Boring Deep Holes in Southern Pine

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Abstract

When holes 10-1/2 inches deep and 1 inch in diameter were made with either a ship auger or a double-spur, double-twist machine bit, clogging occurred at a shallower depth (avg. 6.5 inches) when boring across the grain than when boring along the grain (avg. 10.1 inches). In both boring directions, thrust force and torque demand for unclogged bits were less for the ship auger than for the machine bit. Generally, torque and thrust were positively correlated with chip thickness and specific gravity; they were unrelated to spindle speed when the thickness of chips was held constant. For the machine bit, thrust was less in wet than in dry wood. Although the ship auger required less horsepower than the machine bit, it was slightly less efficient; *i.e.*, more energy was required to remove a unit volume of wood. In boring along the grain, the ship auger made better holes than the machine bit when the wood was dry; in wet wood hole quality did not differ between bit types. When boring across the grain, the machine bit made better holes in both wet and dry wood.

MACHINE BORING is a common operation whenever dowels, rungs, or screws are used in assembling wood components. Holes are also required for bolted connections in poles, crossarms, trusses, and structural beams. In these latter applications, holes are frequently deeper than 3 inches.

In the research reported here, torque, thrust, and hole quality were correlated with spindle speed, chip thickness, wood specific gravity, and wood moisture content. Holes were 10-1/2 inches deep and were bored both along and across the grain. The bits were of two types common in commercial practice. Consideration was also given to chip clogging in relation to hole depth.

Procedure

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

- Bit type — Double-spur, double-twist machine bit; ship auger.
- Spindle speed — 1,200 rpm; 2,400 rpm.
- Chip thickness — 0.010-inch; 0.020-inch; 0.030-inch.
- Wood specific gravity (ovendry weight and volume at 10.4 percent moisture content) — Less than 0.52; more than 0.55.
- Moisture content — 10.4 percent; saturated.
- Direction of boring — Along the grain; across the grain.

Bit diameter was held constant at 1 inch. All bits had 0.5-inch shanks, brad points, and a 12-inch twist. The double-spur, double-twist bit had two cutting lips; the ship auger had only one lip. Figure 1 illustrates the bits and tabulates their geometrical specifications. The specifications are mean values from a 30-percent sample of bits used in the study and are not necessarily representative of the manufacturer's specifications.

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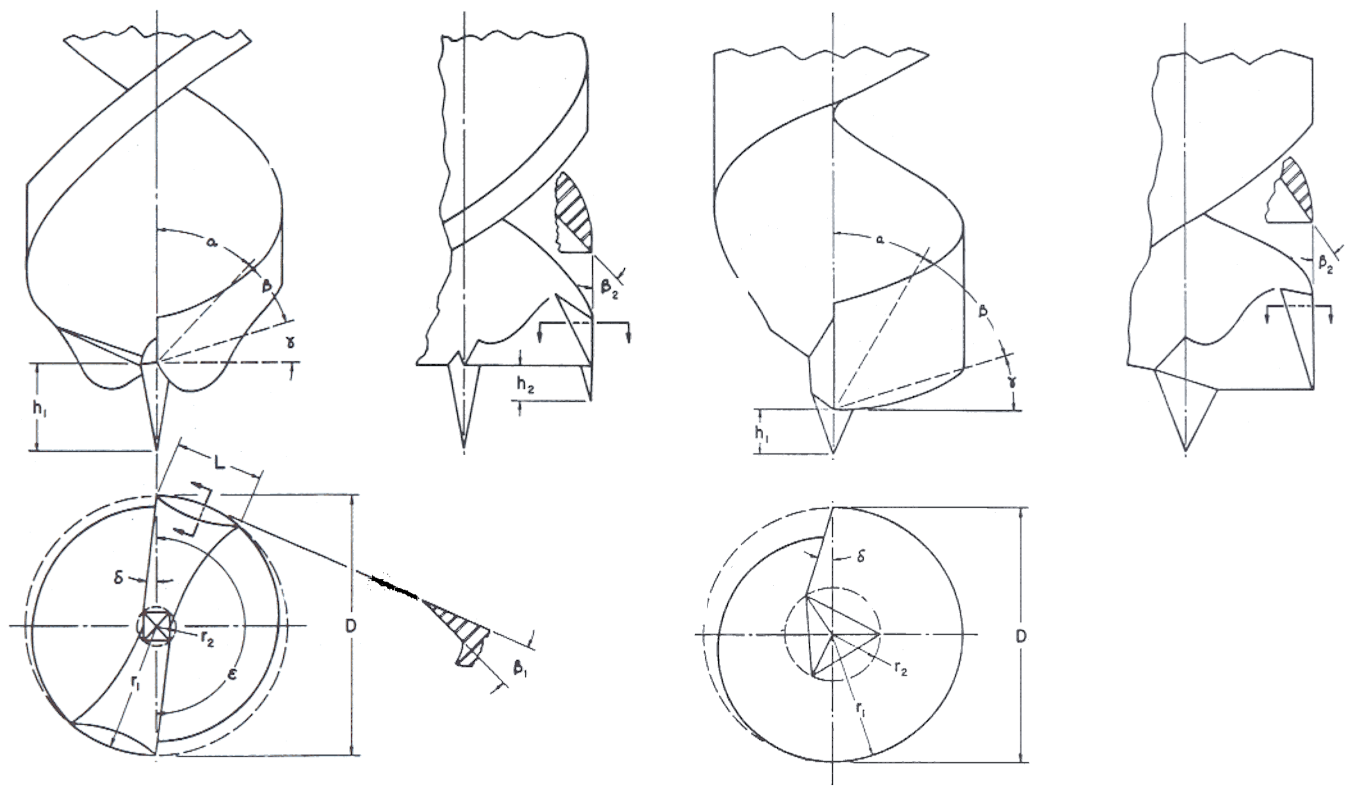
Figure 1 BIT TYPES AND GEOMETRICAL SPECIFICATIONS.

		Double-spur, double-twist machine bit (left)	Ship auger (right)
α =	Rake angle of lips (deg.)	32.8	37.5
β =	Sharpness angle of lips (deg.)	46.5	45.2
β_1 =	Sharpness angle of spurs (deg.)	28.8	....
γ =	Clearance angle of lips (deg.)	11.0	7.3
δ =	Skew angle of lips (deg.)	14.9	15.1
ϵ =	Lead angle (deg.)	180.0	....
D =	Bit diameter (in.)	1.0	1.0
r_1 =	Bit radius (in.)	0.5	0.5
r_2 =	Effective brad radius (in.)	0.13	0.15
h_1 =	Brad height above lip (in.)	0.26	0.29
h_2 =	Spur height above lip (in.)	0.11	
L =	Spur length at root (in.)	0.47	



Bits were used in the condition received from the factory, except that some minor imperfections were corrected by hand honing. Different bits were used for each replication, and only 6 holes were drilled with a given bit. Thus, effects associated with tool wear and variations between bits of the same type were minimized.

Several thousand board feet of rough-sawn southern pine (*Pinus* spp.) 4 by 4's were kiln-dried to approximately 12-percent moisture content and accurately surfaced on four sides to 3-1/2 inches square. 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 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. Average moisture content, determined from a 2-percent sample of all cubes, was 10.4 percent; the standard deviation was 0.55. Average volume was 693.80 cc. with a standard deviation of 6.71.

Because the blocks were essentially uniform in moisture content and volume, it was possible to stratify them into specific gravity classes by weight. Those weighing 400 grams or less were classified as low in specific gravity (0.52 or less), while those weighing 420 grams or more were designated as high in specific gravity (0.55 or more). There were no blocks intermediate to these two classes.

By visual inspection of the annual ring orientation on the end grain, the samples for across-the-grain boring were selected so that holes would run primarily in the radial direction. Samples for each specific-gravity class and boring direction were then matched by weight in groups of three and stacked to provide boring specimens

3-1/2 inches square by 10-1/2 inches deep and of uniform density. Samples classified as low in specific gravity averaged 0.48 while those classified as high averaged 0.60. After the grouped samples had been put into plastic net bags, half of those in each factorial combination were randomly selected and maintained at 10.4-percent moisture content. The remaining half were saturated in water-filled holding tanks, where they attained an average moisture content of 73.3 percent.

Holes were bored in random order with an especially designed machine. A 5-horsepower, synchronous-speed, 3,600 rpm, alternating-current motor with timing belt drive eliminated variation in spindle speed while drilling. Spindle speeds were altered by changing the diameter of the pulleys on the motor and spindle. The spindle rotated in a hydraulically operated quill assembly; the axial feed rate of the quill was regulated by a flow-control valve compensated for temperature and pressure. An electronic timer, actuated by a photosensitive relay system at the beginning and end of the 12-inch stroke, was used to set and monitor the plunge rate. The thickness of chips was held constant (at each spindle speed) by adjusting the plunge rate of the quill assembly.

Chip thickness is a function of spindle speed, plunge speed, and number of cutting lips:

$$t = \frac{f}{nN} \qquad [1]$$

where

t = Chip thickness (in.)
f = Plunge rate (in./min.)
n = Spindle speed (rpm)
N = Number of cutting lips

The following tabulation shows the plunge rates used to produce chips of the desired thickness. The values in parentheses are for the ship auger, which had one cutting lip; the other values are for the two-lipped machine bit.

Chip thickness	1,200 rpm	2,400 rpm
(in.)	- - - - (in./min.)	- - - -
0.010	24 (12)	48 (24)
0.020	48 (24)	96 (48)
0.030	72 (36)	144 (72)

Specimens were clamped in a vise attached to a strain gage dynamometer designed to isolate the thrust force and torque exerted on the workpiece. The output of the dynamometer was recorded with a two-channel oscillograph having a frequency response of 100 Hz. A photosensitive relay system momentarily actuated an auxiliary pen on the oscillograph when the tip of the brad was engaged in the work at a depth of 3, 6, or 9 inches. The dynamometer and recording system permitted measuring torque to 0.25 inch-pound and thrust to the nearest pound.

The surface quality of holes was subjectively evaluated on a rating scale of 1 to 3, with 1 being the highest. Figure 2 illustrates representative surfaces for each direction.

Torque and Thrust

Torque and thrust were measured by visually fitting a straight line through the oscillographic recording and applying a calibration factor to the average pen deflection. Only that portion of the recording showing no evidence of chip clogging was considered. As will be seen, clogging masks normal torque and thrust associated with the cutting action.

Analysis of variance (0.01 level) revealed that torque and thrust did not vary with spindle speed when chip thickness was held constant.

When the data were averaged over all moisture contents, specific gravities, chip thicknesses, and spindle speeds for each direction separately, thrust and torque were lower when boring with the ship auger than with the machine bit.

Bit type	Along the grain		Across the grain	
	Torque	Thrust	Torque	Thrust
	(in.-lbs.)	(lbs.)	(in.-lbs.)	(lbs.)
Machine bit	67.1	132.9	50.4	155.8
Ship auger	39.9	61.1	29.0	38.6

For samples bored along the grain with the machine bit, torque increased with increasing chip thickness. For

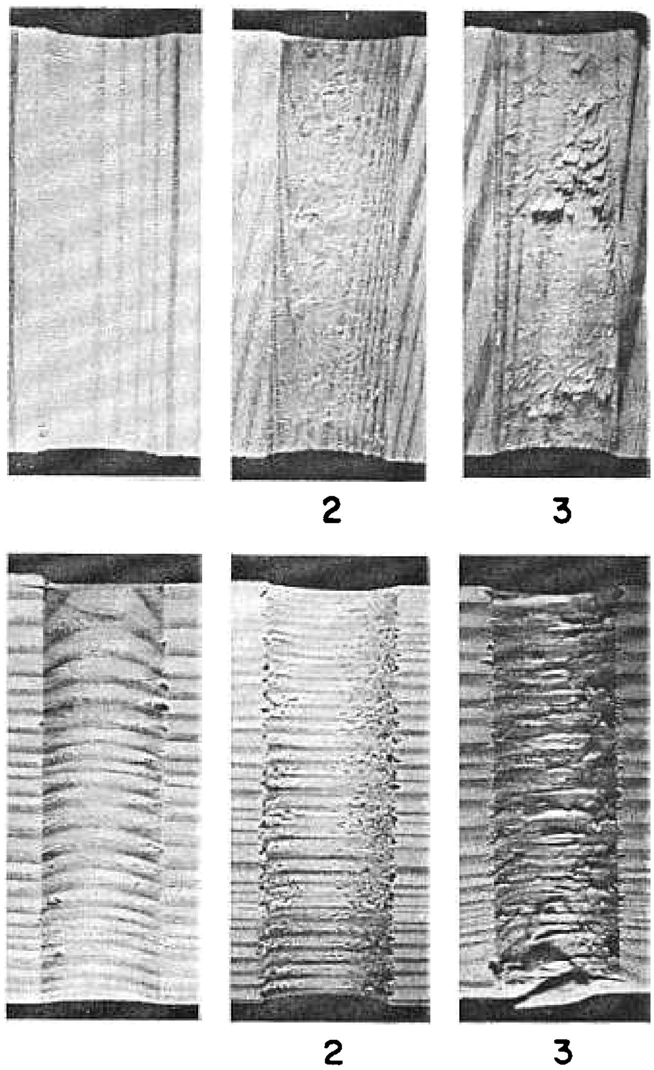


Figure 2. — Holes rated 1 are considered a good quality, 2 are fair, and 3 are poor. Samples in the top row were bored along the grain; those in the bottom row were bored across the grain.

a given thickness, torque was greater in wood of high than of low specific gravity. Moisture content and spindle speed had no effect.

Chip thickness	Specific gravity Low	High
(in.)	- - (in.-lbs.) - -	
0.010	42.8	59.1
0.020	60.1	78.7
0.030	69.7	91.0

Torque in boring across the grain with the machine bit was unrelated to specific gravity but was positively correlated with chip thickness. Mean values were 40.0, 48.6, and 61.9 inch-pounds for chips 0.010, 0.020, and 0.030 inches thick. Torque did not differ significantly between moisture contents or spindle speeds.

When boring along the grain with the machine bit, thrust was greater for wood of high than of low gravity. Wet wood required less thrust than did dry wood. Chip thickness and spindle speed had no effect.

Moisture content	Specific gravity Low	High
	- - - - (lbs.) - - - -	
Dry	112.8	185.4
Wet	95.5	138.0

In boring across the grain with the machine bit, thrust differed with all variables except spindle speed. As shown in the following tabulation, thrust was positively correlated with chip thickness and specific gravity. For a given specific gravity and thickness, it was less in wet than in dry wood.

Chip thickness (in.) and moisture content	Specific gravity Low	High
	--- (lbs.) ---	
0.010		
Dry	128.3	175.8
Wet	79.7	113.7
0.020		
Dry	148.3	253.3
Wet	123.5	155.0
0.030		
Dry	162.5	250.0
Wet	116.7	162.5

With the ship auger, torque and thrust varied with chip thickness and wood specific gravity both along and across the grain. Torque and thrust were unrelated to moisture content and spindle speed. In the tabulation below, the first number in each entry is the torque in inch-pounds; the number following in parentheses is the thrust in pounds.

Boring direction and chip thickness (in.)	Specific gravity Low	High
	- - (in.-lbs.) & (lbs.) - -	
Along the grain		
0.010	26.3 (41.9)	33.8 (51.9)
0.020	37.2 (52.0)	46.6 (66.1)
0.030	41.9 (66.4)	53.5 (80.0)
Across the grain		
0.010	18.8 (18.2)	21.7 (24.6)
0.020	24.5 (31.1)	31.3 (34.8)
0.030	35.9 (53.4)	41.6 (69.3)

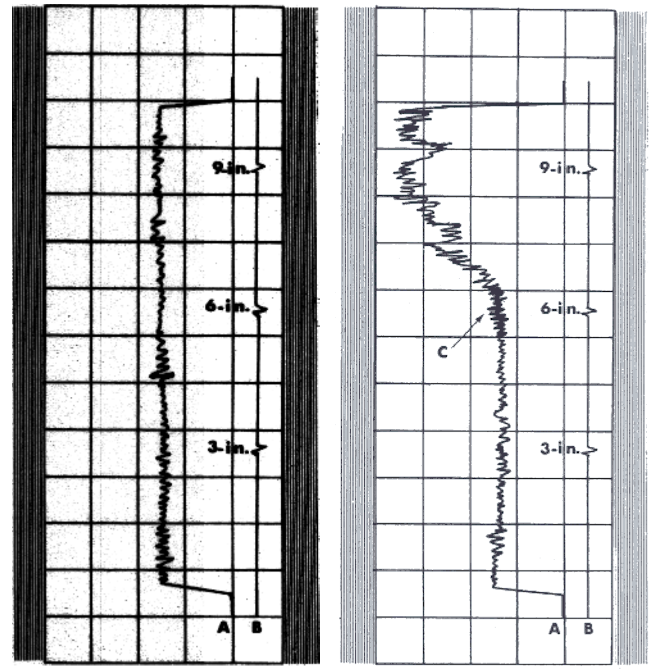


Figure 3. — Typical oscillographic recordings illustrating the effect of chip clogging. A is torque or thrust trace, B is depth trace, C is point of chip clogging.

From the tabulation, torque and thrust increased with increasing chip thickness for wood of all gravities. For a given thickness, torque and thrust were greater when boring wood of high than of low gravity.

Hole Quality

The quality of holes did not differ between specific gravities, chip thicknesses, or spindle speeds. However, significant differences were detected between moisture contents and bit types.

Bit type	Along the grain Dry	Wet	Across the grain Dry	Wet
	- - - (quality units) - - -			
Machine bit	2.1	2.8	1.6	1.6
Ship auger	1.5	2.6	2.1	2.7

In quality of holes bored along the grain, the ship auger excelled in dry wood but was not significantly better than the machine bit in wet wood. Across the grain, the machine bit yielded better holes in both wet and dry wood.

Bit Clogging

When boring a deep hole, operators commonly retract the bit to clear chips from the flutes and then advance it for a further cut. This procedure may be repeated several times until the desired depth is attained. Unless the chips are cleared, power requirements rise rapidly and cutting becomes slow or ceases altogether.

Figure 3 shows two oscillographic recordings. In the one at the left, which is typical of either thrust or torque, the flutes remained unclogged during the entire 10-1/2-inch cut. The recording is relatively smooth, indicating

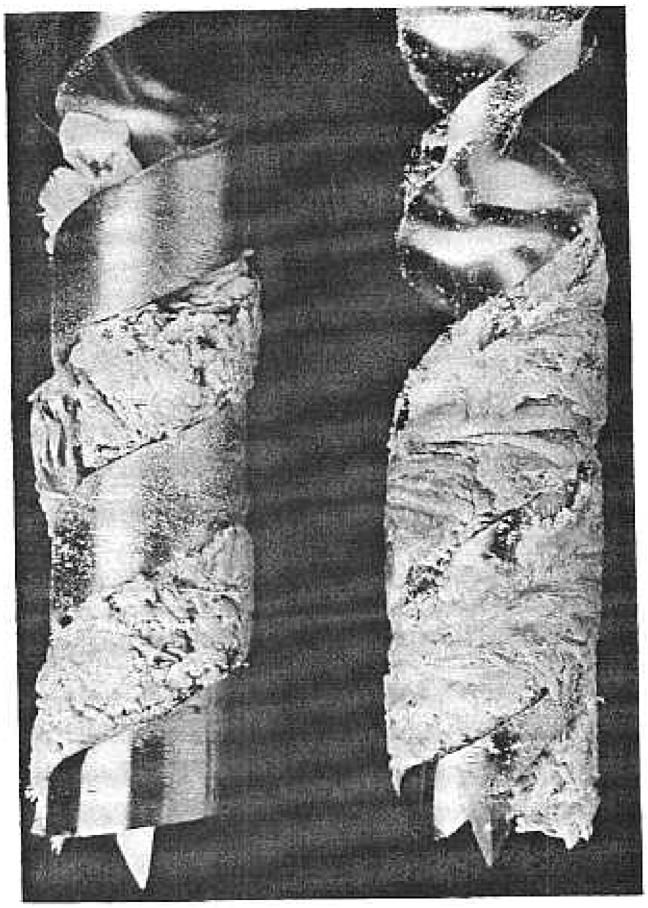


Figure 4. — Severe chip clogging during cross-grain boring with the ship auger (left), and the double-spur, double-twist bit (right).

a stable cutting action. In the recording on the right, clogging occurred at a depth of about 6 inches. From engagement to clogging, the trace is typical of unclogged bits. When clogging occurred, both torque and thrust increased rapidly and the traces became erratic. In some cases, torque exceeded 200-inch-pounds in less than one second — a power demand well above the capacity of most boring machines. Figure 4 shows severe clogging of the flutes when boring across the grain. At this level of compaction cutting action had ceased.

The maximum depth of hole attained without evidence of chip clogging was measured from the oscillographic traces. By analysis of variance (0.01 level) the only test factor significantly associated with clogging was direction of boring. Clogging occurred at a shallower depth (average 6.5 inches) when boring across the grain than along the grain (average 10.1 inches). For a given boring direction there was no significant difference between bit types.

Chips generated by boring across the grain remained relatively intact, while those generated along the grain were fragmented and small. Intact chips are more difficult to exhaust from the hole and are more likely to clog the flutes. The results suggest that bits should be retracted from the work about every 6 inches when boring across the grain, while 10-inch-deep holes can be cut in a single plunge along the grain.

Power Demand and Specific Cutting Energy

In many industrial operations it is useful to interpret torque demand in terms of horsepower. The torques reported in this article may be converted to net horsepower at the spindle by substitution in the equation:

$$P = 1.587 \times 10^{-5} (n)\ (T) \qquad [2]$$

where

P = Net power at the spindle (horsepower)
n = Spindle speed (rpm)
T = Torque (in.-lbs.)

The calculated values neglect no-load idling losses of the motor and spindle assembly. Thus, actual power requirements will be somewhat higher than those indicated by the equation. Neither does the equation include power to overcome thrust when advancing the bit — normally only a fraction of a horsepower, and usually applied by a second power source.

The horsepower demand is shown below for each bit type. The values are averages for mean levels of moisture content, specific gravity, chip thickness, and spindle speed. As expected from the measured torques, demand was greater when holes were bored with the machine bit than with the ship auger.

Bit type	Along the grain	Across the grain

$$E_s = \frac{(15.8)(10^{-3})(P)}{(t)(n)(N)(D^2)} \qquad [3]$$

where

E_s = Specific cutting energy (kilowatt-hrs./cu. in.)
t = Chip thickness (in.)
N = Number of cutting lips
D = Bit diameter (in.)

The specific cutting energies for each bit are tabulated below. The average horsepowers listed above, mean chip thickness (0.020-in.), mean spindle speed (1,800 rpm), and the appropriate number of cutting lips were used in the computation.

Bit type	Along the grain	Across the grain
	- - - - (kilowatt-hrs./cu. in.) - -	
Machine bit	4.2×10^{-4}	3.1×10^{-4}
Ship auger	4.8×10^{-4}	3.5×10^{-4}

Although the ship auger required less power, it was slightly less efficient; *i.e.*, more electrical energy was required to remove a unit volume of wood.