An Analysis of the Lumber Planing Process: Part II[1,2]

PETER KOCH

Associate Professor of Research, Department of Forest Products, Michigan State University, East Lansing, Mich.

This study is Part II of an investigation pertaining to the peripheral-milling process of planing lumber. Some relationships were determined between cutterhead horsepower and various combinations of specimen, cutterhead, and feed factors. Power demand curves were interpreted through comparison with simultaneously taken one micro-second photos of the forming chips. Secondary consideration was given to the quality of surface obtained. The cutterhead variables, feeds, and speeds employed are in the range of those commonly used in industry, i.e., feed speeds to 500 FPM with cutterheads ranging up to 9-inch cutting-circle diameter and carrying up to 8 knives.

THIS DISCUSSION is a continuation of a previous report (4)[3] on fundamental information pertaining to the process of planing lumber. The previous report dealt with the influence of the following factors: number of jointed knives cutting, rake angle, clearance angle, cutterhead type, feed speed, depth of cut, grain type, and moisture content.

The present report discusses cutterhead horsepower demand in a series of six experiments with factors outlined as follows:

- Test Able—*Cutting circle diameter*, number of jointed knives cutting, per cent moisture content, and feed speed.
- Test Easy—*Specific gravity*, depth of cut, and feed speed.
- Test Fox—*Angle between rotational axis of cutterhead and direction of feed*, and depth of cut.
- Test George—*Direction of cutterhead rotation with relation to direction of feed*, and depth of cut.
- Test How—*Knife extension beyond face of gib*.
- Test Ivy—*Width of joint*, and depth of cut.

[1] Presented at Session IX, Wood Machining, FPRS Ninth National Meeting, June 4–7, 1956, in Asheville, N. C.

[2] Based on a dissertation submitted in partial fulfillment of requirements for Ph.D. degree at College of Forestry, U. of Washington, Seattle.

[3] Numbers in parentheses refer to literature cited.

The Author: Peter Koch received B.S. from Montana State College, Ph.D. from U. of Washington. He was assistant to the president, Stetson-Ross Machine Co., from 1946–52; consulting engineer from 1952–55, when he accepted present position.

The kinematics of the process and testing technique, together with preliminary discussions of specimen selection, surface analysis, knives, and cutterheads, are omitted from this report inasmuch as this material was introductory to Part I (4).

Test Results and Discussion

A. Test Able: This four-factor experiment was designed to study the interaction of the variables of cutting-circle diameter, number of jointed knives cutting, per cent moisture content, and feed speed.

The choice of cutting circles was somewhat limited by the necessity of using identical gibs, rake angle, clearance angle, and knife extension on the heads selected. For this reason, the variable of cutting circle diameter was restricted to the consideration of only two values, i.e., 9.02 and 7.63 inches. It might be noted that both of these diameters are popular on 8-knife planers and matchers in industry.

Having chosen heads slotted for eight knives, possibilities for numbers of jointed knives cutting were limited to eight, four, and two. To use a number of knives less than eight simply involved setting back the excess knives to a point where they would not touch the workpiece. The remaining knives were not rejointed after setting back the excess knives, and the resulting knife traces indicated that in each case the joint remained good.

The specimen was tested both dry and green. The dry specimen reached an equilibrium moisture content of 8.2 per cent after several weeks in the laboratory. The green specimen had a moisture content of approximately 82 per cent. The procedure of accomplishing cell wall saturation of the green specimen by pressure treating it in water for eight days at approximately 65 psi resulted in the presence of considerable free water in the cell cavities. The 82 per cent moisture content probably is closer to an approximation of green Douglas-fir sapwood moisture content than it is of the heartwood which made up the specimen. Between tests which extended over several days, the green specimen was submerged in a shallow water tank in order to prevent it from drying out.

Table 1.—RESUME OF FACTORS APPLYING TO TEST ABLE

Variable Factors:
- Cutting-Circle Diameter in Inches; 9.02 and 7.68
- Number of Jointed Knives Cutting: 2, 4, and 8
- Percent Moisture Content (based on O. D. weight):
  - Dry, i.e., 8.2 ± 0.4
  - Green, i.e., 82.0 ± 15.0
- Feed Speed in FPM: Average values 108, 204, 806, 407, and 508

Fixed Factors:
- Specimen:
  - General Description: The test pieces consisted of two eighteen-foot-long 1 by 8's ripped from the central portion of a single, dry (10 percent M.C.), 1 by 6 board. One of these was pressure treated in water at approximately 65 psi for a period of eight days to simulate the green condition.
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: 22 ± 4
  - Width of Machined Surface: 0.798 ± 0.016
  - Angle of Annual Rings to Machined Surface:
    - Dry specimen: 45 ± 1 degrees
    - Green specimen: 80 ± 10 degrees
  - Spiral Grain: 5/8 inch per foot favoring feed
  - Specific Gravity: Based on O.D. weight and green volume 0.446 ± 0.01, Based on O.D. weight and O.D. volume 0.482 ± 0.02
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Bodies: Jointer type slotted for 8 knives, 9.02-inch cutting circle; Jointer type, slotted for 8 knives, 7.68-inch cutting circle
  - Gibs: Concave face
  - Knives: 5/16-inch thick with corrugated back
  - Rake: 80 degrees
  - Clearance: 20 degrees
  - Knife Extension beyond Gib: 0.344 ± 0.015 inches
  - Width of Joint: 0.011 ± 0.002 inches
  - Nominal RPM of Cutterhead: 8600
- Feed:
  - Depth of Cut: 0.0625 inches

Reprinted from the October, 1956, Forest Products Journal (Vol. VI, No. 10), pages 393–402
Forest Products Research Society, P. O. Box 2010, University Station, Madison 5, Wisconsin

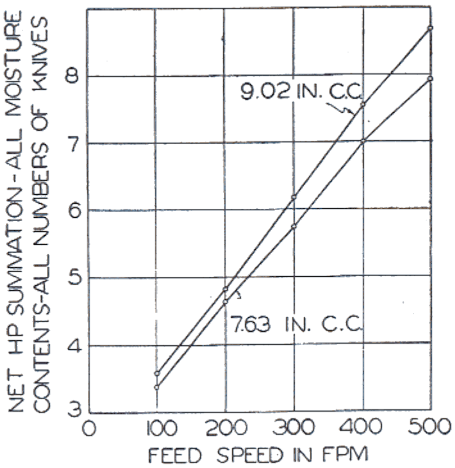

Fig. 1.—Relative net horsepower requirement for wood removal under Test Able conditions comparing 9.02-inch and 7.63-inch cutting-circle diameters at varying feed speeds (ignoring factors of moisture content and number of knives).

The feed speed was varied in approximately 100 FPM increments from 100 to 500 FPM. While it is apparent that 100 FPM is a relatively slow feed speed for an 8-knife machine, and that 500 FPM is an impractical high speed for a 2-knife machine, the extreme range provides a family of data suitable for plotting and analysis. The fixed factors involved as well as the variable factors are outlined in Table 1.

Photographs of this test were limited to the green specimens machined with the 7.63-inch cutting-circle cutterhead, inasmuch as a rather complete set of photographs had been taken on the prior Test Dog which involved two of the same variable factors, i.e., number of knives and feed speed (4). The tabulation of the horsepower requirements is presented in Table 2.

Table 3 shows the combination of factors that produce satisfactory surfaces as previously defined (4). It is evident that high speeds with few knives have an adverse effect on the surface conditions. The green specimens provided the best surfaces under adverse conditions when compared to dry specimens. The controlling defect for both green and dry specimens was the amount of torn grain with considerable chip marking being evident on both green and dry samples. Fuzzy grain was not an important factor, and no raised grain was evident on any of the specimens under any combination of factors.

A perusal of the tabulation of graphs of cutterhead horsepower data reveals that, in a summation of all factor combinations, the 9.02-inch cutting-circle head requires 7.35 per cent more power than the 7.63 inch cutting-circle head (refer to Fig. 1). The larger cutting-circle head required 10.8 per cent more power on green stock than did the smaller head. On dry stock, the difference was not so marked, being only 3.37 per cent.

Because the 9.02-inch diameter head has an 18.2 percent longer moment arm than the 7.63-inch diameter head, each knife is in the cut a relatively shorter length of time. Therefore, the increased moment is nearly cancelled by decreased knife time in the cut. The compensation is not complete, however, because the length of knife engagement of the 9.02-inch cutterhead at 300 FPM and 1/16-inch depth of cut is 0.780 inches, compared with the 7.63-inch cutterhead length of path engagement of 0.726 inches under the same conditions (7), i.e., an increase of 7.44 per cent.

Furthermore, the larger head has a peripheral speed of 8,150 FPM compared to 6,900 FPM for the smaller head. This additional velocity increases the accelerational force exerted by the chip as it forms and therefore raises the horsepower requirement.

The knife path lengths previously mentioned are associated with an average chip thickness for the 7.63-inch cutterhead of 0.01123 inches, and an

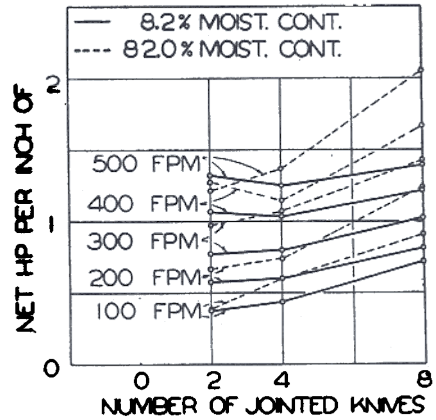

Fig. 2.—Net horsepower requirement for wood removal under Test Able conditions for a 9.02-inch diameter cutting-circle cutterhead comparing green and dry requirements with varying feed speeds and number of knives.

average chip thickness for the 9.02-inch cutterhead of 0.01045 inches (7), or a decrease of 6.9 per cent in average chip thickness.

The 7.35 per cent more power required by the large cutterhead (all factors considered) is attributable to a combination of the following factors:

a. A 7.44 per cent increase in knife path engagement length.
b. An 18.2 per cent increase in knife velocity (causing an emphasis of power demand differential with green stock as compared with dry stock).
c. A 6.9 per cent decrease in average chip thickness.

The effect on the power requirement of a varying number of knives in the head depends to a great extent on the feed speed and on the moisture content of the specimen. The frequently made assumption that the power demand is a straight line function of the number of knives employed and that, under any given set of feed conditions, doubling the number of knives will double the horsepower requirement, is shown to be of dubious validity. On dry stock it is evident with both cutting-circle diameters that horsepower is proportional

Table 2.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST ABLE CONDITIONS*

	Cutting-Circle Diam. in Inches							
	9.02				7.63			
	Dry		Green		Dry		Green	
No. of Knives	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM
2.	1.34	504	1.21	505	1.21	505	1.36	501
	1.08	407	1.31	408	1.08	406	1.08	409
	0.80	309	0.99	306	0.78	306	0.87	305
	0.59	206	0.67	203	0.55	204	0.66	203
	0.40	109	0.42	109	0.31	108	0.42	108
4.	1.27	505	1.88	504	1.32	507	1.30	500
	1.06	407	1.15	407	1.10	408	1.13	405
	0.81	307	1.08	306	0.73	304	0.97	306
	0.61	208	0.75	206	0.69	203	0.80	203
	0.46	108	0.63	109	0.43	107	0.58	107
8.	1.42	504	2.06	498	1.30	506	1.43	502
	1.24	404	1.70	409	1.20	406	1.46	404
	1.08	305	1.46	308	1.09	305	1.32	305
	0.94	209	1.27	204	0.87	202	1.09	204
	0.75	108	0.93	108	0.74	108	0.90	108

*Refer to Table 1 for resume of factors.

Table 3.—COMBINATIONS OF FACTORS UNDER TEST ABLE CONDITIONS THAT PRODUCED SATISFACTORY PLANED SURFACES*

		Cutting Circle Diam. in Inches			
		9.02		7.63	
No. of Knives	Feed Speed FPM	Dry	Green	Dry	Green
2.	508	-----			-----
	407	-----			-----
	306	-----			-----
	204	-----			-----
	108	-----			
4.	508	-----			-----
	407	-----			-----
	306	-----			-----
	204	-----			-----
	108	*			*
8.	508	-----			*
	407	-----			*
	306	-----			*
	204	*			*
	108	*			*

*Asterisk indicates satisfactory surface.

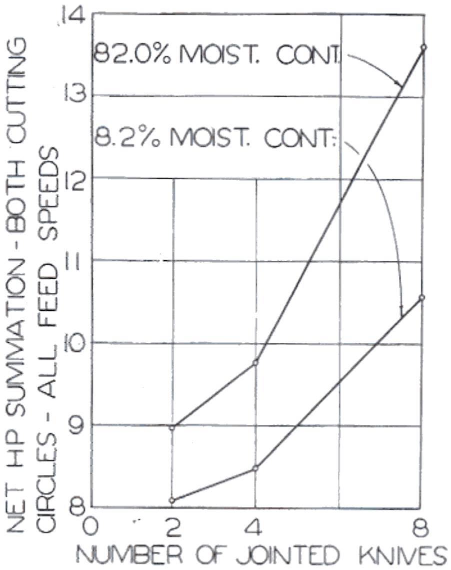

Fig. 3.—Relative net horsepower requirement for wood removal under Test Able conditions comparing 82.0 per cent and 8.2 per cent moisture content specimens machined with a varying number of jointed knives (ignoring factors of cutting-circle diameter and feed speed).

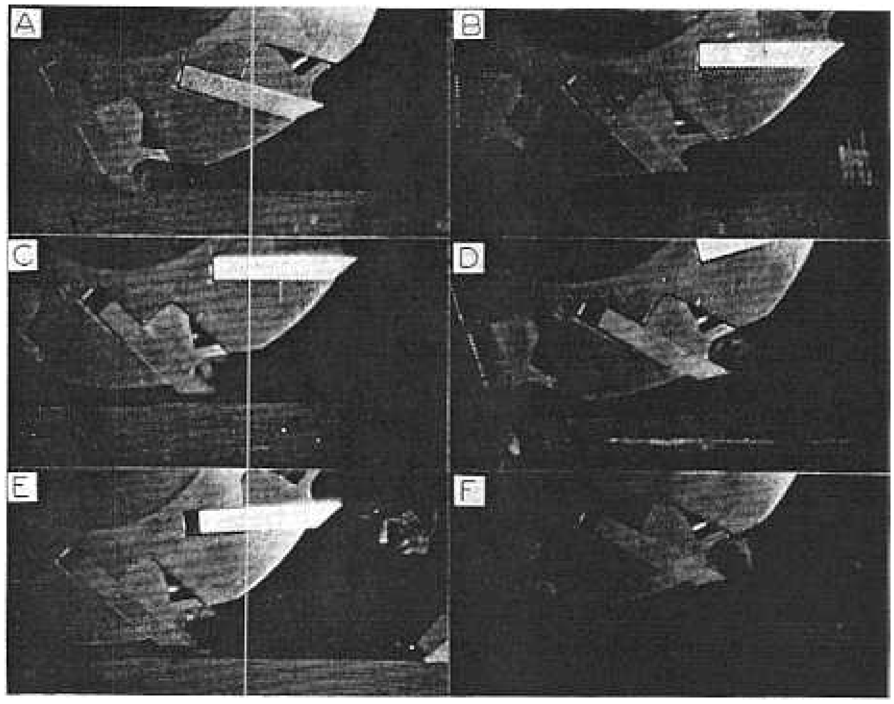

Fig. 7.—Test Able. (A) Number of knives: 2; feed speed: 200 FPM; moisture content: green; cutting-circle diam.: 7.63 inch. (B) Number of knives: 2; feed speed: 400 FPM; moisture content: green; cutting-circle diam.: 7.63 inch. (C) Number of knives: 4; feed speed: 100 FPM; moisture content: green; cutting-circle diam.: 7.63 inch. (D) Number of knives: 4; feed speed: 200 FPM; moisture content: green; cutting-circle diam.: 7.63 inch. (E) Number of knives: 8; feed speed: 400 FPM; moisture content: green; cutting circle diam.: 7.63 inch. (F) Number of knives: 8; feed speed: 500 FPM; moisture content: green; cutting-circle diam.: 7.63 inch.

to number of knives only at low speeds, and then only roughly so. As the feed speed increases, the power requirement becomes more nearly constant regardless of the number of knives employed. This is illustrated in Fig. 2. The reason for this relationship was discussed more fully with the aid of photographs in the previous article (4). It is sufficient to say here that the *extreme* advance splitting that takes place with few knives at high speeds causes a type of higher energy chip deformation than that occurring when a greater number of knives is used.

With the green specimens, a more marked proportionality between horsepower requirement and number of knives is noted. Figs. 7A through 7F indicate that regardless of the feed speed or number of knives employed, a reasonably coherent chip is formed. Due to the increased plasticity of the green wood, the chip is less subject to advance splitting, and hence it is logical that for any given feed speed, fewer knives will require less power, for the reason that a larger chip is removed by each knife, with correspondingly fewer chips and fewer fibers requiring severance.

Figs. 2 through 6 show that the green specimens take significantly more power than do the dry specimens. As previously commented (4), part of the explanation lies in the fact that the additional weight of the green chip, due to both its free and adsorbed water, increases the force necessary to accelerate it to cutterhead velocity. Other things being equal, this increase in force would be directly proportional to the increase in mass of the undeformed chip. The change in velocity is considerable, inasmuch as in conventional milling or up-milling, (which applies to this test), the stock and the undeformed chip are traveling in one direction at a speed up to 500 FPM, whereas the knife which must pick up the deformed chip is traveling at approximately 8000 FPM in the opposite direction. The transition from

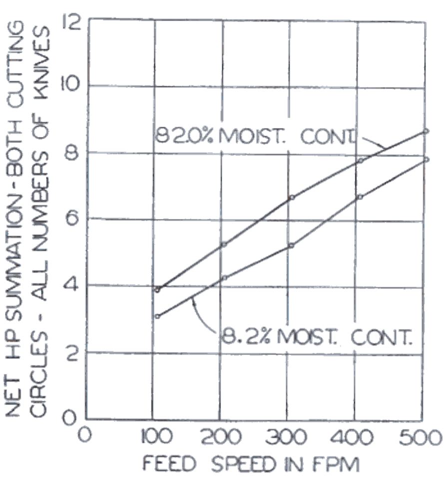

Fig. 4.—Relative net horsepower requirement for wood removal under Test Able conditions comparing 82.0 per cent and 8.2 per cent moisture content specimens at varying feed speeds (ignoring factors of cutting-circle diameter and number of knives).

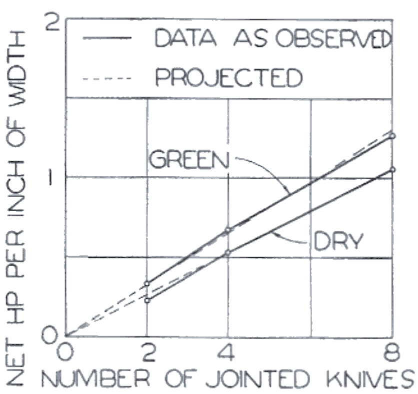

Fig. 5.—Net horsepower requirement for wood removal under Test Able conditions comparing 2, 4, and 8 knife requirements for a surface quality of 8 knife marks per inch using a 7.63-inch diameter cutting-circle cutterhead machining both green and dry wood.

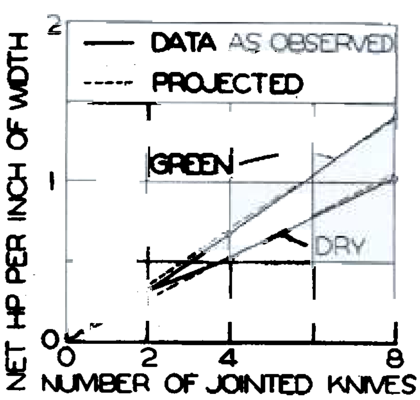

Fig. 6.—Net horsepower requirement for wood removal under Test Able conditions comparing 2, 4, and 8 knife requirements for a surface quality of 8 knife marks per inch using a 9.02-inch diameter cutting-circle cutterhead machining both green and dry wood.

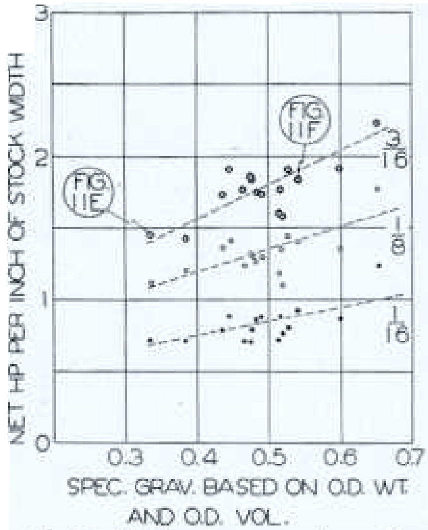

Fig. 8.—Net horsepower requirement for wood removal under Test Easy conditions comparing 1/16, 1/8, and 3/16 inch depth cuts at 150.5 FPM and at varying specific gravities.

attached undeformed chip with a velocity of −500 FPM to unattached deformed chip with a velocity of +8000 FPM takes place within a distance of approximately 3/4 inch, the exact distance depending on cutterhead and feed conditions.

Considering all readings of green and dry horsepower values, the green stock required 19.2 per cent more power than the dry stock. Using the 9.02-inch cutting-circle head, the green specimens required 23.3 per cent more power than the dry specimens. Using a 7.63-inch cutting-circle head, the green samples took 15.0 per cent more power than the dry samples.

If the variables of cutting-circle diameter and feed speed are ignored, cutting green stock with two knives required 11 per cent more power than cutting dry stock with two knives. With four knives the green specimens required 15.2 per cent more power than the dry specimens, and with eight knives the green stock required 28.8 per cent more power than

Table 4.—RESUME OF FACTORS APPLYING TO TEST EASY

Variable Factors:
- Specific Gravity: Sixteen values from 0.334 to 0.651 based on O.D. volume and O.D. weight
- Depth of Cut in Inches: 1/16, 1/8, and 3/16
- Feed Speed in FPM: Average values 150.5 and 306.7

Fixed Factors:
- Specimen:
  - General Description: The test pieces consisted of sixteen different surfaced, dry, eighteen-foot-long 1 by 3's of varying specific gravity, but with similar grain and annual ring orientation
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: Average 28, standard deviation ±13
  - Width of Machined Surface: Average 0.778 inches
  - Angle of Annual Rings to Machined Surface: 43±18 degrees
  - Spiral Grain: Average 3/8 inch per foot favoring direction of feed
  - Percent Moisture Content (based on O.D. weight): 8.5±1.1
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Body: Jointer type, 8-knife, 9.03-inch cutting circle
  - Gibs: Concave face
  - Knives: 5/8-inch thick with corrugated back
  - Number of Knives: 8
  - Cutting-Circle Diameter in Inches: 9.03
  - Rake: 30 degrees
  - Clearance: 20 degrees
  - Knife Extension beyond Gib: 0.33 inches
  - Width of Joint: 0.008±0.003 inches
  - Nominal RPM of Cutterhead: 3600

the dry stock. This is illustrated in Fig. 3.

Fig. 4 illustrates that if only feed speed and moisture content are considered, green stock shows less percentage power penalty at 500 FPM than it does at 100 FPM feed speed.

A typical chip from a green specimen is shown in Fig. 7B. The shaving is coherent with no advance splitting taking place until the instant before the chip is detached, at which point the harder summerwood of the annual rings splits slightly, giving the comb appearance shown. Fig. 7E shows the abrupt deformation that takes place in the chip as a result of gib shape.

Figs. 5 and 6, which show horsepower requirements with varying numbers of knives but at a constant surface quality of eight knife marks per inch, and a constant depth of cut of 1/16 inch, reveal an approximate straight line relationship that can be expressed

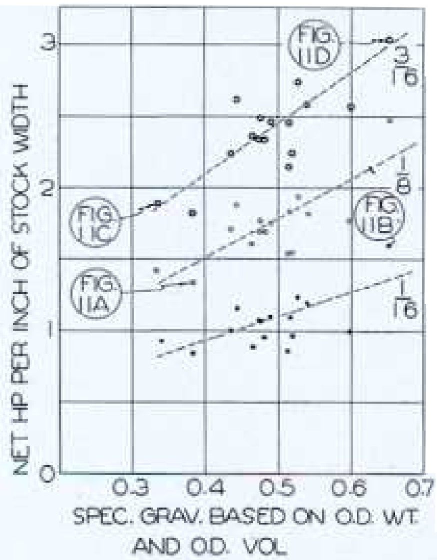

Fig. 9.—Net horsepower requirement for wood removal under Test Easy conditions comparing 1/16, 1/8, and 3/16 inch depth cuts at 306.7 FPM and at varying specific gravities.

$$W_n = CT$$

where

W_n = net horsepower requirement per inch of stock width

T = number of knives

C = a constant having the values

	9.02-inch diameter cutting-circle	7.63-inch diameter cutting-circle
dry	0.131	0.131
green	0.175	0.163

B. Test Easy: This three-factor experiment was designed to study the interaction of the variables of specific gravity, depth of cut, and feed speed.

The 16 specimens involved were purchased in a dry, surfaced condition and allowed to reach an equilibrium moisture content of 8.5 per cent. The specific gravity of the specimens (based on oven-dry weight and oven-dry volume) ranged from 0.334 to 0.651. A considerable effort was made to select boards of varying spe-

Table 5.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST EASY CONDITIONS*

		Depth Cut in Inches					
		1/16		1/8		3/16	
		Average Feed Speed FPM		Average Feed Speed FPM		Average Feed Speed FPM	
Specimen No.	Specific Grav.†	150.5	306.7	150.5	306.7	150.5	306.7
1	0.598	0.87	1.00	1.35	1.76	1.92	2.56
2	0.519	0.76	0.97	1.10	1.54	1.58	2.24
3	0.516	0.88	1.09	1.35	1.83	1.77	2.46
4	0.435	0.78	1.00	1.36	1.71	1.73	2.23
5	0.443	0.88	1.16	1.41	1.88	1.92	2.62
6	0.476	0.79	1.07	1.30	1.81	1.84	2.49
7	0.481	0.86	0.96	1.27	1.69	1.75	2.33
8	0.490	0.88	1.09	1.30	1.75	1.74	2.41
9	0.474	0.70	1.07	1.32	1.69	1.86	2.34
10	0.466	0.71	0.88	1.24	1.60	1.77	2.36
11	0.527	0.80	1.23	1.45	1.94	1.92	2.74
12	0.513	0.72	0.86	1.18	1.53	1.60	2.14
13	0.383	0.71	0.84	1.20	1.33	1.43	1.82
14	0.334	0.72	0.93	1.11	1.42	1.46	1.88
15	0.540	0.93	1.19	1.41	1.81	1.84	2.58
16	0.651	1.24	1.59	1.78	2.48	2.24	3.04

*Refer to Table 4 for resume of factors.
†Based on O.D. weight and O.D. volume.

Table 6.—COMBINATIONS OF FACTORS UNDER TEST EASY CONDITIONS THAT PRODUCED SATISFACTORY PLANED SURFACES*

		Depth Cut in Inches					
		1/16		1/8		3/16	
		Average Feed Speed FPM		Average Feed Speed FPM		Average Feed Speed FPM	
Specimen No.	Specific Grav.†	150.5	306.7	150.5	306.7	150.5	306.7
14	0.334	*	*	*	*	*	*
13	0.383	*	*	*	*	*	*
4	0.435	*	*	*	*	*	*
5	0.443	*	*	*	*	*	*
10	0.466	*	.....	*	.....	*	...
9	0.474	*	*	.....	.....	.....	...
6	0.476	*	.....	*	.....	*	...
7	0.481	*	*	*	*	*	*
8	0.490	*	*	.....	*	.....	...
12	0.513	*	.....	*	.....	.....	...
3	0.516	*	.....	*	.....	*	...
2	0.519	*	*	*	*	*	*
11	0.527	*	*	*	*	*	*
15	0.540	*	.....	*	.....	*	
1	0.598	*	.....	*	.....	*	
16	0.651	*	*	*	*	*	

†Based on O.D. weight and O.D. volume.
*Asterisk indicates satisfactory surface.

cific gravities but with otherwise similar characteristics, as recorded in Table 4.

Readings were taken at depths of cut of 1/16, 1/8 and 3/16 inches. Feed speeds of 150.5 and 306.7 FPM were utilized. An 8-knife, 30-degree rake angle, 9-inch nominal cutting-circle head with concave-face gibs was employed.

Table 5 is a tabulation of the horsepower requirements. The combinations of factors that produced satisfactory surfaces are shown in Table 6. It can be observed that the combination of fast feeds with deep cuts has an adverse effect on quality of surface. With these particular specimens, the incidence of defective surfaces increased somewhat with increase in specific gravity. Torn grain in local areas of diagonal grain accounted for most of the surface defects, although specimens 8 and 9, which were somewhat resinous, were defective because of excessive chip marking. None of the samples exhibited any fuzzy grain or more than a trace amount of raised grain.

Figs. 8 and 9 show the net horsepower requirements at 150.5 FPM and 306.7 FPM respectively for varying specific gravities and varying depths of cut. In general, the power demand increases with specific gravity, but the relationship is not clearly indicated.

Fig. 10 is a plot of the average net cutterhead horsepower requirement for the two feed speeds involved at depths of cut of 1/16, 1/8, and 3/16 inch. The relationship involved may be expressed as follows:

$$W_n = X + Yd = 0.4 + 0.6\sqrt{V}\, d$$

where

W_n = net cutterhead horsepower requirement per inch of stock width

X = a constant = 0.4

Y = $0.6\sqrt{V}$

V = feed speed in FPM

d = depth of cut in inches

(Note: The above relationship is valid only in the range of $d = 1/16$ to $d = 3/16$ inch)

It is apparent that a doubling of depth of cut for either of the two feed speeds considered by no means doubles the horsepower requirement.

In reviewing the pictures of chip formation under Test Easy conditions, it is indicated from a comparison of Figs. 11C and 11D, as well as 11E and 11F, that the chips form under a lesser degree of control, i.e., with more advance splitting, at the higher specific gravities. However, this in itself, unless carried to an extreme degree, should not account for the higher power consumption at higher specific gravities. On the contrary, it might lessen the power consumption. However, the increased mass of the higher specific gravity chip is sufficient in itself to cause a linear increase in power demand, the accelerational force involved being equal to mass multiplied by acceleration. More than this consideration must enter the picture, however, as the strength properties of wood vary with specific gravity (9) according to the general parabolic equation:

$$y = aS^n + b$$

where

y = strength property under consideration

S = specific gravity

a = a constant

b = a constant (zero if it is assumed that wood has no strength at zero specific gravity)

n = a constant

If in this equation b becomes zero and n is taken as unity (6), then the compressive strength parallel to the grain as measured by maximum crushing strength and fiber stress at proportional limit become straight line functions of specific gravity.

In conventional milling (i.e. up-milling) the chip failure in evidence at the initial point of contact involves compressive strength parallel to the grain together with shear parallel to the grain. This type of failure is particularly evident with low rake angles. As the knife moves upward in its path, the action changes to one of shear at an angle to the grain. If advance splitting takes place before the knife emerges from the cut, it is caused by cleavage and failure in tension perpendicular to the grain.

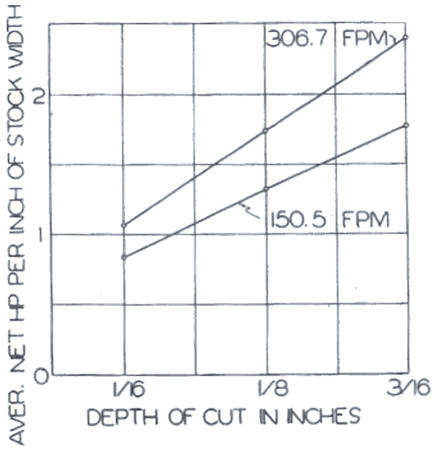

Fig. 10.—Average net horsepower requirement for wood removal under Test Easy conditions comparing feed speeds of 306.7 and 150.5 FPM at varying depths of cut.

Kollman (5) reports that with increasing wood density, or more accurately expressed, with increased shear resistance parallel to the fiber, the planing work and feed force increase.

Kivimaa (3), on parallel to the grain tests involving a multiplicity of species, found that there was a somewhat curvilinear relationship between main cutting force parallel to knife tip motion and specific gravity, i.e, as specific gravity was doubled, the main cutting force increased, but in a lesser proportion.

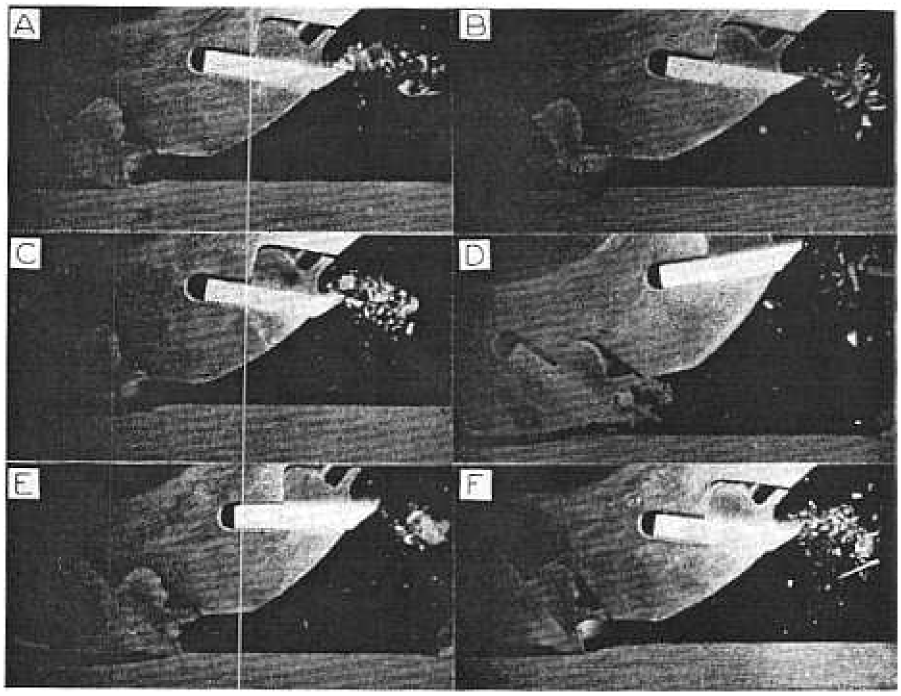

Fig. 11.—Test Easy. (A) Spec. grav.: 0.383; depth cut: 1/8 inch; feed speed: 300 FPM. (B) Spec. grav.: 0.651; depth cut: 1/16 inch; feed speed: 300 FPM. (C) Spec. grav.: 0.334; depth cut: 3/16 inch; feed speed: 300 FPM. (D) Spec. grav.: 0.651; depth cut: 3/16 inch; feed speed: 300 FPM. (E) Spec. grav.: 0.334; depth cut: 3/16 inch; feed speed: 150 FPM. (F) Spec. grav.: 0.540; depth cut: 3/16 inch; feed speed: 150 FPM.

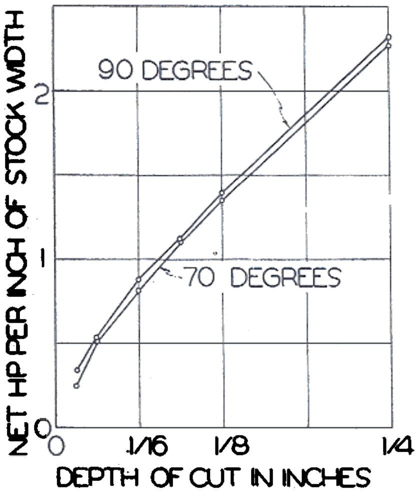

Fig. 12.—Net horsepower requirement for wood removal under Text Fox conditions comparing 90 and 70 degree angles between the rotational axis of the cutterhead and the direction of feed.

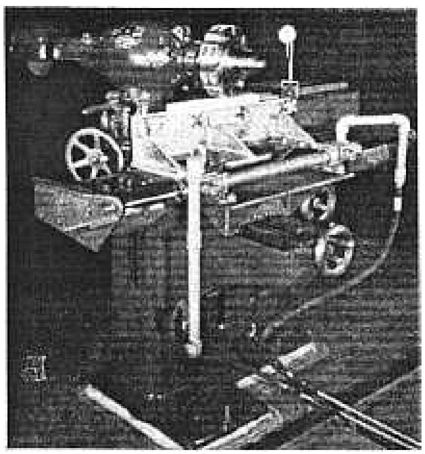

Fig. 13.—Test Fox. Apparatus for planing specimens with the cutterhead rotational axis oriented to any desired angle with relation to the direction of feed.

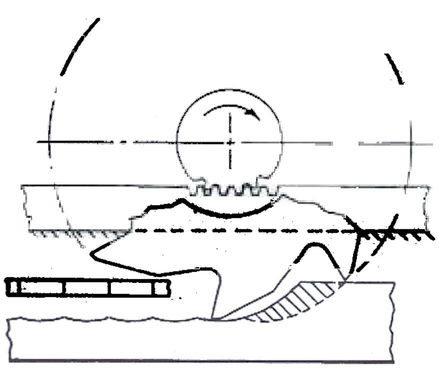

Fig. 14.—Path generated by down-milling cutter knife.

Table 8.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST FOX CONDITIONS*

Depth of Cut in Inches	Angle Between Axis of Cutterhead Spingle and Direction of Feed: 90 Degrees	70 Degrees
1/64	0.34	0.25
1/32	0.53	0.51
1/16	0.88	0.82
3/32	1.12	1.11
1/8	1.39	1.35
1/4	2.32	2.27

*Refer to Table 7 for resume of factors.

Davis and Nelson (1) found that combined feed and cutterhead power consumption shows a somewhat consistent relationship to specific gravity, the heavier woods in general requiring more power than the lighter ones; however, it is noted that power consumption in machining different woods is not always directly proportional to their specific gravity. Yellow poplar, for instance, requires more power than some heavier woods such as red gum and southern yellow pine.

These findings are not in disagreement with the results reported herein. Between-species comparisons were not tested here.

C. Test Fox: This two-factor experiment was designed to test the interaction of the variables of depth of cut, and the angle between the rotational axis of the cutterhead and the direction of feed. In the execution of this test, an 8-knife, 30-degree rake angle, 9.08-inch cutting-circle cutterhead was used. The feed speed involved was approximately 200 FPM. All readings were taken serially on a single specimen as described in Table 7.

The means of rotating the cutterhead spindle axis to the desired degree is shown in Fig. 13. The short specimen shown in testing position is for illustrative purposes only, as this experiment was conducted using a board 9 feet in length. Readings were taken at depths of cut of 1/64, 1/32, 1/16, 3/32, 1/8, and 1/4 inches.

Table 7.—RESUME OF FACTORS APPLYING TO TEST FOX

Variable Factors:
- Angle between Rotational Axis of Cutterhead and Direction of Feed: (90 degrees and 70 degrees)
- Depth of Cut in Inches: (1/64, 1/32, 1/16, 3/32, 1/8, and 1/4)

Fixed Factors:
- Specimen:
  - General Description: The test piece [illegible] foot-long dry 1 by 3 board.
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: 17 ± 2
  - Width of Machined Surface: 0.785 ± 0.002 inches
  - Angle of Annual Rings to Machined Surface: 30 ± 4 degrees
  - Spiral Grain: None
  - Percent Moisture Content (based on O.D. weight): 8.9 ± 0.3
  - Specific Gravity (based on O.D. weight and O.D. volume): 0.374 ± 0.008.
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Body: Jointer type, 8-knife
  - Gibs: Flat (i.e. not concave) chipbreaking surfaces at right angles to the knife face
  - Knives: 5/16-inch thick with corrugated back
  - Number of Knives: 8
  - Cutting Circle Diameter: 9.08 inches
  - Rake: 30 degrees
  - Clearance: 20 degrees
  - Knife Extension Beyond Gib: 0.344 ± 0.010 inches
  - Width of Joint: 0.007 ± 0.001
  - Nominal RPM of Cutterhead: 3600
- Feed:
  - Speed: 206 ± 2 FPM

No unsatisfactory surfaces were produced by any combination of variables. Table 8 is a tabulation of the horsepower requirements. Fig. 12 presents the data in more easily interpreted form. These data indicate that the slewed cutterhead axis results in a slightly lower power demand. One possible explanation of this situation lies in the fact that the chip in all probability takes a longer path to reach the gib face when the cutterhead axis is slewed (12) and hence the slewed head has a greater effective knife extension with corresponding decrease in power demand. On the other hand, the knives in the cutterhead used for Test Fox already had a liberal extension beyond the gib face (0.344 inches). Fig. 17 indicates that further knife extension will not substantially decrease the cutterhead power requirement.

Both plots show a tendency to curve rather sharply to zero horsepower requirement as zero depth of cut is approached, thus altering the approximately linear relationship that exists between 1/16 inch depth of cut and 1/4 inch depth of cut.

D. Test George: This two-factor experiment was designed to test the interaction of the variables of depth of cut and direction of cutterhead rotation with relation to direction of feed. As discussed in connection with Figs. 2 and 3 of the previous article (4), there are two primary directions of cutterhead rotation with relation to the direction of feed. Up-milling applies to all of this test series except the one under consideration. In this test a brief comparison is drawn between the up-milling process and that process known as down-milling. Fig. 14 illustrates the geometry of down-milling.

An understanding of the kinematic relationships between up-milling and down-milling may be attained through a study of the formulae developed by Martellotti (7) (8). If these formulae are applied to a situation in which a jointed, 8-knife, 9-inch cutting-circle cutterhead revolving at 3450 RPM is taking a 1/8 inch deep cut at a feed speed of 300 FPM, the information in the table below is revealed:

In other words, down-milling results in a greater wave height on the finished surface, a shorter radius of knife trace curvature, a shorter length of knife engagement, and a thicker undeformed chip than does up-milling under similar circumstances. A large

	Distance between knife marks or feed per knife in inches	Wave height in inches	Instantaneous radius of curvature of knife path in inches	Length of knife engagement in inches	Average undeformed chip thickness in inches
Up-Milling	0.180	0.000441	4.83	1.100	0.0148
Down-Milling	0.180	0.000511	4.18	1.022	0.0160

wave height and a short radius of knife trace curvature are usually considered detrimental when evaluating the quality of a planed surface.

An 8-knife, 9.08 inch diameter cutting-circle cutterhead with a 30-degree rake angle was used in this test. A feed speed of 206 FPM was employed with depths of cut ranging from 1/64 to 1/4 inches.

Both up-milling and down-milling readings were taken serially from the same specimen as described on the test data sheet. The photographs employed in the discussion were not taken of the actual test specimen. They illustrate the principle involved rather than individual test readings, as has been the case previously.

The surfaces produced by both up- and down-milling under the conditions of the test were satisfactory at all depths of cut. The most striking difference to be observed was the elimination by down-milling of the moderate amount of chip marking present during the up-milling process. This is a reasonable result, as in down-milling the knife tips have a chance to wipe themselves clean of adhering chips and fiber bundles before they reach that short final section of engagement that defines the resulting surface. Further, in down-milling it is possible that each element of the resultant surface is not produced by direct contact of the knife tip with the surface, but rather is defined by the intersections of the planes of shear failures of the deforming chips.

By contrast, the initial fraction of an inch of knife engagement defines the resultant surface in up-milling. Therefore, if there is anything adhering to the knife tip it is sure to register as an indentation of the finished surface. Of course, it wave height or knife trace radius is used as a measuring stick of surface quality, then the down-milling process presents a surface inferior to up-milling for a given feed per knife.

Table 10 presents the horsepower requirements in tabular form. Fig. 15 gives the same information in chart form. From these data it is observed that the down-milling process as tested requires more cutterhead power than does up-milling.

Table 10.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST GEORGE CONDITIONS*

Depth of Cut in Inches	Direction of Cutterhead Rotation with Relation to Direction of Feed: Conventional Up-Milling (Against Feed)	Down-Milling (With Feed)
1/64	0.34	0.41
1/32	0.53	0.65
1/16	0.88	1.06
3/32	1.12	1.45
1/8	1.39	1.86
1/4	2.32	----

*Refer to Table 9 for resume of factors.

It will be noted from a comparison of the two processes that there is a fundamental difference in the manner of knife approach. In up-milling the knife engages the work in nearly tangential relationship to the surface previously milled by the preceding knife, and therefore beginning chip thickness is minute. By contrast, the down-milling knife approaches the rough or unmachined surface at a distance equal to the feed per knife from the path generated by the previous knife, and after chip formation emerges in a nearly tangential fashion. It is apparent that the down-milling knife engages at a point of much greater chip thickness than does the up-milling knife.

An explanation for the higher cutterhead power demand of down-milling as compared to up-milling lies in the fact that average chip thickness is greater for down-milling than it is for up-milling, and due to the attitude of the knife at engagement, energy-saving advance splitting that is frequently characteristic of up-milling is not so likely to occur in the down-milling process.

It has been determined by Kivimaa (3) that in the range of rake angles most frequently used, i.e., plus 15 to plus 45 degrees, the cutterhead has a tendency to lift the work piece away from the bedplate when using a circular path type chip testing device. This approximates the situation with up-milling where holddown mechanisms are necessary to keep the work piece from lifting under action of the cutterhead. By contrast, in the down-milling process the work is held strongly against the bedplate due to

Table 9.—RESUME OF FACTORS APPLYING TO TEST GEORGE

Variable Factors:
- Direction of Cutterhead Rotation with Relation to Direction of Feed: (Conventional up-milling against feed and down-milling with feed)
- Depth of Cut in Inches: (1/64, 1/32, 1/16, 3/32, 1/8, and 1/4)

Fixed Factors:
- Specimen:
  - General Description: The test piece was a nine-foot-long dry 1 by 8 board
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: 17 ± 2
  - Width of Machined Surface: 0.785 ± 0.002 inches
  - Angle of Annual Rings to Machined Surface: 80 ± 4 degrees
  - Spiral Grain: None
  - Percent Moisture Content (based on O.D. weight): 8.9 ± 0.3
  - Specific Gravity (based on O.D. weight and O.D. volume): 0.374 ± 0.008
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Body: Jointer type, 8-knife
  - Gibs: Flat (i.e. not concave) chipbreaking surfaces at right angles to the knife face
  - Knives: 5/16-inch thick with corrugated back
  - Number of Knives: 8
  - Cutting Circle Diameter: 9.08 inches
  - Rake: 30 degrees
  - Clearance: 20 degrees
  - Knife Extension beyond Gib: 0.344 ± 0.010 inches
  - Width of Joint: 0.007 ± 0.001
  - Nominal RPM of Cutterhead: 3600
- Feed:
  - Speed: 206 ± 3 FPM

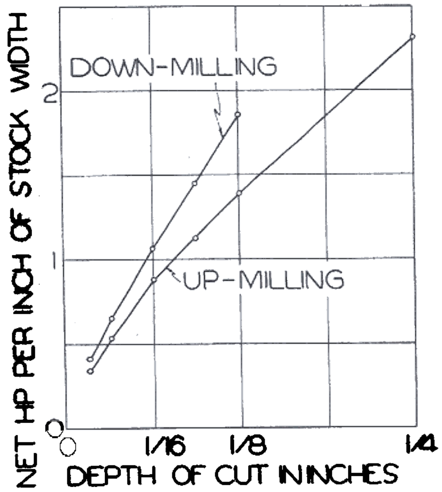

Fig. 15.—Net cutterhead horsepower requirement for wood removal under Test George conditions comparing conventional up-milling against feed to down-milling with feed.

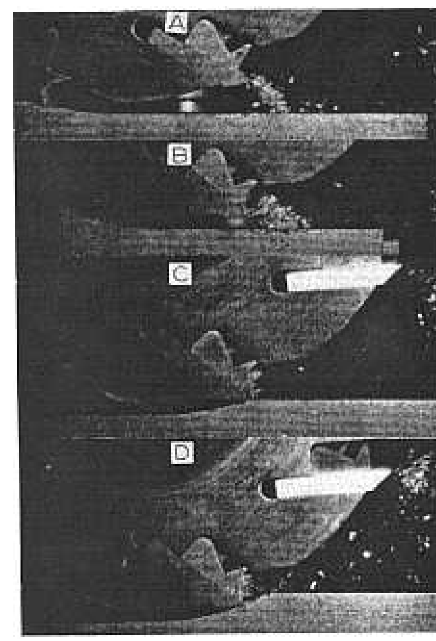

Fig. 16.—Test George. (A) Down-milling; 1/4-inch depth of cut; 175 FPM feed speed. (B) Down-milling; 1/2-inch depth of cut; 175 FPM feed speed. (C) Up-milling; 1/4-inch depth of cut; 175 FPM feed speed. (D) Up-milling; 1/2-inch depth of cut; 175 FPM feed speed.

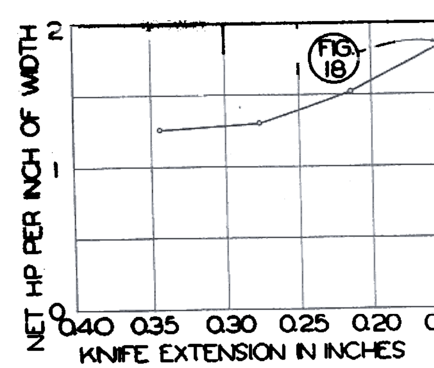

Fig. 17.—Net horsepower requirement for wood removal under Test How conditions comparing various distances of knife extension beyond gib face.

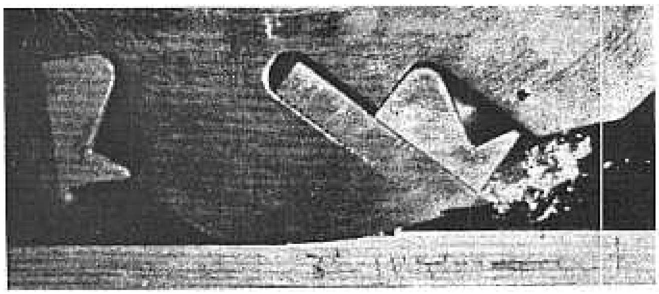

Fig. 18.—Test How. 8-knife, 8.70-inch cutting-circle cutterhead with knives extended 0.152 inch from gib face taking a 3/32-inch deep cut at a feed speed of 300 FPM.

the manner of knife engagement, as illustrated in Figs. 16A and 16B. While the foregoing force encountered in down-milling may be of some advantage, the accompanying horizontal force vector, which tends to bring together cutterhead and work piece at an uncontrolled rate, is a definite disadvantage in view of the continuous manner in which lumber is planed. In general, it is undesirable to operate a planer with the outfeed rolls firmly engaged because of the additional chip marking they cause, and for this reason it does not seem practical to attempt to use them or a similar device to retard and control the flow of lumber through a machine employing the down-milling process.

A further difficulty incidental to down-milling is observed in Fig. 16B, which indicates that chip collecting might be more difficult than under up-milling conditions as illustrated in Figs. 16C and 16D.

Martellotti (8) in his study of metal milling found that cutterhead spindle power was greater for down-milling than for up-milling under a given set of conditions, but that this power penalty was more than offset by a decrease in necessary feed power. In other words, when both spindle and feed power requirements were considered, down-milling required less power than up-milling.

Engelsson, Hvamb, and Thunell (2), in their studies of circular sawing techniques, reported that down-milling required 50 to 70 per cent more spindle power than did up-milling under their test conditions. Under the conditions of their tests, the decreased feed power required for down-milling was not sufficient to compensate for the increased spindle power. In other words, in this instance the total power required was greater for down-milling than it was for up-milling.

Other studies by Thunell (13) as well as research by Skoglund and Hvamb (11) discuss up- and down-milling as applied to circular sawing technique, but they are of such a nature that they do not permit direct comparison with this work.

The results reported herein are not inconsistent with the findings cited above.

E. Test How: This single factor experiment was designed to study the effect of varying the knife extension beyond the face of the gib. In order to have a definite surface from which to gauge the extension, gibs having a flat face at right angles to the knife face were selected. These gibs are illustrated in Fig. 18. While there is little doubt that gib shape has an important bearing on the relationship between horsepower requirement and knife extension, this test considers only the gib shape illustrated.

The increments of knife extension were determined by the distance between corrugations on the back of the 5/16-inch-thick knives. As the knives were reseated at each succeeding lesser extension, the cutting circle diameter was reduced by a corresponding amount. The effect on horsepower requirement of this reduction of cutting circle diameter was partially offset by an increase in joint width occasioned by rejointing following each reseating of the knives.

An 8-knife cutterhead, a feed speed of 300 FPM, and a depth of cut of 3/32 inches were selected as a representative median situation. Fig. 17 indicates that from a point of view of power consumption, this particular gib should utilize a knife extension of not less than 9/32 inches when operating under these conditions. A knife extension of 0.152 inches uses 46.8 per cent more power than a knife extension of 0.344 inches.

Fig. 18 permits visulization of the abrupt chip deformation caused by a smaller knife extension.

F. Test Ivy: This two-factor experiment was designed to study the interaction of the variables of width of joint and depth of cut. The tests were run serially on a single specimen as described in Table 13. The depths of cut ranged from 1/64 to 1/4 inch. An 8-knife, 9.08-inch diameter cutting-circle, 30 -degree rake angle cut-

Table 11.—RESUME OF FACTORS APPLYING TO TEST HOW

Variable Factor:

Knife Extension in Inches beyond Face of Gib	Corresponding Cutting-Circle Diam. in Inches	Corresponding Width of Joint in Inches
0.344 ± 0.011	9.08	0.007 ± 0.001
0.277 ± 0.015	8.95	0.011 ± 0.002
0.214 ± 0.012	8.82	0.017 ± 0.006
0.152 ± 0.011	8.70	0.019 ± 0.008

Fixed Factors:
- Specimen:
  - General Description: The test piece was a 9-foot-long dry 1 by 3 board
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: 17 ± 2
  - Width of Machined Surface: 0.785 ± 0.002
  - Angle of Annual Rings to Machined Surface: 30 ± 4 degrees
  - Spiral Grain: None
  - Percent Moisture Content (based on O.D. weight): 8.9 ± 0.3
  - Specific Gravity (based on O.D. weight and O.D. volume): 0.374 ± 0.008
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Body: Jointer type, 8-knife
  - Gibs: Flat (i.e. not concave) chipbreaking surfaces at right angles to the knife face.
  - Knives: 5/16-inch thick with corrugated back
  - Number of Knives: 8
  - Rake: 30 degrees
  - Clearance: 20 degrees
  - Nominal RPM of Cutterhead: 3600
- Feed:
  - Speed: 300 ± 1 FPM
  - Depth of Cut: 3/32 inch

Table 12.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST HOW CONDITIONS*

Knife Extension Beyond Gib Face Inches	Cutting-Circle Diameter Inches	Net Horsepower
0.344	9.08	1.26
0.277	8.95	1.30
0.214	8.82	1.52
0.152	8.70	1.85

*Refer to Table 11 for resume of factors.

Table 13.—RESUME OF FACTORS APPLYING TO TEST IVY

Variable Factors:
- Width of Joint in Inches: (0.007 ± 0.001 and 0.040 ± 0.009
- Depth of Cut in Inches: (1/64, 1/32, 1/16, 3/32, 1/8, and 1/4)

Fixed Factors:
- Specimen:
  - General Description: The test piece was a nine-foot-long dry 1 by 3 board.
  - Species: Pseudotsuga taxifolia
  - Wood Type: Heart
  - Rings per Inch: 17 ± 2
  - Width of Machined Surface: 0.785 ± 0.002
  - Angle of Annual Rings to Machined Surface: 30 ± 4 degrees
  - Sprial Grain: None
  - Percent Moisture Content (based on O.D. weight): 8.9 ± 0.3
  - Specific Gravity (based on O.D. weight and O.D. volume): 0.374 ± 0.008
  - Inclination of Diagonal Grain to Direction of Feed: None
- Cutterhead:
  - Head Body: Jointer type, 8-knife
  - Gibs: Flat (i.e. not concave) chipbreaking surfaces at right angles to the knife face
  - Knives: 5/16-inch thick with corrugated back
  - Number of Knives: 8
  - Cutting-Circle Diameter: 9.08 inches
  - Rake: 30 degrees
  - Clearance: 20 degrees
  - Knife Extension beyond Gib: 0.344 ± 0.010 inches
  - Nominal RPM of Cutterhead: 3600
- Feed:
  - Speed: 206 ± 3 FPM

Table 14.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST IVY CONDITIONS*

Depth of Cut in Inches	Width of Joint in Inches 0.007	0.040
1/64	0.34	0.47
1/32	0.53	0.71
1/16	0.88	1.01
3/32	1.12	1.30
1/8	1.39	1.58
1/4	2.32	--

*Refer to Table 13 for resume of factors.

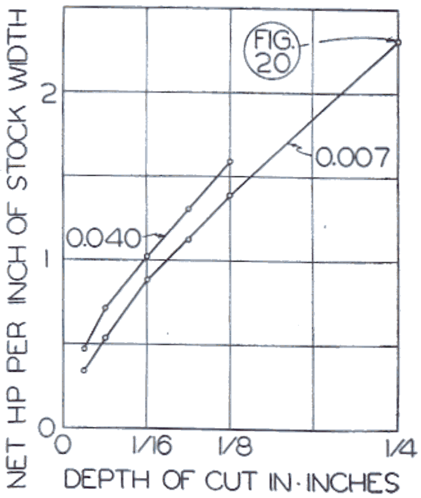

Fig. 19.—Net horsepower requirement for wood removal under Test Ivy conditions comparing 0.040-inch and 0.007-inch widths of joint.

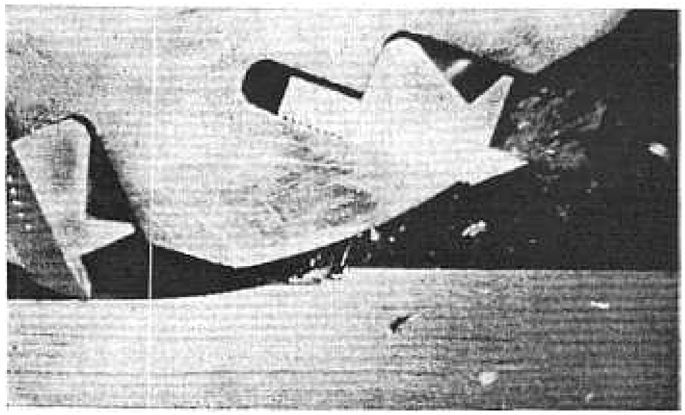

Fig. 20.—Test Ivy. 8-knife, 9.08-inch cutting-circle cutterhead with knives jointed to a heel width of 0.007 inch taking a ¼-inch deep cut at a feed speed of 206 FPM.

terhead was employed with a feed speed of 206 FPM.

The horsepower readings were first taken for the 0.040-inch width of joint, after which the knives were heel ground and lightly rejointed to a joint width of 0.007 inches.

The surfaces produced were generally satisfactory, although considerable chip marking was evident with both widths of joint at all but the lightest cuts. Table 14 shows the net horsepower requirements. Fig. 19 is a plot of this same information. Considering depths of cut up to and including 1/8 inch, the cutterhead mounting knives with 0.040-inch width joint took 19.3 per cent more power than the same cutterhead mounted with knives having an 0.007-inch width of joint. Fig. 20 illustrates the cutterhead used. Knives with a wide joint require more power for the same reason that knives with exceedingly low clearance require more power, i.e., the heel interferes with the machined surface as the knife nears the end of its path. It will be observed from pictures presented that the clearance angle decreases and the rake angle increases from the nominal values as the knife moves toward emergence in the up-milling process. Therefore, the jointed surface of the knife, by the nature of its generation, is certain to interfere to some degree with the work piece.

It will be noted that the percentage of power penalty occasioned by the greater joint width tends to decrease as the depth of cut increases. The percentage of penalty ranges from a high of 38.2 per cent at 1/64-inch depth of cut to a low of 13.7 per cent at ⅛-inch depth of cut. The explanation may lie in the possibility of more advance splitting taking place at the larger depths of cut with correspondingly less interference between knife heel and work piece.

Petter (10) reports that a heavily jointed cutterhead requires approximately 75 per cent more power than a lightly jointed cutterhead. In the absence of details on the widths of joints involved in the test cited, the information seems in general agreement with the results reported here.

Conclusions

The various factors tested to determine their relationship to net cutterhead horsepower requirement have been discussed as they occurred in the individual tests of the series being reported. A re-inspection of the information permits some conclusions to be drawn. The comments are grouped according to the factor involved.

Cutterhead Factors

A. Diameter of Cutting-Circle (Test Able): For any given combination of factors, an increase in cutting-circle diameter will increase the cutterhead power requirement. Under the test conditions, it was found in a summation of all factors that a 9.02-inch diameter cutting-circle cutterhead requires 7.35 per cent more power than a 7.63-inch diameter cutting-circle head. This difference in power demand is more pronounced with green stock, on which the large cutterhead requires 10.8 per cent more power than the smaller head. On dry stock, the large head requires 3.37 per cent more power than the small head.

B. Knife Extension Beyond Face of Gib (Test How): Up to a certain critical value, the knife extension beyond the face of the gib is inversely related to the horsepower requirement of the cutterhead. The critical value of knife extension depends on the conformation of the knife and gib combination. In the simplified test situation where the gib face is perpendicular to a 30-degree rake angle knife face, it was found that the knife extension should be at least 9/32 inch beyond the face of the gib. Under the conditions of the experiment, a 5/32-inch extension requires approximately 40 per cent more power than does a 9/32 inch extension.

C. Width of Joint (Test Ivy): The width of joint exerts a very pronounced influence on the cutterhead power demand. The magnitude of the effect is inversely related to the depth of cut. These experiments indicate that, under the test conditions on dry stock, a joint width of 0.040 inches requires 38.2 per cent more power than does a joint width of 0.007 inches when operating at a 1/64 inch depth of cut. At a ⅛ inch depth of cut, the cutterhead with the wider joint took 13.7 per cent more power.

Feed Factors

A. Angle between Rotational Axis of Cutterhead and Direction of Feed (Test Fox): A slight cutterhead horsepower advantage was noted when the rotational axis of the cutterhead was slewed to make a 70-degree angle with the direction of feed as compared with the conventional 90-degree angle. Although the cutterhead employed for the tests had adequate knife extension as previously defined, it is possible that the greater effective knife extension obtained when the spindle axis was slewed from its normal position accounts for the horsepower saving recorded.

B. Direction of Cutterhead Rotation with Relation to Direction of Feed (Test George): Under the test conditions using an 8-knife cutterhead in conjunction with a 206 FPM rate of feed on dry stock, down-milling takes an average of 25.4 per cent more cutterhead power than does up-milling in the conventional fashion. The percentage of penalty is related to the depth of cut involved, ranging from 20.6 per cent at a 1/64-inch depth of cut to 33.8 per cent at a ⅛-inch depth of cut.

Workpiece Factors

A. Specific Gravity (Test Easy): In general the net cutterhead horsepower requirement increases with an increase in specific gravity of the wood being machined. This relationship exists at varying depths of cut. Under the conditions of the test, the percentage increase in net cutterhead horsepower demand is sensitive to the feed speed involved. At 150 FPM an increase in specific gravity from 0.35 to 0.70 (oven dry weight, oven dry volume basis) results in an average of 60-per cent increase in power demand, while at 307 FPM the per cent increase is 70 per cent. The test results show such a spread of horsepower demand values for specimens with equal or nearly equal specific gravity values that a valid generalization is difficult to make.

Literature Cited

1. Davis, E. M. and Nelson, H. 1954. Machining tests of wood with the molder. Jour. of F.P.R.S. IV(5):237–245.
2. Englesson, T., Hvamb, G., and Thunell, B. 1954. Nagra resultat fran undersökningar över med- och motsagning. Svenska Träforskningsinstitutet Träteknik. Meddelande 53B. Stockholm.
3. Kivimaa, E. 1950. Cutting force in woodworking. The State Institute for Technical Research, Finland. Pub. 18.
4. Koch, Peter. 1955. An analysis of the lumber planing process—Part I. For. Prod. Jour. V(4):255–264.
5. Kollmann, F. 1936. Technologie des Holzes, Berlin, Julius Springer. Pg. 511.
6. Luxford, R. F., Trayer, G. W., et al. 1940. Wood handbook, U. S. Dept. of Agric., Forest Products Laboratory, Forest Service. Table 10.
7. Martellotti, M. E. 1941. An analysis of the milling process. Trans. of Am. Soc. of Mech. Eng. 63:677–700.
8. Martellotti, M. E. 1945. An analysis of the milling process. Part II—Down Milling. Trans. of Am. Soc. of Mech. Eng. 67:233–251.
9. Newlin, J. A. and Wilson, T. R. C. 1919. The relation of shrinkage and strength properties of wood to its specific gravity. U. S. Dept. of Agric. Bul. 676.
10. Petter, J. C. 1954. Development work on wood planers. Jour. of F.P.R.S. IV(5):234–236.
11. Skogland, C. and Hvamb, G. 1953. Sagtandvinklars inverkan pa kraftförbrukningen vid med och motsagning. Svenska Träforskningsinstitutet Träteknik. Meddelande 37B. Stockholm.
12. Stabler, G. V. 1951. The fundamental geometry of cutting tools. The Institution of Mechanical Engineers (London). Proceedings 165 (W.E.P. No. 63), pg. 14.
13. Thunell, B. 1953. Forschung und Entwicklung auf dem Gebiete der Sägewerkstechnik. Holz als Roh- und Werkstoff, Bd. 11, pg. 420–429.

Discussion

Milton H. Mater (Mater Engineering Co.): Did you calculate the horsepower required to remove one cubic inch of wood under varying circumstances?

Mr. Koch: The ordinates of the horsepower curves we have been discussing represent net horsepower consumption per inch of stock width. Inasmuch as the depth of cut and the feed rate is known for each test situation, the rate of wood removal (in cubic inches per minute) can be easily calculated. Corresponding horsepower consumption can be read directly from the horsepower curves (or from the tables of data relating to each test).

Mr. Mater: Did you try climb milling with different rake and clearance angles to determine the effect on horsepower requirements?

Mr. Koch: No, I didn't; however, the results of the rather extensive upmilling test (test Charlie) involving the variables of rake angle, clearance angle, depth of cut and per cent moisture content were reported in Part I of this paper (published in the August 1955 Forest Products Journal). A similar experiment could be executed for climb-milling.

R. V. Reynolds (Kennametal, Inc.): Is testing equipment available for general testing?

Mr. Koch: Perhaps half the equipment required is immediately available and the other half could be readily obtained with the cooperation of industry.

W. J. Tomford (James E. Stark, Co.): Were there any differences other than power observed in slewing or changing knife angle?

Mr. Koch: All of the surfaces produced in this experiment (Test Fox) were satisfactory, regardless of whether they were produced by slewed or conventional cutterhead orientation. It was observed, however, that on lumber that was prone to chip-marking the diagonal orientation of the chip marks (as produced by the slewed head) made them more obvious to the eye. The effect of the slewed head on torn grain needs further exploration. In passing it might be observed that the slewed head is not a new idea. As early as 1884 such a machine was produced in this country by the S. A. Woods Company.