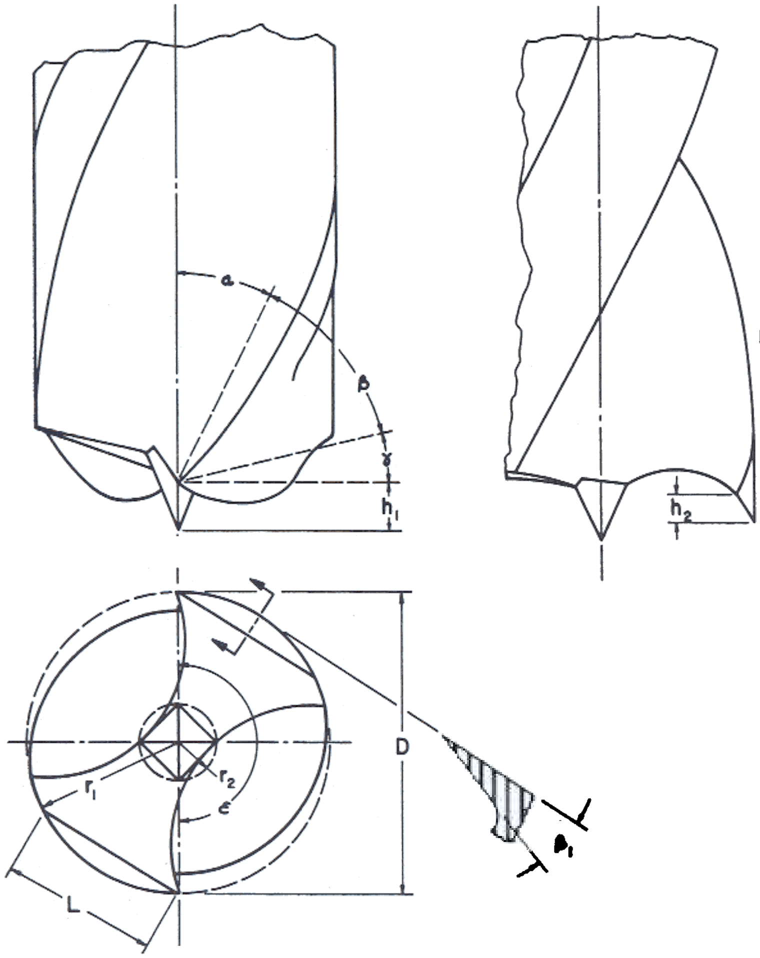


**Figure 1. — Geometrical specifications of spur machine bit.**

$\alpha$ = mean rake angle—20°
$\beta$ = mean sharpness angle—60°
$\beta_1$ = sharpness angle of spurs—35°
$\gamma$ = clearance angle of lips—10°
$\epsilon$ = angle of lead (spur to lip, measured at circumference)—180°
$h_1$ = height of brad—0.20 inch
$h_2$ = height of spur—0.10 inch
L = length of spur at root—0.53 inch
D = bit diameter—1.00 inch
$r_1$ = bit radius—0.50 inch
$r_2$ = radius of brad at root—0.09 inch

From a 2-percent sample of the total population, the average moisture content was 10.4 percent; the standard deviation was 0.55. The average volume per block was 693.80 cc. with a standard deviation of 6.71.

Blocks weighing 410±3 g. (*i.e.,* those with 0.53 specific gravity) were selected from the population and separated into samples suitable for radial, tangential, or longitudinal drilling by visual inspection of the annual ring orientation on the end grain (Fig. 2).

Samples for each of the three directions were randomly assigned to the eight nominal moisture-content classes. Blocks to be bored at zero percent moisture content were ovendried at 212°F.; humidity chambers were used to condition blocks to moisture contents of 3, 6, and 10 percent. Moisture contents of 15, 30, 50, and 80 percent were obtained by enclosing blocks in plastic bags with sufficient water to raise the moisture content to the desired level.

Holes were made with a boring machine especially designed for research. A 5-hp., synchronous-speed, 3,600-rpm, alternating-current motor with timing belt drive assured constant spindle speed (2,400 rpm) while under load. The spindle rotated in a hydraulically operated quill assembly; the desired feed rate of the quill was maintained by a temperature-pressure compensated flow-control valve on the out-flow port. An electronic timer, actuated by a photo-sensitive relay system at the beginning and end of the stroke, was used to set and monitor the feed rate.

Specimens were clamped in a vise attached to a strain-gage dynamometer designed to isolate torque from the thrust force exerted on the workpiece and to measure each separately. The output of the dynamometer was charted on a two-channel oscillographic recorder. The photo-sensitive relay system momentarily actuated an auxiliary

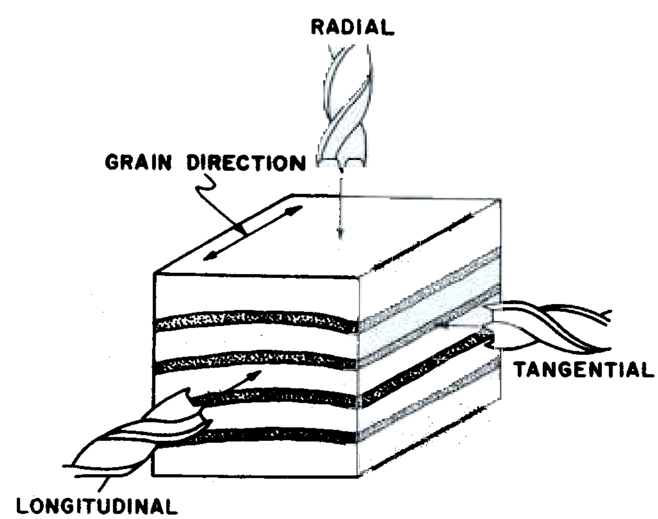


**Figure 2. — Primary boring directions.**

**Table 1 RESULTS OF THRUST, TORQUE, AND MOISTURE CONTENT DETERMINATIONS.**

| Across the Grain | | | Along the Grain | | |
|---|---|---|---|---|---|
| 0.0 | 146 | 32 | 0.0 | 109 | 39 |
| 4.4 | 186 | 35 | 4.5 | 135 | 42 |
| 6.8 | 175 | 36 | 6.6 | 120 | 48 |
| 10.7 | 150 | 34 | 10.6 | 107 | 52 |
| 19.0 | 120 | 32 | 18.7 | 81 | 39 |
| 32.7 | 117 | 33 | 32.4 | 78 | 39 |
| 56.3 | 100 | 30 | 56.7 | 84 | 40 |
| 79.9 | 108 | 32 | 78.2 | 72 | 38 |

pen on the oscillograph when the tip (brad) of the bit was at depths of 1, 2, and 3 inches. Torque and thrust were calculated by applying a calibration factor to the pen deflection at each depth and averaging the results.

After holes were bored, the moisture content of each block was determined by ovendrying.

## Results

### Thrust and Torque

When averaged over all levels of moisture content, the values for thrust and torque were:

| Drilling direction | Thrust (Lbs.) | Torque (In.-lbs.) |
|---|---|---|
| Tangential | 139 | 33 |
| Radial | 136 | 32 |
| Longitudinal | 98 | 42 |

By variance analysis (0.01 level), thrust was lower and torque was higher in the longitudinal direction than in either the tangential or radial direction. Thrust and torque in the tangential and radial directions were not significantly different by Duncan's multiple range test (0.01 level); this result agrees with that reported by Goodchild (2). Accordingly, data for these two directions were averaged. Table 1 lists thrust and torque when blocks at the several moisture contents were drilled across and along the grain.

The relationship between moisture content and thrust is charted in Figure 3. The curves were fitted by hand. For both drilling directions, thrust rose to a maximum in wood of about 5 percent moisture content, decreased rapidly to a minimum at about 30 percent moisture, and then remained relatively constant. Thrust was considerably less for wood above the fiber-saturation point (about 28 percent moisture) than for either ovendry or air-dry (10 percent moisture) wood. For all moisture contents, thrust was less along the grain than across the grain.

For practical engineering purposes, thrust across the grain averaged about 150 pounds for air-dry wood and 110 pounds for green wood. Values along the grain were about 100 and 80 pounds.

Torque increased with increasing moisture to a maximum between 5 and 10 percent (Fig. 4). The increase was considerably greater along the grain than across the grain. With further increases in moisture, torque decreased to a constant value at about 30 percent moisture,

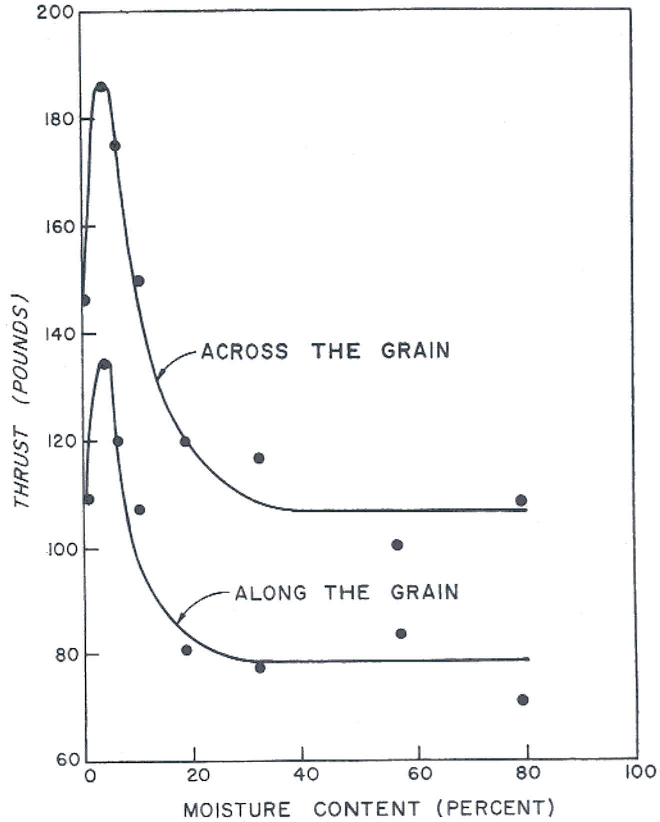


**Figure 3. — Effect of moisture content on thrust.**

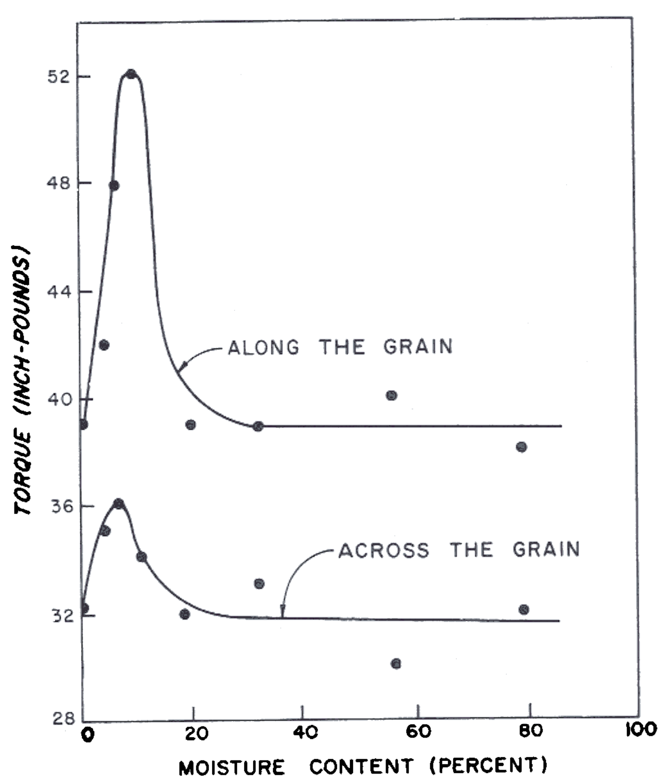


**Figure 4. — Effect of moisture content on torque.**

where it was about equal to that required for ovendry wood. At all moisture contents, torque was less across the grain than along the grain.

For engineering purposes, torque along the grain averaged about 52 inch-pounds for air-dry wood and 39 inch-pounds for green wood. Values across the grain were about 35 and 32 inch-pounds. These torques may be used to compute net horsepower at the spindle at various spindle speeds (when cutting 0.020-inch-thick chips), as shown in the following tabulation. Tests with this bit type indicated that torque was unrelated to spindle speed when chip thickness was held constant.

| Spindle speed | Plunge speed | Along the grain | | Across the grain | |
|---|---|---|---|---|---|
| | | Air-dry | Green | Air-dry | Green |
| (Rpm) | (In./sec.) | - - - - - | - - (Hp.) | - - - - | - - |
| 1,200 | 0.8 | 0.99 | 0.74 | 0.66 | 0.61 |
| 2,400 | 1.6 | 1.98 | 1.48 | 1.33 | 1.22 |
| 3,600 | 2.4 | 2.97 | 2.23 | 2.00 | 1.83 |

Power increases linearly with increasing spindle speed, since this parameter appears in the numerator of the power equation. In boring along the grain, about 25 percent less power was required for green than for air-dry wood. For cross-grain boring, moisture content had little effect on power requirement.

## Chip Formation

When drilling is in the longitudinal direction, the action of the lips (the cutting edges generating chips) approximates orthogonal cutting across the grain. Two general chip types have been described by McKenzie (7) and observed by Woodson and Koch (12) for this direction.

McKenzie Type I chips form when splits occur parallel to the grain below the cutting plane. The splits may be small, or they may be frequent and deep. The chip generated above the cutting plane is essentially equal to the depth of cut and consists of numerous subchips formed by shear parallel to the grain. Type I chips form more readily in wet than in dry wood.

Type II chips form when wood failure occurs perpendicular to the grain and at a variable distance below the cutting plane. The failure may be intermittent (Type IIa) or continuous (Type IIb). The chip above the cutting plane may be sheared into numerous subchips of irregular shape and thickness or may be relatively continuous. Type II chips are most frequent in wood of low moisture content.

Sample chips from this study were collected and examined with a low-power microscope in an attempt to detect general trends in formation with changes in wood moisture content. Typical chips are illustrated in Figure 5.

Chips produced at zero and 10 percent moisture content resembled those of McKenzie Type II (Fig. 5A, B). Chips formed above the cutting plane (upper portions of the figures) were sheared into numerous small subchips at zero percent moisture; they were longer and more continuous at 10 percent. Chips formed below the cutting plane (lower portions of the figures) were somewhat smaller for holes bored at zero percent moisture than for holes bored at 10 percent. At 80 percent moisture, typical Type I chips were formed (Fig. 5C). Although shear failures were present, most particles remained relatively intact.

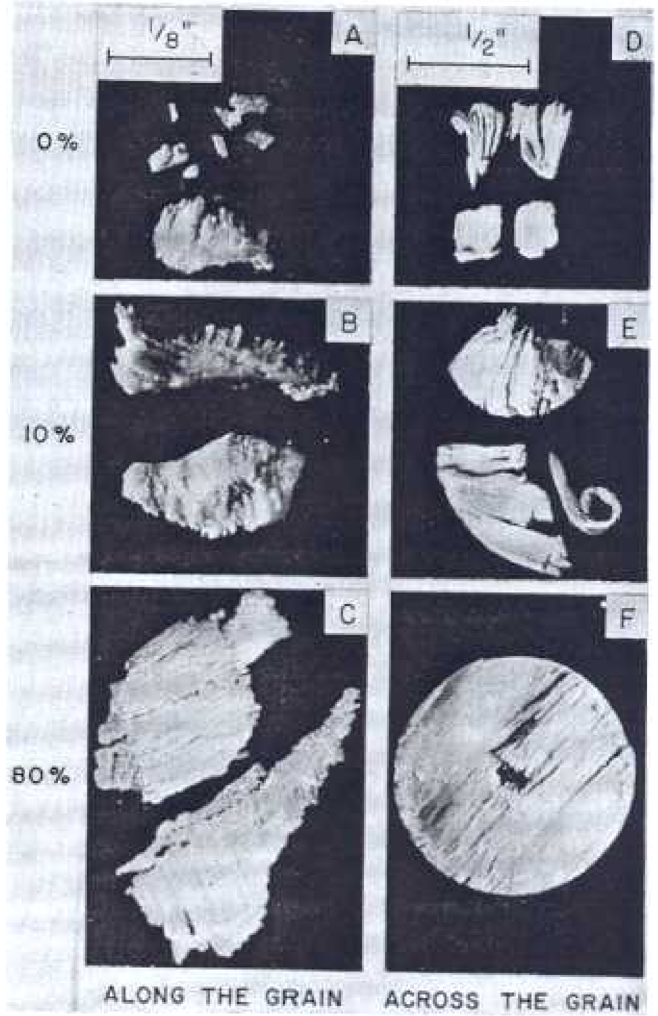


Figure 5. — Typical chips formed when boring in two directions at three moisture contents. The scale in A is applicable to B and C as well; the scale in D is applicable to E and F.

In cross-grain boring, trends in chip formation were more difficult to identify, because the cutting action of the lips continuously alternates between the veneer cutting direction and the planing direction.

Several basic modes of veneer formation have been recognized by McMillin (9), Leney (6), and Woodson and Koch (12).

1) Continuous — An unbroken sheet of veneer in which the original wood structure is essentially unchanged.
2) Cantilever beam — Veneer formed when wood splits ahead of the knife and fails as a cantilever beam. Maximum tensile stress in bending may occur at variable distance from the cutting edge.
3) Compression tearing — Veneer formed when the cutting edge deflects the wood into a slight bulge ahead of the knife. The compacted cells then fail in tension either above or below the cutting plane.

Three basic chip types are observed when machining in the planing direction (1, 3, 4, 12).

Franz Type I chips are formed when the wood splits ahead of the cutting edge and the split portion fails as a cantilever beam. Low moisture contents favor formation of this chip type.

Type II chips are characterized by continuous diagonal shear failures that extend from the cutting edge to the chip surface. An unbroken, smooth, spiral chip is formed. Intermediate to high moisture contents favor formation of Type II chips.

Type III chips form when the wood ahead of the tool ruptures in shear and compression parallel to the grain and the deformed wood is then compacted against the tool face. When the accumulation of compressed material becomes critical, buckling occurs and the chip escapes upward.

Examination of the particles produced at zero and 10 percent moisture content indicated that Franz Type I chips were generally formed when the lips were cutting in the planing direction (lower portion of Fig. 5D, E). The chips generated at zero percent moisture were considerably shorter and less curled than those produced at 10 percent. At 80 percent moisture, chips similar to Franz Type II were most frequently formed (Fig. 5F).

Failures of the cantilever beam type were generally observed when cutting in the veneer direction at zero and 10 percent moisture content (upper portion of Fig. 5D, E). Failure occurred closer to the cutting edge for wood at zero percent than at 10 percent moisture. At 80 percent moisture, chips appeared to form by failure in compression tearing (Fig. 5F).

## Discussion

It is generally held that the thrust force in machine boring is related to the force required to advance the spurs and brad into the work and to the normal force component exerted by the cutting lips (2). The relative influence of the normal force could be estimated from the oscillographs by comparing the maximum dynamic thrust required to advance the spurs and brad into the surface of the sample block to the average thrust while boring the hole. Analysis indicated that no more than 5 percent of the total thrust was associated with the normal tool force on the cutting lips. It was concluded that, for the type of bit used here, effects associated with the normal tool force are small and can be neglected, *i.e.*, 95 percent of the trust force observed was attributable to spurs and brad.

In boring across the grain, the brad exerts forces perpendicular to the long axis of fibers while the spurs cut in a direction which continuously alternates between the parallel and perpendicular axes. Since fibers are stronger when in a direction perpendicular to their axes, greater thrust forces would be expected across than along the grain.

Most strength properties of wood decrease with increasing moisture from ovendry to the fiber-saturation point. Above the saturation point, strength remains constant. It is probable that the force required to advance the spurs and brad is proportional to workpiece strength, and it was expected that thrust forces would follow the same general trend with variation in moisture. However, ovendry wood required less thrust than did wood at 5 percent moisture.

Wood weakens with increasing temperature (11, p. 89), but wet wood has greater thermal conductivity than dry wood (8). Temperatures near the cutting edge may exceed 300°C. (10), and low conductivity of ovendry wood may prevent the heat from dissipating — with consequent reduction in strength and hence in thrust. Lower thrusts may also have resulted from strength losses that occurred when the sample blocks were ovendried.

Torque is primarily related to forces exerted by the spurs and brad and the parallel tool force component of the lips. Analysis of the oscillographs indicated that a relatively constant torque of about 12 inch-pounds was imposed by the spurs and brad for all moisture contents and drilling directions. By contrast, torque associated with the parallel tool force exerted by the cutting lips varied with both drilling direction and moisture content.

In drilling along the grain, the lips sever tracheids perpendicular to their long axes. In cross-grain drilling, fibers are cut in a plane parallel to their axes. Since tracheids are stronger when in the perpendicular direction, greater torque would be expected when boring along than across the grain.

For certain combinations of rake angle, depth of cut, and cutting direction, the parallel tool force has been shown to exhibit a maximum value with increasing moisture content. For example, in orthogonal machining of loblolly pine earlywood in the planing direction with a knife having a 25° rake angle, Woodson and Koch (12) reported average parallel forces of 1.8, 5.7, and 2.9 pounds per 0.1 inch of knife at 7, 15.5, and 30 percent moisture content, respectively. It is possible that the parallel tool force exerted on the cutting lips of the bit exhibited a similar trend with increasing moisture.

## Literature Cited


1. Franz, N. C. 1958. An analysis of the wood-cutting process. Ph.D. thesis. Univ. Mich. Press, Ann Arbor, Mich. 152 pp.
2. Goodchild, R. 1955. The machine boring of wood. G. B. Dep. Sci. Ind. Res., Forest Prod. Res. Bull. 35, London. 19 pp.
3. Koch, P. 1955. An analysis of the lumber planing process: Part I. Forest Prod. J. 5:255-264.
4. ———. 1956. An analysis of the lumber planing process: Part II. Forest Prod. J. 6:393-402.
5. ———. 1964. Wood Machining Processes. Ronald Press Co., New York, N.Y. 530 pp.
6. Leney, L. 1960. Mechanism of veneer formation at the cellular level. Mo. Agric. Expt. Sta. Res. Bull. 744. 111 pp.
7. McKenzie, W. M. 1961. Fundamental aspects of the wood cutting process. Ph.D. thesis. Univ. Mich. Press, Ann Arbor, Mich. 161 pp.
8. MacLean, J. D. 1941. Thermal conductivity of wood. Heat., Piping and Air Cond. 13:380-391.
9. McMillin, C. W. 1958. The relation of mechanical properties and nosebar pressure in the production of veneer. Forest Prod. J. 8:23-32.
10. Okushima, S., H. Sugihara, and M. Umemoto. 1969. Temperature of cutter-cusp in wood cutting. J. Jap. Wood Res. Soc. 15(5):197-202.
11. U. S. Department of Agriculture, Forest Products Laboratory. 1955. Wood handbook. USDA Agric. Handb. 72. 528 pp.
12. Woodson, G. E., and P. Koch. 1970. Tool forces and chip formation in orthogonal cutting of loblolly pine. USDA Forest Serv. Res. Pap. SO-52, South. Forest Expt. Sta., New Orleans, La. 25 pp.