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EFFECTS OF SEVERAL FACTORS
ON THE
POWER REQUIRED FOR PLANING WOOD

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THE BUSS MACHINE WORKS
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EFFECT OF SEVERAL FACTORS
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HISTORY AND DEVELOPMENT

The project of which these studies are a part is based upon a practical need for scientific facts on the design and performance of planing machines. This need has long been recognized by the Buss Machine Works, and their interest and support have made possible a research project in this field. The series of studies covered by this report are one of the principal phases of this work and are the most extensive investigation of the power requirements for planing that are known to have been conducted.

Although power requirement is one of the most important factors in planer design and operation, there has been almost no technical data available to industry on the subject. The primary reason for this lack has undoubtedly been the size of investment necessary to provide adequate research facilities. Recently, the School of Natural Resources of the University of Michigan installed at the Wood Technology Laboratory more than $20,000 worth of equipment of the type needed to determine planing power requirements. It then became practicable for a machine builder such as the Buss Machine Works to support an investigation of this kind through the University's Engineering Research Institute without a heavy investment of the sponsor's money for research equipment. As a result, it has been possible to retain the entire support of the sponsor for personnel and materials.

In cooperation with the Buss Machine Works the staff of the Wood Technology Laboratory outlined an investigation which would determine the relationship between cutterhead drive power and other major factors involved in planing wood. Since there was little research of this type to draw upon, the approach was almost entirely original, and the experimental techniques used were, in the main, new to woodworking research.

Fundamental facts, when established under carefully controlled conditions, can be applied to many specific problems. In this investigation it was obviously more economical and valuable to seek such basic facts than to conduct unrelated experiments which had limited objectives. Consequently, the results which are presented in this report are mainly fundamentals which can be enlarged upon to provide specific answers. The Buss engineering staff will undoubtedly want to use these results for certain design purposes and for answers to customers' problems. In many cases the needed data can be drawn directly from the report. In others it will be necessary to modify the given information to fit the specific situation. It should be recognized, however, that only a beginning has been made in determining the many complex relationships which exist between power and cutting conditions in planing.

By limiting the number of species and conditions studied, it was possible to explore most of the major factors affecting cutterhead power without consuming excessive amounts of time and materials. Although the results obtained are valid only for the species studied, it is believed that results for other species would parallel these in a general way. No close correlation was found, however, which would make it possible to group woods on the basis of some common physical characteristic.

Part I of this report deals with the effect of depth of cut and width of cut, condition of knives, grain direction, and specific gravity on power, and evaluates dimensional variation and repeatability of results. A study of head speed and feed rate is described in Part II. Part III gives the results of an additional study made to determine the effect of knife condition on power. Part IV is a study of the effect of cutting velocity on power and surface quality.

FACILITIES

The University makes all of its research facilities available to the sponsor of an Engineering Research Institute project; and although the work on this project has been centered mainly at the Wood Technology Laboratory, several other units of the University have been particularly helpful in such ways as furnishing statistical, photographic, and editorial services.

An explanation of the physical equipment which has been employed in this investigation will be helpful in understanding the procedures used.

The principal components of equipment were a Buss Model 4L single surfacing planer, a General Electric frequency converter, an Esterline-Angus Model AW recording wattmeter, and a General Radio Strobotac. These are described below. In addition to these specific items, this investigation has been dependent on other facilities of the Laboratory, such as its machine shop, moisture conditioning rooms, and dry kiln.

Buss Model 4L Planer

This machine has had light and intermittent use since 1947 for instruction and research. Before this investigation was begun, the machine was completely checked and adjusted by a Buss field engineer. Other adjustments were made when needed throughout the work by the Laboratory staff.

Capacity: 30" x 8"

Cutting Circle: 5-3/16", approximately

Feed Motor: 2 HP — 4 speeds giving 23, 35, 46, 68 ft per minute

Cutterhead Motor: General Electric Model No. 5K324D426 15 HP — giving 3600 RPM at 60 cycles per second. 3480 RPM minimum at rated load

Characteristic	Rated Load	3/4 Load	1/2 Load
Motor efficiency (%)	89.0	90.0	89.5
Power factor (%)	88.5	87.0	81.0
Torque (ft. lbs.)	22.5	37.8	52.0

Depth Setting: Depth of cut set by accurate micrometer dial to nearest one-thousandths inch

Knives: Thin high speed steel

Cutting Angle: 25° (used for all studies reported)

Sharpness Angle: 50° (nominal)

General Electric Frequency Converter

This unit is composed of a General Electric Type MM Converter (Model 5 MM 1405 BK 1) driven by a General Electric Type ACA variable-speed motor (Model 5ACA 1404 A1R). With this unit, a range of frequencies from 80 to 130 cycles per second is available.

The coupling between the drive and converter is a 3-belt "V" drive. This unit may be used to supply either the cutterhead or the feed motor independently or both together at the same frequency. Either motor may be operated on line frequency while the other is supplied by the converter.

Esterline-Angus Model AW Recording Wattmeter

This instrument is of a portable type and has been fitted with a connection by which it may be conveniently attached to the laboratory machines. It is equipped with appropriate current transformers to cover a wide range of power readings.

A continuous graphic record is made of the tare or idling power or the gross power required under load.

General Radio Type 631-B Strobotac

The Strobotac is a stroboscopic light, used in this case to determine the exact spindle speed of the cutterhead in revolutions per minute. When this instrument is calibrated and precisely read, the speed may be determined within an accuracy of a few revolutions per minute.

Plates II-A and II-B, pages 36 and 37, show a typical equipment setup for power studies.

TERMINOLOGY

Definitions of several basic terms of mechanics which are used in this report are included below for convenient reference. The definitions have been elaborated upon where possible to put them in the context of this investigation. Other terms which are used in the report have not previously been applied to the machining of wood but are standard terminology in analogous fields. These have been adapted to fit the characteristic practices of woodworking and are defined here in this form.

Work

Work is the product of a force applied and the distance through which it acts. It is stated in units of foot-pounds or dyne-centimeters.

Power

Power is the time rate of doing work and is expressed in foot-pounds, or dyne-centimeters, per second or in the practical units of horsepower (33,000 foot-pounds per minute) or kilowatts (10^{10} dyne-centimeters per second).

Since the primary aim of a machining operation is to obtain desired dimensions and shapes by removing material, it is important to know how this can be done most effectively. The power input to the cutterhead motor is comparatively easy to measure and is a sensitive indicator of cutting conditions. Consequently, power is a logical standard to use in determining the effectiveness of many machining operations.

There are two important aspects of machining power which must be considered: first, the power required to run the cutting tool without cutting, which is commonly referred to as tare power, and second, the power which is required to remove chips from the stock, or net power. Tare power is a characteristic of the machine itself and has no relation to the other factors of cutting except velocity. The net power, on the other hand, reflects the physical characteristics of the stock, the feed rate, the depth of cut, and tool condition in addition to the tool velocity, and is a measure of the work required to remove the excess material from the stock.

In this investigation three classes of net power are considered; net power delivered to the motor after deducting tare power, net power delivered to the spindle after electrical losses in the motor, and net power available for cutting after mechanical losses in bearings, windage, etc. These are designated as follows: P_m = net power to motor; P_n = net power to spindle; P_e = net power available for cutting. Only P_m and P_n could be determined in this investigation. A complex dynamometer installation would have been required to find P_e. For the purposes of this work P_n was considered to be the net power available for cutting. The following equations represent these power relationships.

$$P_g - P_t = P_m \tag{1}$$

$$P_m - L_e = P_n \tag{2}$$

$$P_n - L_m = P_e, \tag{3}$$

where

P_g = Gross power
P_t = Tare power
P_m = Net power to motor
P_n = Net power to spindle
P_e = Net power available for cutting
L_e = Electrical losses = P_m x M
L_m = Mechanical losses
M = Motor efficiency

Tare power, since it is a characteristic of the machine, is individual for every machine. However, when the same material is machined under the same conditions of cutting, the net power is theoretically the same for any machine and is a more absolute measuring stick for machinability than gross power (tare plus net). The data presented in this report is based on net power, and this should be taken into account when interpreting the results. Since net power is theoretically the same for any machine, the data given here may be applied to the tare power for any similar machine to obtain the minimum horsepower rating. The net power obtained for the conditions being considered should be divided by the motor efficiency and added to the tare power for the particular machine. The equation for this is

$$\text{Minimum HP rating} = \frac{P_n}{M} + P_t, \qquad (4)$$

where

P_n = Net power to spindle (HP)

P_t = Tare power for the machine (HP)

M = Motor efficiency (%)

Efficiency of Removing Material

The term "efficiency" as used in this report is the efficiency of removing material. It expresses the volume of material which can be removed in a given time with a given amount of power delivered to the spindle in excess of the tare power. It is stated in units of cubic inches per minute per horsepower. The equation for efficiency is

$$E = \frac{w \times d \times F}{P_m \times M \times 1.341}, \qquad (5)$$

where

E = Efficiency of removing material (cu in/min/HP)

w = Width of cut (in.)

d = Depth of cut (in.)

F = Feed rate (in./min)

P_m = Net power to motor (KW)

M = Motor efficiency (%)

1.341 = Factor to convert KW to HP

The application of this concept of power rate is new in woodworking practice and research. It has been used in an analogous way in metalworking for many years, however, and offers considerable advantage over values of horsepower alone. It may be thought of as a means of combining power and productivity in a single term. This avoids cumbersome values whose interrelationships are difficult to visualize.

Since efficiency of removing material can be easily converted to horsepower for a given situation, there is no difficulty in translating it into practical values. The relationship is expressed by the equation

$$P_n = \frac{w \times d \times F}{E}, \qquad (6)$$

where

P_n = Net power to spindle (HP)

w = Width of cut (in.)

d = Depth of cut (in.)

F = Feed rate (in./min)

E = Efficiency of removing material (cu in./min/HP)

Velocity

In woodworking practice the speed of the cutting tool is usually referred to in terms of revolutions per minute, which does not take into account the diameter of the cutting circle or the peripheral speed of the tool. Since speed in revolutions per minute is proportional to peripheral speed only for a given cutting circle, there is an advantage in stating velocity in feet per minute. This permits comparison of the performance of various diameter cutterheads.

In Parts I, II, and III of this report velocity is considered in terms of revolutions per minute of the cutterhead, while in Part IV peripheral velocity is used. These values are proportional in this study since only one cutting circle diameter is considered. Fig. IV-1, page 48, shows this proportionality between head speed and velocity for the Buss 4L planer and values of peripheral velocity in feet per minute for various cutterhead speeds.

As more becomes known about the effect of various conditions on the machining of wood, it is likely that peripheral feet per minute will be accepted as the standard way of stating velocity, as has been the case for abrasive wheels, lathe work, milling, and many other processes.

Feed Rate

Feed rates are conventionally stated in feet per minute for most woodworking machines. For machine specifications this expression of feed rate is undoubtedly the most convenient. From the results of this investigation, however, it appears that the most significant relation between power and feed rate can be drawn when feed is expressed in terms of the head speed and number of knives, or as inches per knife.

It can be tentatively assumed on the basis of this investigation that efficiency of removing material is constant for a given feed-velocity-knife relationship at any given depth of cut. That is, it is equally efficient to machine at any combination of head speed, feed rate, and number of knives, which will give the same feed in inches per knife. An example of this relationship would be a head speed of 3600 revolutions per minute, feed of 68 feet per minute, and a 4-knife head as opposed to 5400 revolutions per minute, feed of 88 feet per minute, and a 3-knife head. In each case the feed rate would be .065 inch per knife, and the efficiency of removal would be the same, assuming that the depth of cut is equal in both cases. At the same efficiency, however, a higher cutting velocity is obtained at 5400 revolutions per minute. This takes on considerable significance if it can be assumed that higher cutting velocities give better surfaces.

The results which are given in Table IV-b, page 57, are strong evidence that an assumption of constant efficiency for a given feed in inches per knife is justified. It can be seen that for each depth of cut there are only slight variations in efficiency between the various velocity-feed combinations, with only one exception. The one case where the divergence is considerable was believed to be due to an experimental error, and the lesser variations may be traceable to the approximations of velocity under load. Other data obtained in this investigation also tend to confirm the constant efficiency theory, although much more information is needed to support it conclusively.

Chipped Grain

Chipped grain is a machining defect which results when the wood fibers are broken off below the plane of cutting. The fibers are torn out ahead of the cutting action instead of being cleanly severed by the knife. Since the tearing usually follows the direction of the grain, chipped grain is more prevalent in cross-grained material.

Torn Grain

Torn grain is an exaggerated form of chipped grain. Splinters of considerable length and width are torn from the piece, leaving large depressions below the plane of cutting.

Fuzzy Grain

Fuzzy grain results from the lifting of fibers ahead of the cutting. Instead of being broken off entirely as in the case of chipped grain, however, these fibers are merely bent over in the direction of feed. After the knife passes over, these fibers partially recover their initial position and stand up above the surface giving it a "fuzzy" appearance.

Chip Marks

Chip marks are defects caused by chips which have been pressed into the surface by the knives.

PART I

THE EFFECT OF SEVERAL VARIABLES ON POWER REQUIREMENTS FOR PLANING

Summary

This study revealed basic facts on several variables which affect the power required for planing wood. The primary aim of this work was to establish a procedure for making power-requirement studies. In addition, a fairly complete set of power-consumption data was obtained for hard maple. Similar studies should be conducted for other species of wood, but because of the high cost in time and material of studying several species under a number of variable conditions, only hard maple was used here.

An intensive investigation was conducted under closely controlled conditions. As nearly as possible each variable was isolated and investigated individually with respect to power. In order to verify the accuracy of the procedure, several of the determinations were repeated at widely-spaced intervals. It was found that results could be reproduced almost exactly. This finding was significant in that it indicated that the sample was suitable in size and nature for the study and also that the variables were being closely controlled.

The machining relationships established in this study follow a pattern which is consistent with theory, and it is reasonable to assume that they will hold in a broad sense for most woods under similar conditions of planing, even though hard maple was the only species used.

A. Width of Cut. The determination of the effect of width of cut on power followed rather closely the logical supposition that a directly proportional increase in power should result from any increase in width of cut

and that power is the product of the power per unit width and the units of width.

B. Depth of Cut. The depth-of-cut investigation revealed that the efficiency, (cubic inches per minute per horsepower) increased rapidly to a point, then gradually leveled off and showed signs of decreasing with greater depths of cut.

C. Grain Direction. No direct correlation of grain angle with respect to power was feasible, but there was some evidence that grain direction has considerable influence on the power requirement, with more power being required to cut with the grain than against the grain.

D. Specific Gravity. A very general correlation was found between specific gravity and required power, with heavier pieces generally requiring more power.

E. Jointing. Knife jointing brought about a significant increase in power requirement. This is dealt with more fully in Part III of this report.

F. Knife Dulling. The effect of knife dulling on power requirement could not be adequately evaluated in this study. Consequently, an auxiliary study, which is described in Part III of this report, was made.

G. Knife Grinding. The power values seemed to remain about the same for successive knife grindings when the knives were not subsequently jointed.

H. Dimensional Variation. Measurements taken at several points on each specimen showed some variation in thickness after planing, but the average thickness was found to be approximately the same as the planer setting.

I. Repeatability. It was found that results of power determinations could be closely reproduced when the same material was used for successive runs but varied somewhat when the study was repeated with different lots of material.

Discussion

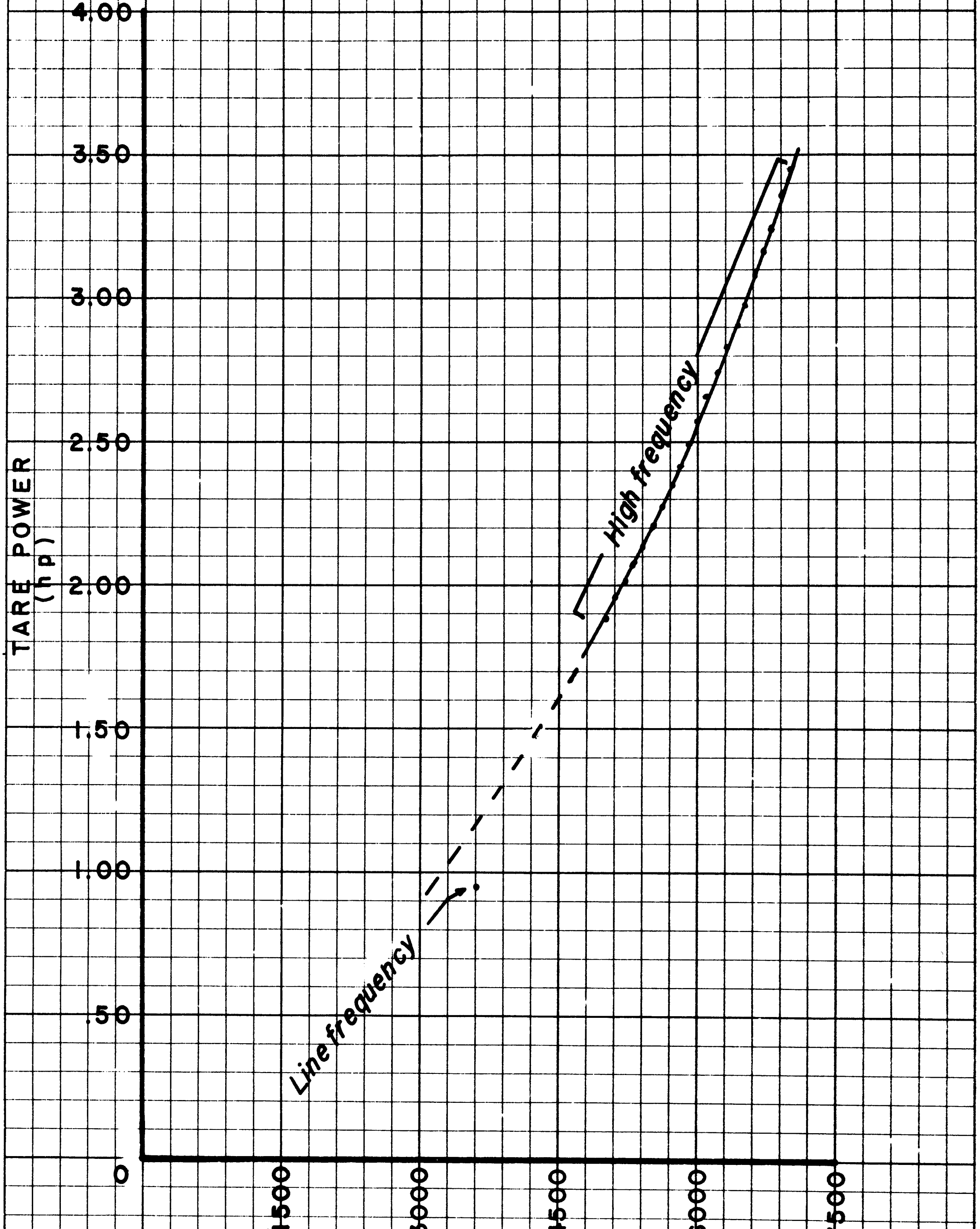
This series of studies was designed to simplify the basic power-requirement determinations which were the primary aim of the investigation as a whole. Only one species, hard maple, was used in this series, but it is believed that most of the relationships found would also hold for other species.

The factors which were considered in this study are of two types: variables which are intentionally introduced or can be controlled in the manufacturing process and those which cannot be controlled due to the nature of the material or to the limitations of the equipment. Factors in the first category include variable depth of cut and variable width of cut, variable degree of knife jointing, and the direction of grain in relation to feed. The second group includes possible variation in power for successive equal cuts on the same piece and on different pieces, possible variation due to the dulling of the knives, variation in thickness of the product, and variation in specific gravity.

Tare power was determined for the Buss 4L planer at various cutter-head speeds. Fig. I-1 shows a plot of the values of tare power for both line frequency speed of 3600 revolutions per minute and the high frequency speeds from 5000 to 7000 revolutions per minute.

The test specimens used were hard maple boards 6 inches wide by 48 inches long which were initially about 1-1/4 inches thick. These specimens were sound cuttings taken from large 6/4 boards which had been kiln dried at the Laboratory on a very mild schedule to approximately 8 per cent moisture content. After the specimens were prepared, they were carefully conditioned to an equilibrium moisture content of 8 per cent. Before the specimens were planed to thickness, they were faced one side on a hand-fed jointer in order to get one flat reference surface.

FIG. 1-1 TARE POWER REQUIREMENT FOR CUTTERHEAD DRIVE – BUSS 4L 30" PLANER WITH 15 HP MOTOR.



A. Effect of Width of Cut on Power Requirement. Five pairs of book-matched pieces were used for determining the effect of width on power requirements. These 1 x 4 x 48-inch pieces were run through the planer at a feed rate of 46 feet per minute and a head speed of 3600 revolutions per minute with a 1/16-inch depth of cut. Each pair was given a number and each piece in a pair designated as the "a" or "b" piece. These were then run in the following order:

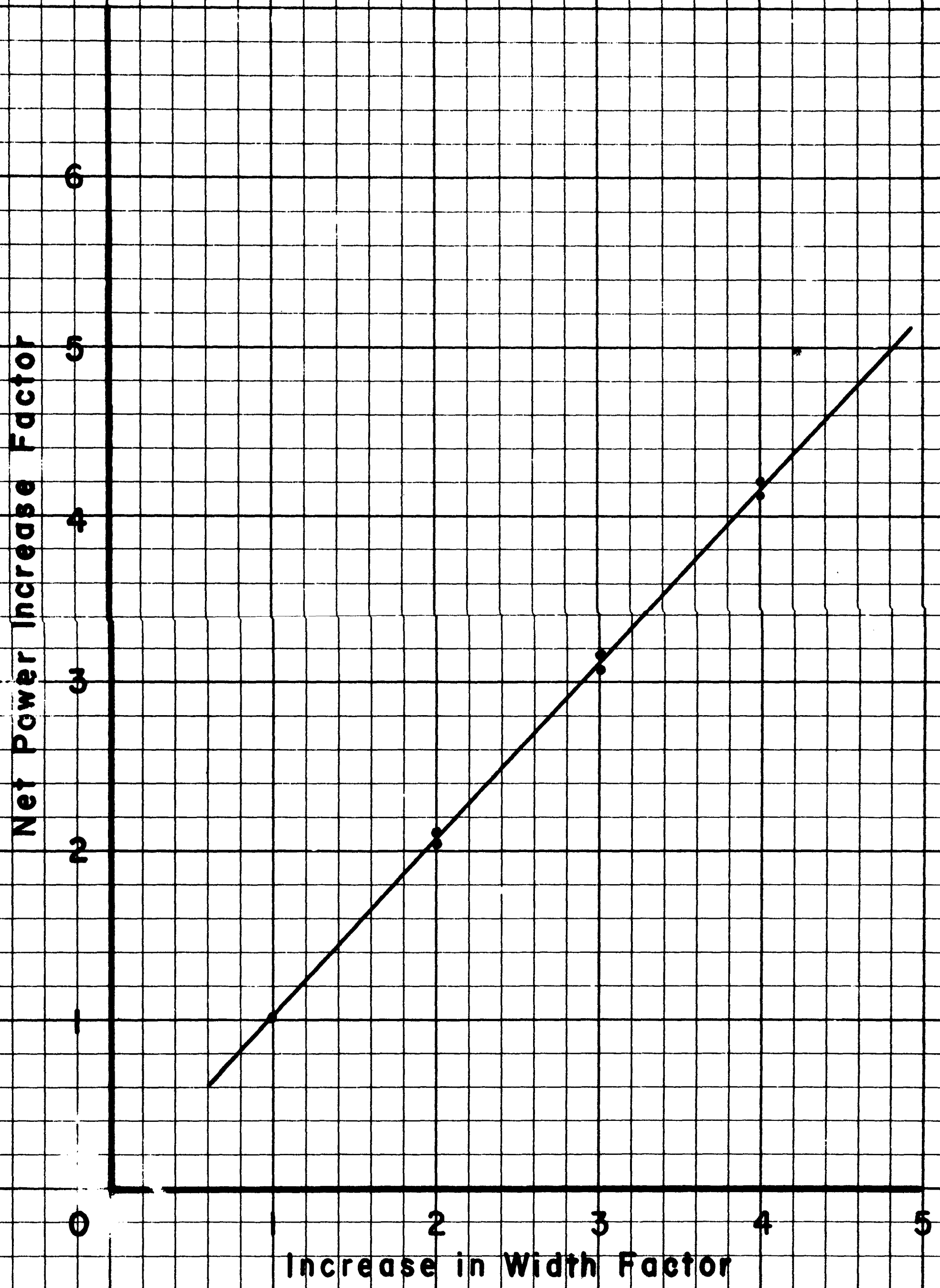
1) the "a" pieces of all pairs separately, followed by the "b" pieces of all pairs,
2) the "a" pieces of pairs 1 and 2 together, followed by the "b" pieces of these pairs together,
3) the "a" pieces of pairs 3, 4, and 5 together, followed by the "b" pieces of these pairs together,
4) the "a" pieces of pairs 1, 2, 3, and 4 together, followed by the "b" pieces of these pairs together,
5) the "a" and "b" pieces of pairs 5 and 1 separately in that order,
6) the "a" pieces of pairs 2, 3, 4, and 5 together, followed by the "b" pieces of these pairs together.

The power readings for each of these runs were recorded by wattmeter and later used for calculating the net power for each. The data were then compared to determine the relationship between width of cut and power requirement.

The relationship of power to width is shown graphically in Fig. I-2, page 17. It will be noted that this is a straight-line relationship having a slope of about one. The slope of the curve is actually slightly more than one, and this may possibly be due to the fact that the amount of joint was not uniform along the entire length of the knife. It was observed that the

FIG. 1-2 EFFECT OF WIDTH OF CUT ON POWER REQUIREMENT.

Hard maple planed at 3600 rpm and 46 fpm.



mid-portions of the knives received a relatively lighter joint than did the ends. It seems reasonable to suppose that this gradual variation in jointing increased the power values because of the decreased cutting efficiency at the areas with heavy jointing. Thus, the greater width of some of the specimen billets resulted in cutting with a larger proportion of the heavily jointed edge.

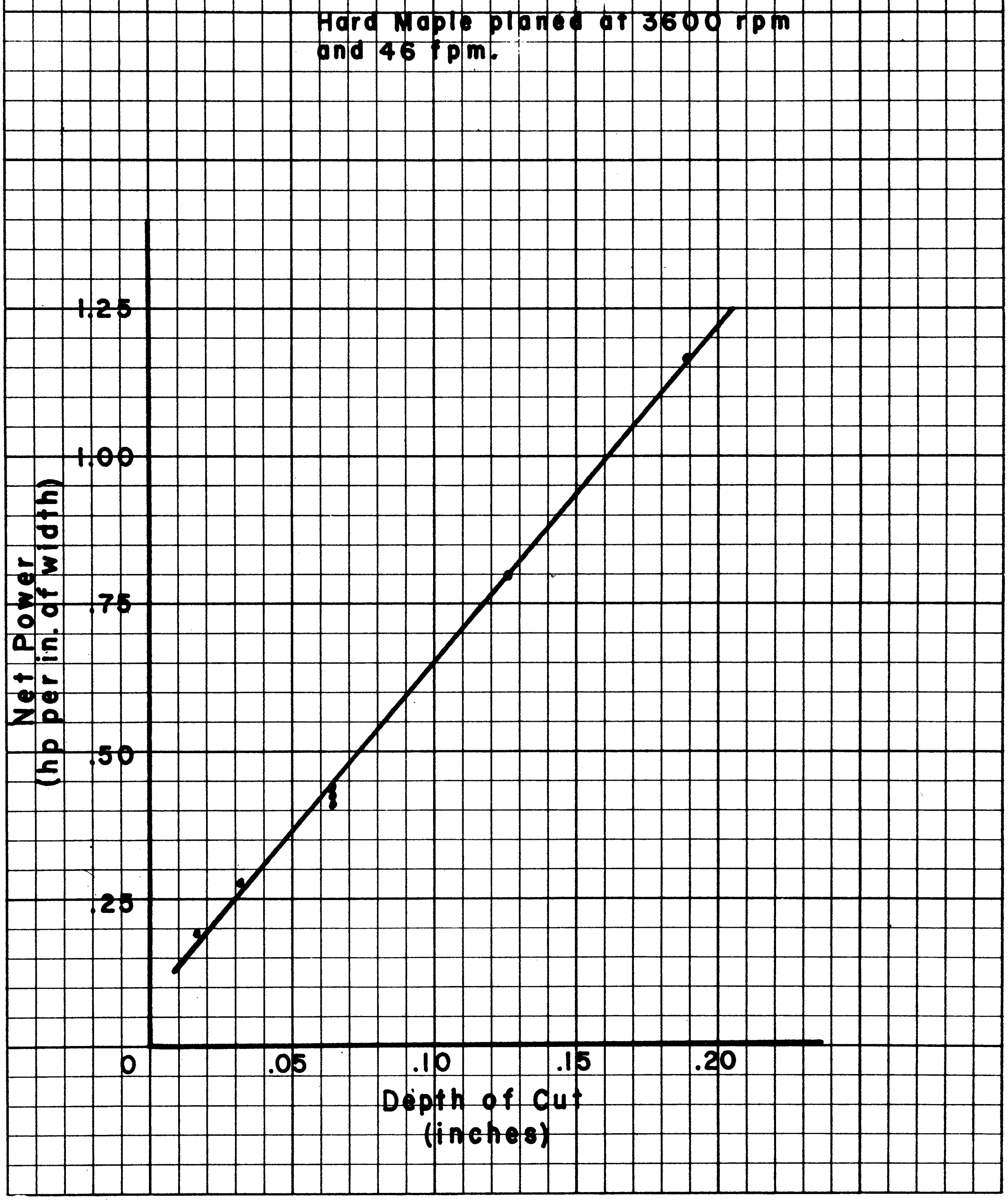
It was assumed from these data that under ideal conditions a given change in width of cut produces a directly proportional change in the required power; e.g., if the width is doubled, the power necessary is also increased two-fold.

B. Effect of Depth of Cut on Power Requirement. The material used for a study of the effect of the depth of cut on power consisted of 12 pairs of face-matched pieces of hard maple stock 6 x 48 inches in surface measurement. All 24 specimens were surfaced at a feed rate of 46 feet per minute and a head speed of 3600 revolutions per minute, for each run with various depths of cut. This included cuts of 1/64, 1/32, 1/16, 1/8, and 3/16 inch. A recording wattmeter (Esterline-Angus Model AW) was used to obtain data on power for each piece at each of the various cuts. Calculations for the efficiency of removing material were based on Eq 5, page 8.

Figs. I-3, I-4, and I-5, pages 19, 20, and 21, respectively, demonstrate the relative effect of depth of cut on power consumption, volume-time rate of removal, and efficiency of removing material. The relationship between power consumption and depth of cut at a constant head speed and feed rate, Fig. I-3, is a straight line within the limits plotted. The slope and placement of this curve hold in this one case only; they would vary with such factors as species, moisture content, grain direction, and specific gravity.

Fig. I-4 shows the increase in volume removed per unit of time as depth of cut increases.

FIG. I-3 EFFECT OF DEPTH OF CUT ON POWER REQUIREMENT.



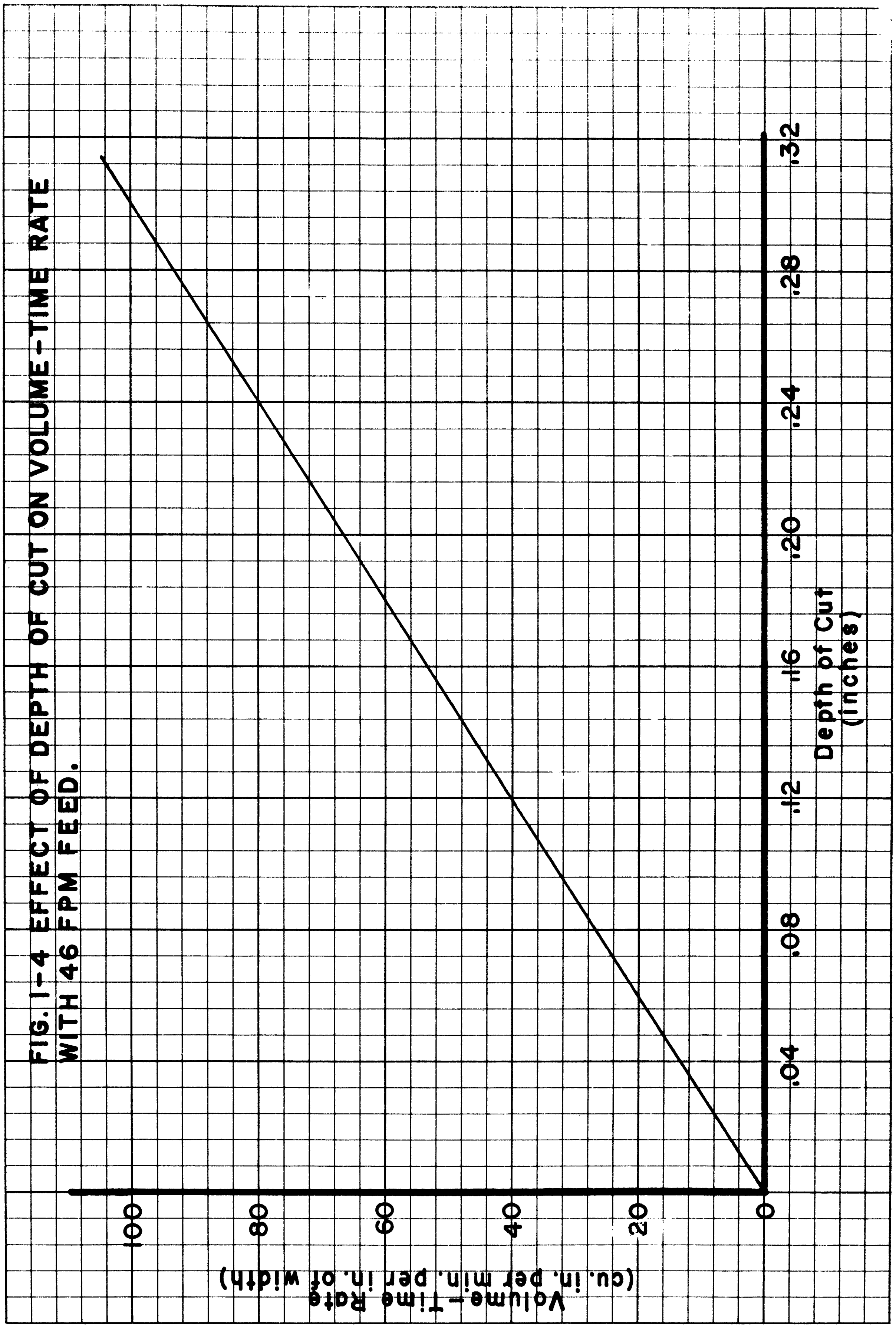


FIG. I-4 EFFECT OF DEPTH OF CUT ON VOLUME-TIME RATE WITH 46 FPM FEED.

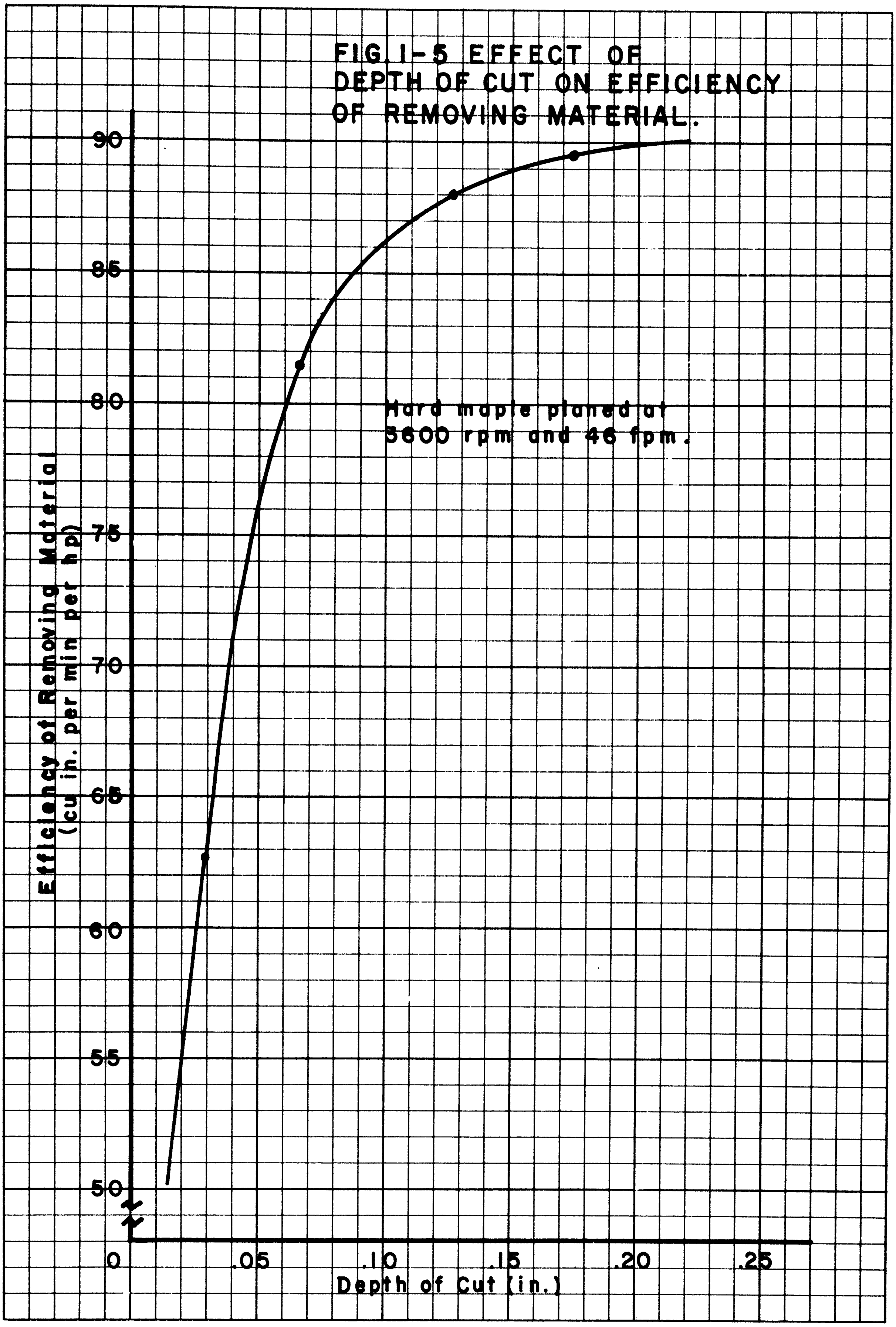


FIG. 1-5 EFFECT OF DEPTH OF CUT ON EFFICIENCY OF REMOVING MATERIAL.

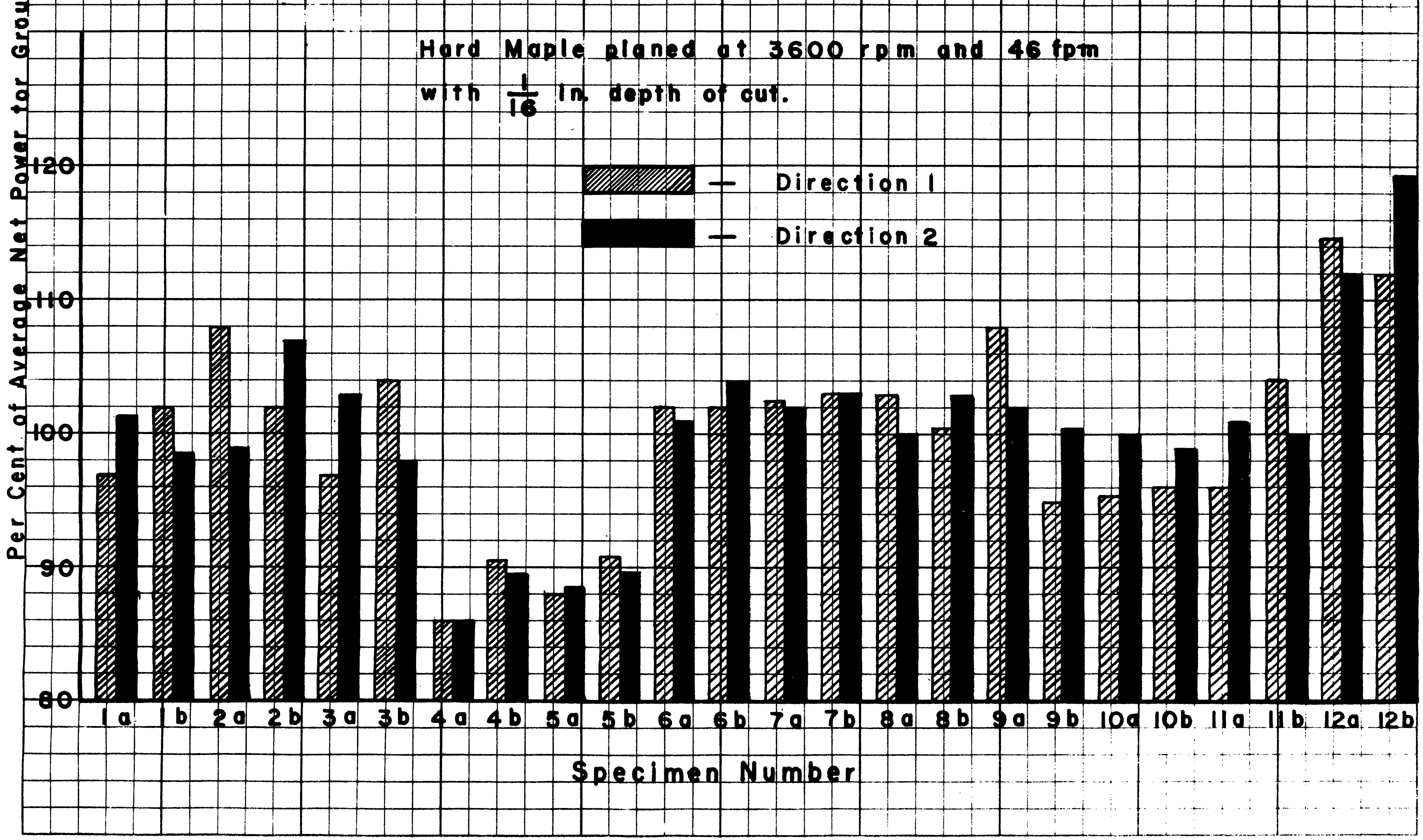
Hard maple planed at 3600 rpm and 46 fpm.

If the equations represented by Figs. I-3 and I-4 are solved for common depths of cut, the ratios of their solutions are values of cubic inches removed per minute per horsepower. These values when plotted show a curve of the form illustrated in Fig. I-5. Since power and volume removed per unit of time increase at the same rate as does width of cut, width can be disregarded when computing cubic inches removed per horsepower per minute. It can be seen from Fig. I-5 that the efficiency of removal increases sharply as the depth of cut increases beyond a skimming cut. This sharp gradient gradually diminishes as the depth of cut continues to increase. For the conditions examined, there seems to be little advantage from the standpoint of efficiency to increase the depth of cut beyond approximately 1/4 inch. It seems likely that beyond a certain limit in the depth of cut, the efficiency would decrease sharply.

C. Effect of Direction of Grain in Relation to Feed. In order to study the effect of the direction of cut, 12 pairs of 6 x 48 inch book-matched hard maple boards were used. All 24 pieces were run in one direction with a depth of cut of 1/16 inch, a feed rate of 46 feet per minute, and a head speed of 3600 revolutions per minute. Power consumption values were recorded by a wattmeter for each piece. Similarly, all 24 pieces were run in a direction counter to the previous feed.

Fig. I-6, page 23, shows the relative power requirements for stock fed successively in opposite directions. Each double bar represents one specimen, with the solid and cross-hatched divisions showing opposite directions of feed. Primarily, the comparison shows the general effect of grain direction on power consumption. It can be seen that in most instances the book-matched specimens of a pair, e.g., 1-a and 1-b, show similar power characteristics but in reverse. One piece in a pair usually shows a higher value for one direction of feed, while the mate shows a higher value for the

FIG. I-6 CORRELATION BETWEEN DIRECTION OF GRAIN AND THE POWER REQUIRED FOR INDIVIDUAL SPECIMENS.



opposite direction. The reversal may be logically attributed to the reversed grain direction. Although no precise substantiating data was secured in the study, it was observed that greater amounts of power are generally needed for cutting with the grain than against it. This consideration is tempered, of course, by the superior finish obtained in cutting with the grain.

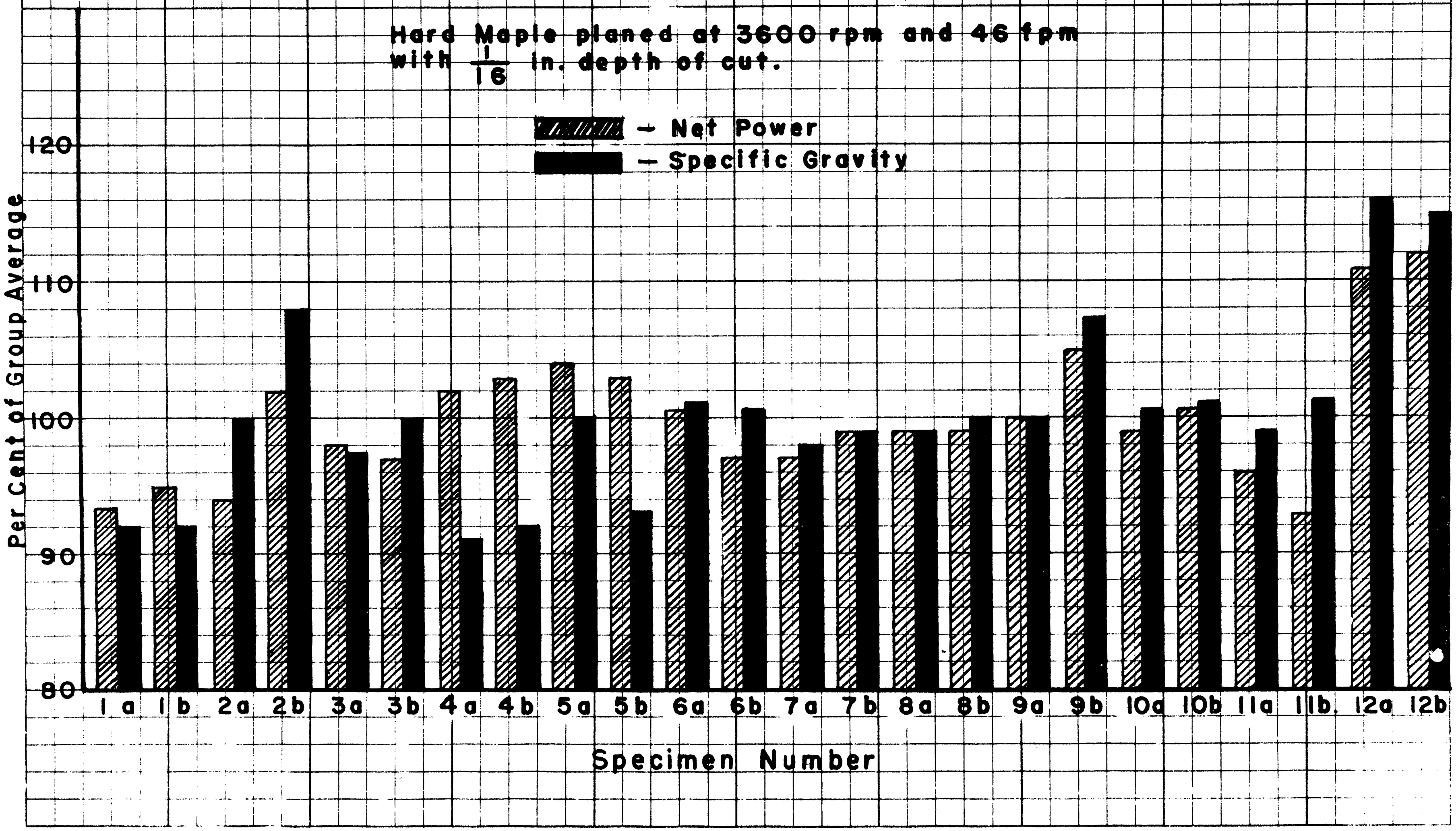
D. Effect of Specific Gravity on Power Requirement. After all of the other determinations in this series were completed, samples were cut from each specimen for the determination of specific gravity. These were one inch in the direction parallel to the grain and the full width and thickness of the stock. Three were cut from each of the "a" and "b" pieces of the 12 book-matched pairs at points 1-1/2 inches from either end and at the mid-point. These samples were oven-dried, measured, and weighed. It was then possible to compute the specific gravity of each on the basis of oven-dry weight and volume.

The relative effect of variations in specific gravity on power requirements is shown in Fig. I-7, page 25. The average power needed for a given test specimen and the average specific gravity of the specimen are represented as percentages of the average for all specimens in the test.

A general correlation can be seen for the group, although some individual values vary considerably. The variation is to be expected, however, since the values of power consumption are probably influenced by such outside factors as grain or structural irregularities, mineral streak, and variations in the chemical structure of the cell walls. The variations in any of these uncontrollable factors could alter power consumption sufficiently to distort the actual effect of specific gravity.

The United States Forest Products Laboratory and others have shown that specific gravity is an index of the strength properties of wood[1]. Since machining characteristics would seemingly be closely tied also to the strength properties, it was hoped that a clear-cut relationship could be discovered

FIG. 1-7 CORRELATION BETWEEN SPECIFIC GRAVITY AND THE POWER REQUIRED FOR INDIVIDUAL SPECIMENS.



between specific gravity and power requirement. Even though this work does not conclusively show such a relationship, it is entirely possible that with further study a correlation could be found which would make it practicable to predict power requirement and other machinability behavior on the basis of specific gravity.

E. Effect of Knife Jointing on Power Requirement. The number of runs made to determine the effect of knife jointing on power requirement was insufficient to show conclusively how much power increased with a given amount of jointing. Several technical difficulties, such as jointing the entire length of each knife uniformly and all of the knives in the head the same amount, made it difficult to determine this precisely.

Indications were that newly ground knives which had not been jointed gave very consistent power consumption values when the average for all specimens was considered. Knives which were jointed lightly gave an average value about 6 per cent higher than that for newly ground knives. Although no method was found for determining the amount of jointing quantitatively, it can be said that it was about the minimum amount to approach four-knife cutting.

A more complete study on the effect of knife jointing is given in Part IV of this report.

F. Effect of Knife Dulling on Power Requirement. In conjunction with the other determinations in this series, a group of 3 pairs of face-matched specimens were run to attempt to determine the effect of knife dulling on power requirement. One specimen from each pair was run at a given position along the head which was reserved as a control zone. The other three specimens were run prior to the regular run through the zone used for all the other specimens. The purpose was to compare the values obtained with slightly used knives with those obtained for the knives being dulled as the determinations progressed. The results of this test were so inconsistent that the relationship of dulling to power was entirely obscured. It was found that it would be necessary to run a very large amount of material through a limited zone of the planer to get this information. An even better way of getting this information would be to study the power requirement of a planer in a production operation. One which was being used for long periods of time to surface panels of approximately capacity width would give the most accurate data.

G. Effect of Regrinding Knives on the Power Requirement. As has been mentioned before, the power required for widely-spaced tests made under the same conditions was remarkably consistent. In the tests from which this was determined it was also found that regrinding which was done under approximately the same circumstances did not affect the power values appreciably.

H. Variation in Thickness of the Specimen after Planing. After three sets of the determinations in this series, the thickness of each specimen was measured at six different points to the nearest thousandth of an inch by means of micrometer calipers. Although these data were not analyzed completely, it was found that there were variations of as much as .020 inch from point to point on the specimen. The average of the thickness measurements, however, was very close to the thickness for which the planer was set, using the micrometer gauge. It is possible that a large part of this variation was due to the difficulty of obtaining a perfectly flat reference surface with a hand-fed jointer.

I. Effect of Successive Equal Cuts on Power Requirement. At the outset of this study it was expected that a great deal of difficulty would be experienced in obtaining consistent results on repeated runs due to the many variables encountered. To test the variability of results three sets of values were obtained for the entire group of 24 specimens at widely-spaced intervals of time so as to permit minor variations in moisture content, machine condition, flatness of the specimen, etc. In one of these tests the specimens were fed in the opposite direction. It was found that the averages of these sets of values compared very closely. The relationship was in the ratio of 519 to 520 to 523.

The repeatability of results was not quite so favorable, however, when the conditions were repeated, the specimens being taken from different stock. This was borne out in some of the determinations of Part II of this investigation. It can be assumed from this that experiments which must be carried out under very close control should be made on the same stock. This is something of a limitation in organizing and conducting studies of this kind.

PART II

THE EFFECT OF FEED RATE, HEAD SPEED, AND SPECIES ON THE POWER REQUIRED FOR PLANING HARDWOODS

Summary

The object of this study was to determine the power requirements for four hardwood species when planed with various feed rates and cutterhead speeds. The effect of feed rate and cutterhead speed on power consumption of the cutterhead motor was observed while all other influencing factors were held as nearly constant as possible.

The results of this study are presented in two ways: first, the net power required for each of the four species is shown for various cutterhead speeds as the feed rate in feet per minute is increased; second, the effect on efficiency of removing material is shown for increasing feed rate in inches per knife.

A number of important conclusions can be drawn on the basis of this study.

A. Effect of Feed Rate on Power. An increase in feed rate expressed in feet per minute increases the power required, although the rise in power is not proportional to the increase in feed rate (Figs. II-1 through II-4, pages 30 - 33). After a rapid initial increase in the power consumption of the cutterhead motor up to about 30 to 35 feet per minute feed, the rate of change of power to feed becomes much more gradual for all the species studied.

B. Effect of Feed Rate on Efficiency of Removing Material. Feed rate may be considered in terms of lineal travel of the stock or as a function of cutterhead speed and number of knives in addition to lineal travel. This is discussed extensively under "Feed Rate" in the Terminology section of this report (page 10). When feed rate is considered in inches per knife, it is found that efficiency of removing material is apparently constant for any feed rate, regardless of the specific values of feed and cutterhead speed which enter into the rate.

Fig. II-5, page 34, illustrates the increase in efficiency which occurs when feed rate in inches per knife is increased. The trend is generally the same for all four species studied. Each species is individual in its critical points, however. There is an indication in the results for basswood that there is a critical limit beyond which efficiency diminishes when feed rate is increased.

C. Effect of Cutterhead Speed. Figs. II-1 through II-4 show separate power consumption curves for each cutterhead speed. There is a general relationship which shows that higher cutterhead speeds require more power at given feed rates. It appears from the results of this study that the power required for cutting at various cutterhead speeds may be approximately the same at the upper and lower limits of feed. In the normal operating range of

FIG. II-1 EFFECT OF FEED RATE ON NET POWER AT VARIOUS CUTTERHEAD SPEEDS.

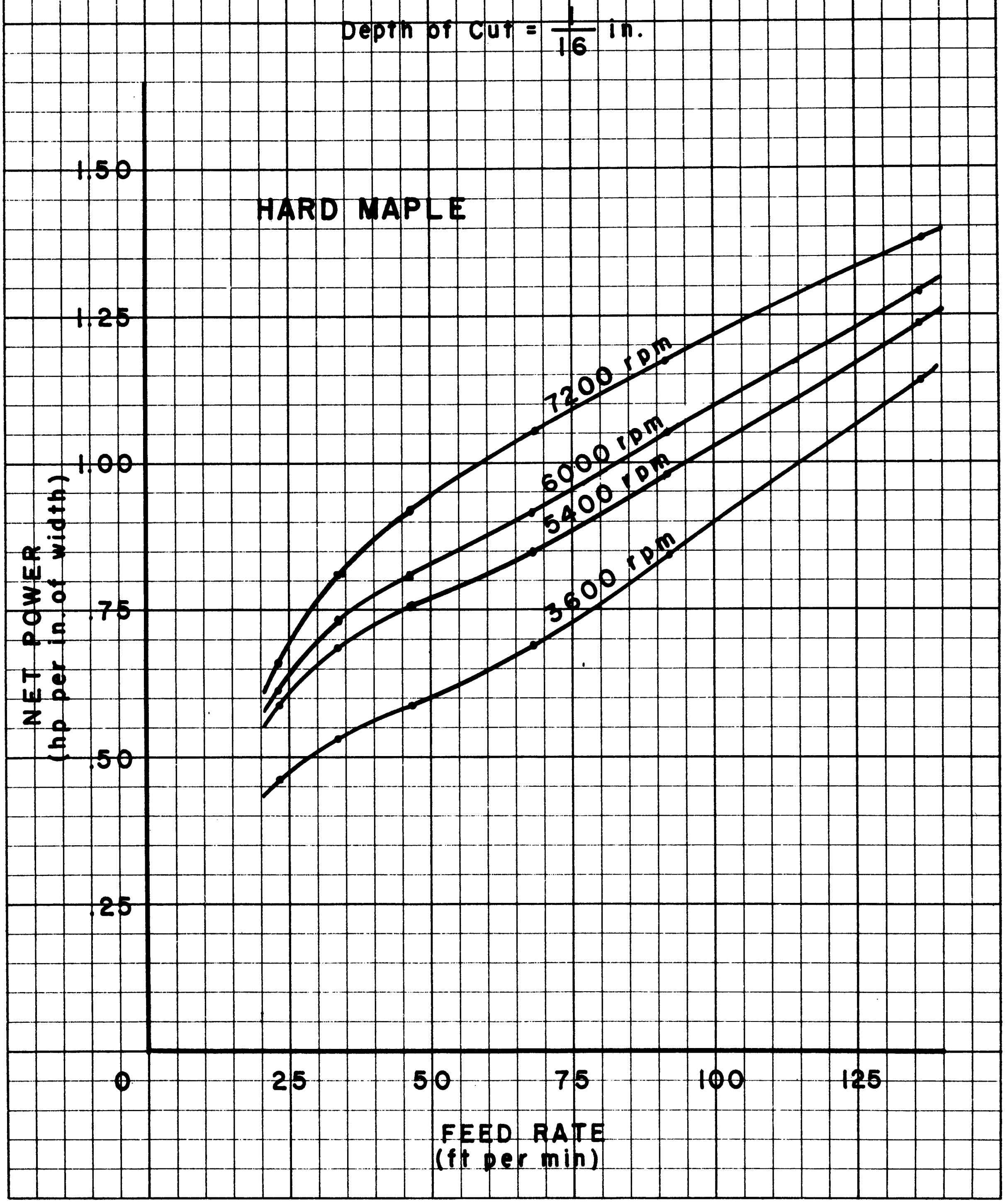


FIG. II-2 EFFECT OF FEED RATE ON NET POWER AT VARIOUS CUTTERHEAD SPEEDS.

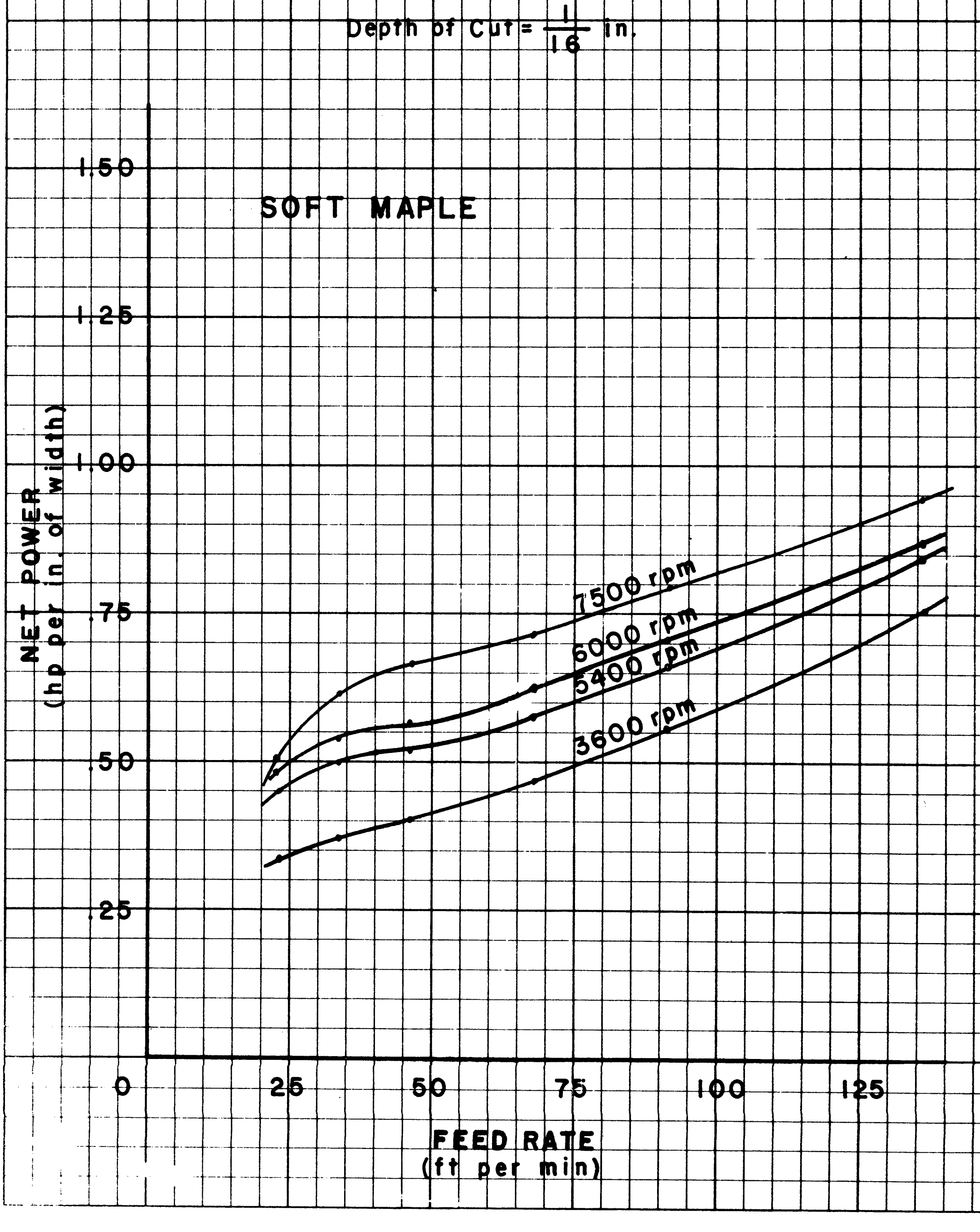


FIG. II-3 EFFECT OF FEED RATE ON NET POWER AT VARIOUS CUTTERHEAD SPEEDS.

Depth of Cut = $\frac{1}{16}$ in.

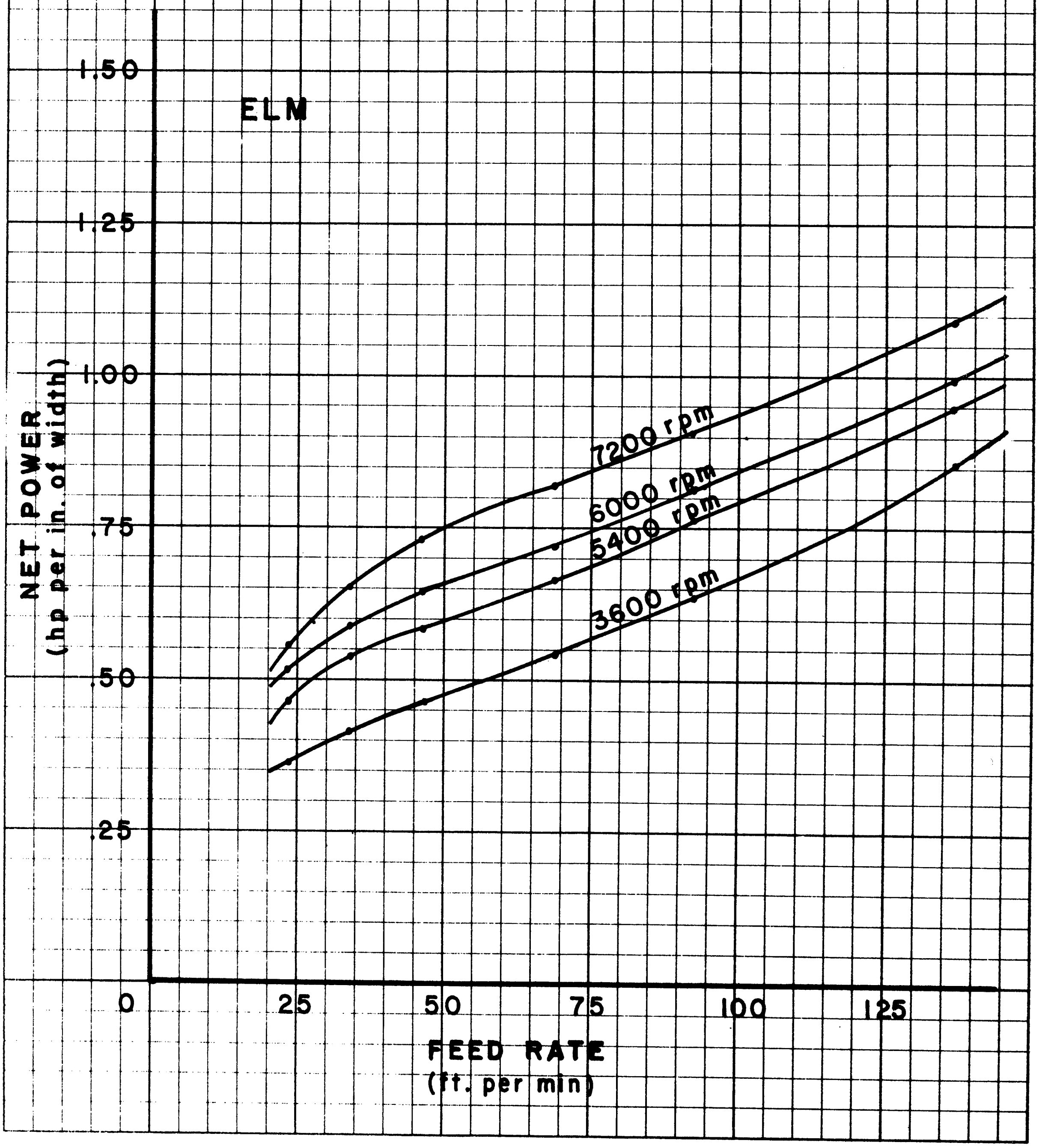


FIG. II-4 EFFECT OF FEED RATE ON NET POWER AT VARIOUS CUTTERHEAD SPEEDS.

Depth of Cut = $\frac{1}{16}$ in.

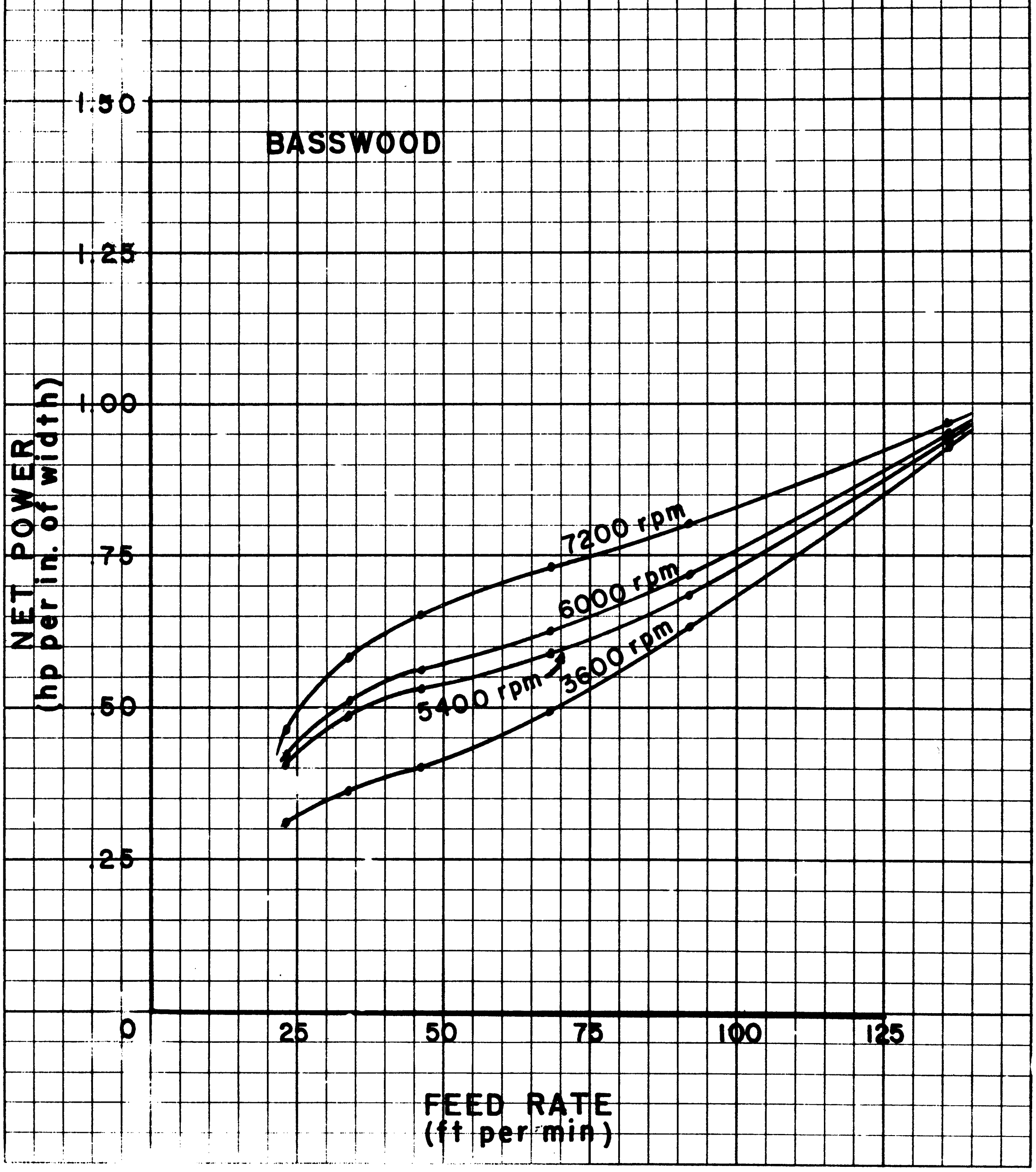
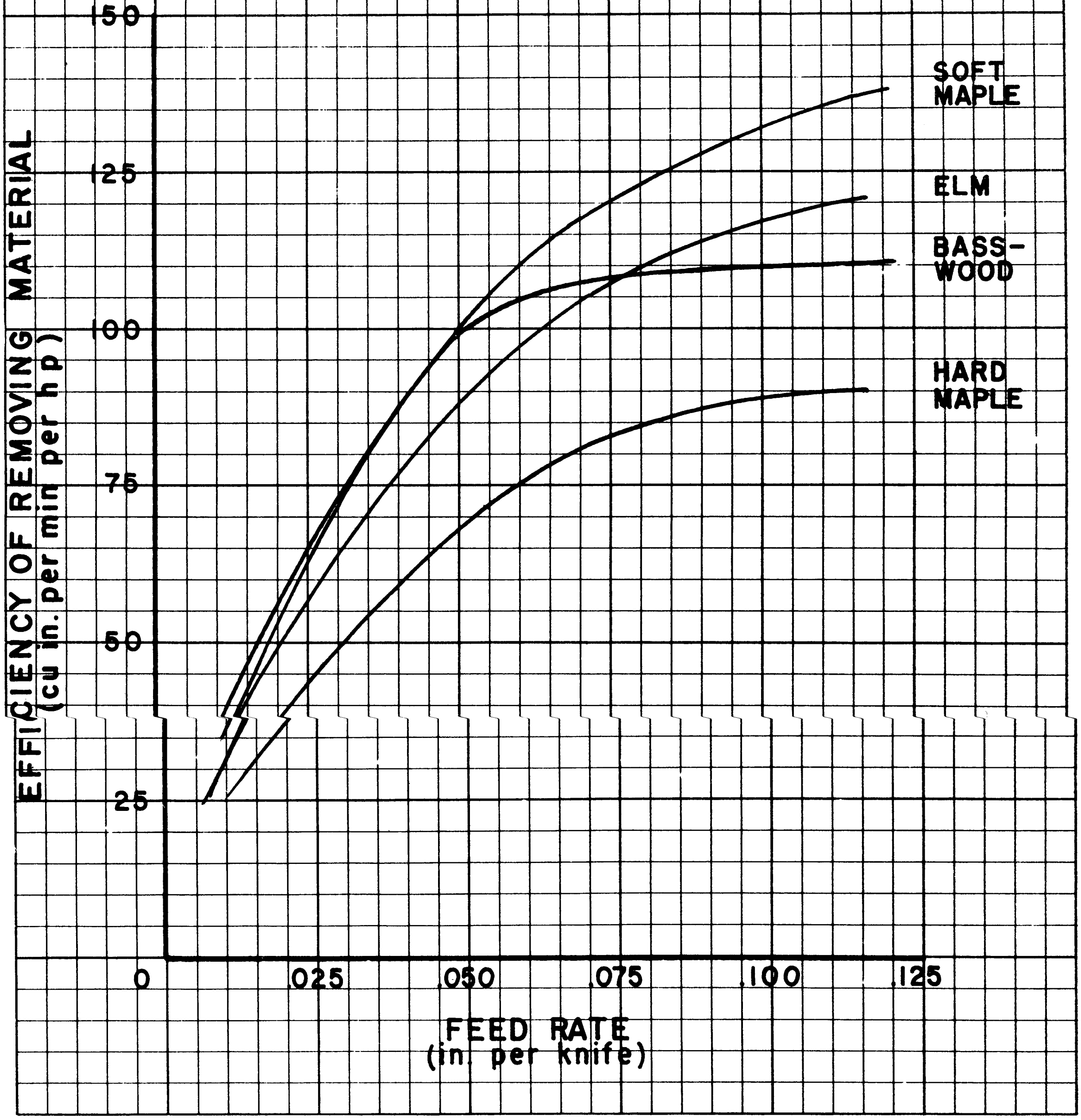


FIG. II-5 EFFECT OF FEED RATE (IN. PER KNIFE) ON EFFICIENCY OF REMOVING MATERIAL.

Depth of Cut = $\frac{1}{16}$ in.



feeds, however, there is a spread which is approximately proportional to the cutterhead speed.

From Figs. II-1 through II-4 optimum conditions of feed can be selected for any cutterhead speed at 1/16-inch depth of cut.

Discussion

Since feed rate and cutterhead speed are factors in planing which should be very significant to every operator, it was felt that the most comprehensive portion of this investigation should deal with their effect on power. As a result, a comparatively large amount of each of four hardwood species was machined with only feed and speed being varied. All other factors were held as nearly constant as possible. Since 20 different combinations of feed and speed were studied for each species, the sample had to be somewhat smaller than was desired for each condition. After the data were analyzed, however, it was felt that results obtained were significantly, if not absolutely, indicative of the effect of feed and speed on power.

The equipment used in this study is described under "Facilities" in the introductory section of this report. Plate II-A shows a sample billet being machined. The recording wattmeter which was used for measuring power is pictured in Plate II-B.

The four species which were selected for this work were four commonly used commercial hardwoods -- hard maple, soft maple, elm, and basswood. These were considered representative of the differences in structure, density, and other physical properties which are found in domestic hardwoods.

A total of about 5,500 board feet of these species were obtained in a partially air-dried condition. All this material was of southern Michigan growth. Each species was carefully kiln-dried at the Laboratory and subsequently conditioned to a uniform moisture content of 7-9 per cent in a

PLATE II-A. POWER REQUIREMENT STUDY — BUSS MODEL 4L PLANER.

Obtaining power requirement data for specimens made up of random width pieces. Guides clamped to infeed table align specimens so that the same portion of cutterhead is used for each specimen.

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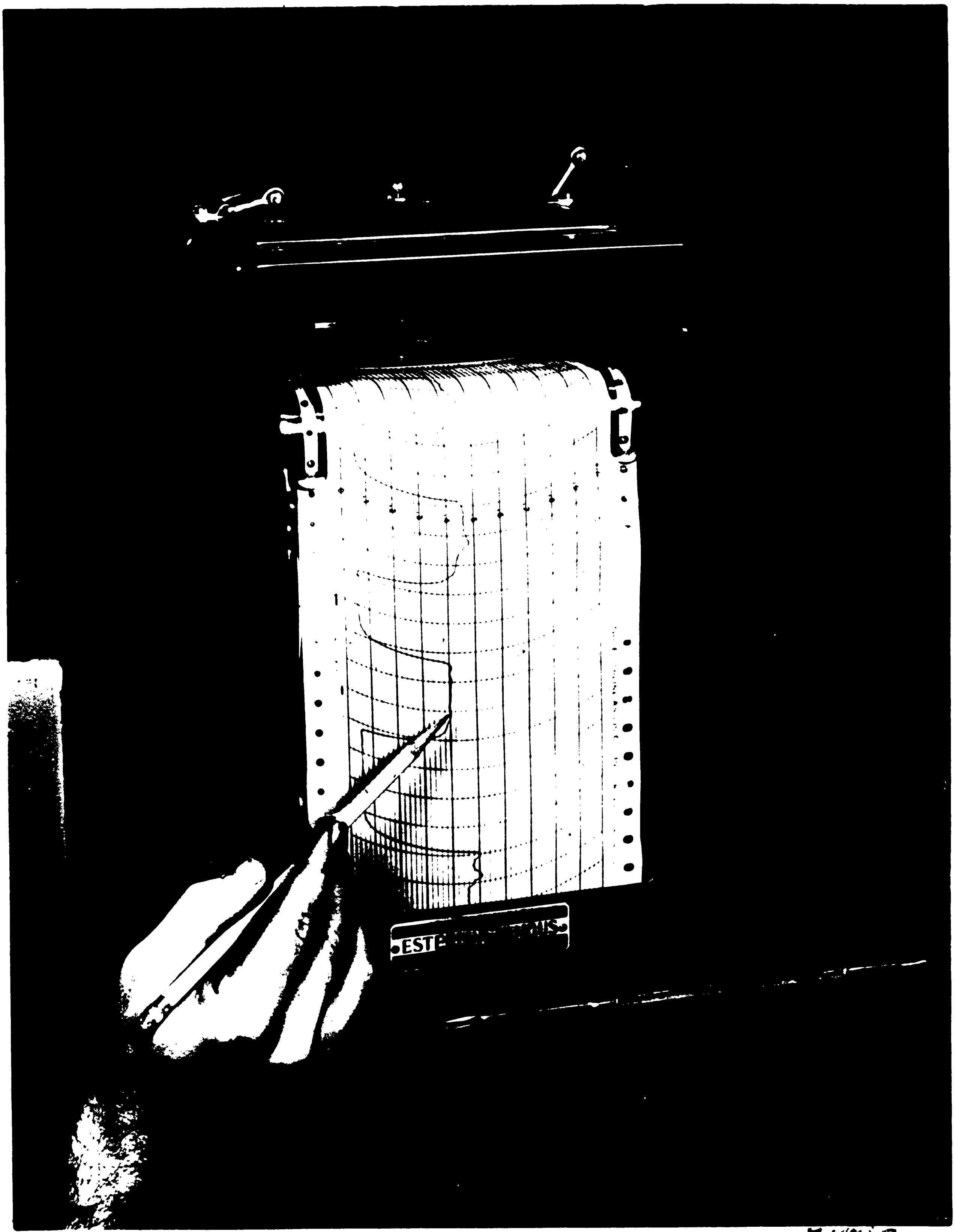

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PLATE II-B. CLOSE-UP OF RECORDING WATTMETER SHOWING A TYPICAL POWER REQUIREMENT CHART.

Each node on chart represents power requirement for a given specimen. Flat portions of curve near left margin indicate tare power.

controlled-temperature and humidity room. At the time of the power determinations the material was spot checked with an electronic moisture meter to assure uniformity in moisture content.

The specimens for this study were selected from stock which showed general uniformity of structure throughout a 48-inch length. Random widths ranging from 2 inches to 8 inches were admitted. These were accurately machined to a 48-inch length and to even thickness and widths. Billets of approximately 15 inches in width were made up from the random-width specimens to assure a relatively constant load on the machine for each determination. A sufficient quantity of all four species was prepared to provide a minimum of 100 square feet of surface for each of the 20 conditions of planing.

The average width of each specimen in the billet was measured to the nearest hundredth of an inch, and these were totaled to obtain the width of the billet. This procedure was necessary for determining the power required per unit of width.

All billets were given a light thicknessing cut just before the power determinations were made to eliminate possible variation in thickness. Subsequently, all billets were machined at a depth of cut of 1/16 inch and power determinations were made under each of the conditions tabulated below.

TABLE II-A

FEED-SPEED COMBINATIONS USED IN PART II

Feed Rate (FPM)	Cutterhead Speed (RPM)			
	3600	5400	6000	7200
23	*	*	*	*
34	*	*	*	*
46	*	*	*	*
68	*	*	*	*
92	*			*
136	*			*

Values of efficiency of removing material were computed from the net-power data and were plotted against feed rate in inches per knife as shown in Fig. II-5. The smooth curve which was drawn through the plotted efficiency values then served as a basis for determining the horsepower curves given in Figs. II-1 through II-4. This information could also have been found by obtaining, directly, average horsepower per inch of width, but it was believed that the slight experimental deviation of values obtained directly might obscure the general behavior. The magnitude of mechanical details involved in a study such as this is evidenced by the approximately 2500 computations which were condensed after analysis into five graphs of Figs. II-1 through II-5.

Figs. II-1 through II-4 show the effect of feed rate in feet per minute and cutterhead speed in revolutions per minute on the net horsepower required. The effect, in general, of feed rate appears to be similar for all cutterhead speeds. In each case the curve reverses slightly at some feed rate. This seems to indicate an optimum condition from the standpoint of power, with power consumption increasing less rapidly than feed rate. If it is assumed that zero net power is required at zero feed, it can be seen that the initial rise in power from zero feed to about 30 or 35 feet per minute is very rapid for all species.

In relation to the effect of cutterhead speed the curves show that initially the various speeds require about the same net power. However, as the feed increases, the curves fan out, with the lower speeds requiring less power. There is a strong indication, particularly in the case of basswood, that the curves would again converge at a rate of feed which is beyond the upper limit of the range studied here.

Fig. II-5 shows the effect of feed rate in inches per knife on the efficiency of removing material. These curves indicate in condensed form how efficiency increases as each knife is required to do more work, up to a certain point at least. As was stated previously, it was found that efficiency is constant for any given feed rate in inches per knife, regardless of the specific conditions of feed and speed. Consequently, the efficiency for any set of conditions of cutterhead speed and feed rate can be determined from the curves in Fig. II-5 after the feed in inches per knife for those conditions has been computed.

The relationship between the efficiency curves for the various species does not lead to any definite conclusions on the properties of wood which affect the efficiency of removing material. These data indicate that efficiency is not directly related to specific gravity or hardness of the species, basswood requiring more power than soft maple. Further research on more species might define a pattern which would permit classification of woods on the basis of some common physical property.

PART III

THE EFFECT OF KNIFE DULLING ON THE POWER REQUIREMENTS FOR PLANING HARD MAPLE LUMBER WITH THE BUSS 4L SINGLE SURFACER

Summary

This study was made to determine the relationship between knife dulling and power when planing hard maple with the Buss 4L single surfacer. Cutting power requirements were explored under three sets of knife conditions: sharp, artificially dulled, and dulled by actual planing of lumber. The procedure for the power determinations was generally the same as in Part I of this report.

The findings were as follows:

A. Knives Ground, Not Jointed. The efficiency of cutting with newly-ground, unjointed knives compared very closely with that obtained in previous studies with sharp, unjointed knives. Consequently, it was felt that this efficiency value was a dependable reference quantity with which to compare the values obtained for various degrees of jointing and dulling.

B. Artificially Dulled Knives. The efficiency of cutting with knives dulled by jointing decreased approximately in proportion to the measured width of the jointing land. Jointing reduced the efficiency as follows:

Light jointing	15%
Medium jointing	25%
Heavy jointing	40%

In the one determination made with knives which were heavily jointed and additionally abraded with a coarse stone, the efficiency was the lowest obtained in the entire study. This was 65 per cent below the value for newly-ground knives.

C. Knives Dulled by Planing. The efficiency of cutting with knives dulled through usage became progressively lower when the knives became duller, as would be expected.

Since there was no way of measuring the amount of dulling which took place under this condition, only an approximation could be made of the relation of dullness to the increased power required. It was found that under the rather severe dulling conditions which were imposed, a run of about 1-1/2 hours reduced the efficiency by approximately 50 per cent from the value for newly-ground knives. An additional run of about 1-1/2 hours reduced efficiency further, about 55 per cent of that for newly-ground knives.

The knives for these two determinations were jointed a medium amount before the dulling run was begun; consequently, it would, perhaps, be more accurate to compare the results with those for medium jointed knives. When this is done, it is found that the first 1-1/2 hours reduced the efficiency value about 30 per cent and that the efficiency for the second 1-1/2 hours was 50 per cent lower.

The results of all the determinations are presented in graphic form in Fig. III-1, page 43.

Since the purpose of this work was limited to determining the effect of dulling on power, no attempt was made to evaluate quantitatively the characteristics of the surfaces produced under the various knife conditions. Except in the most severe cases of dullness, the surfaces obtained would probably have been acceptable for most gluing or sanding. It should be emphasized, however, that the duller the knives become, the more the surface wood fibers are compressed and torn. This results in such defects as raised and fuzzy grain. Also, scorching of surface fibers at high ratio of head speed to feed speed frequently results when planing with dull knives.

Discussion

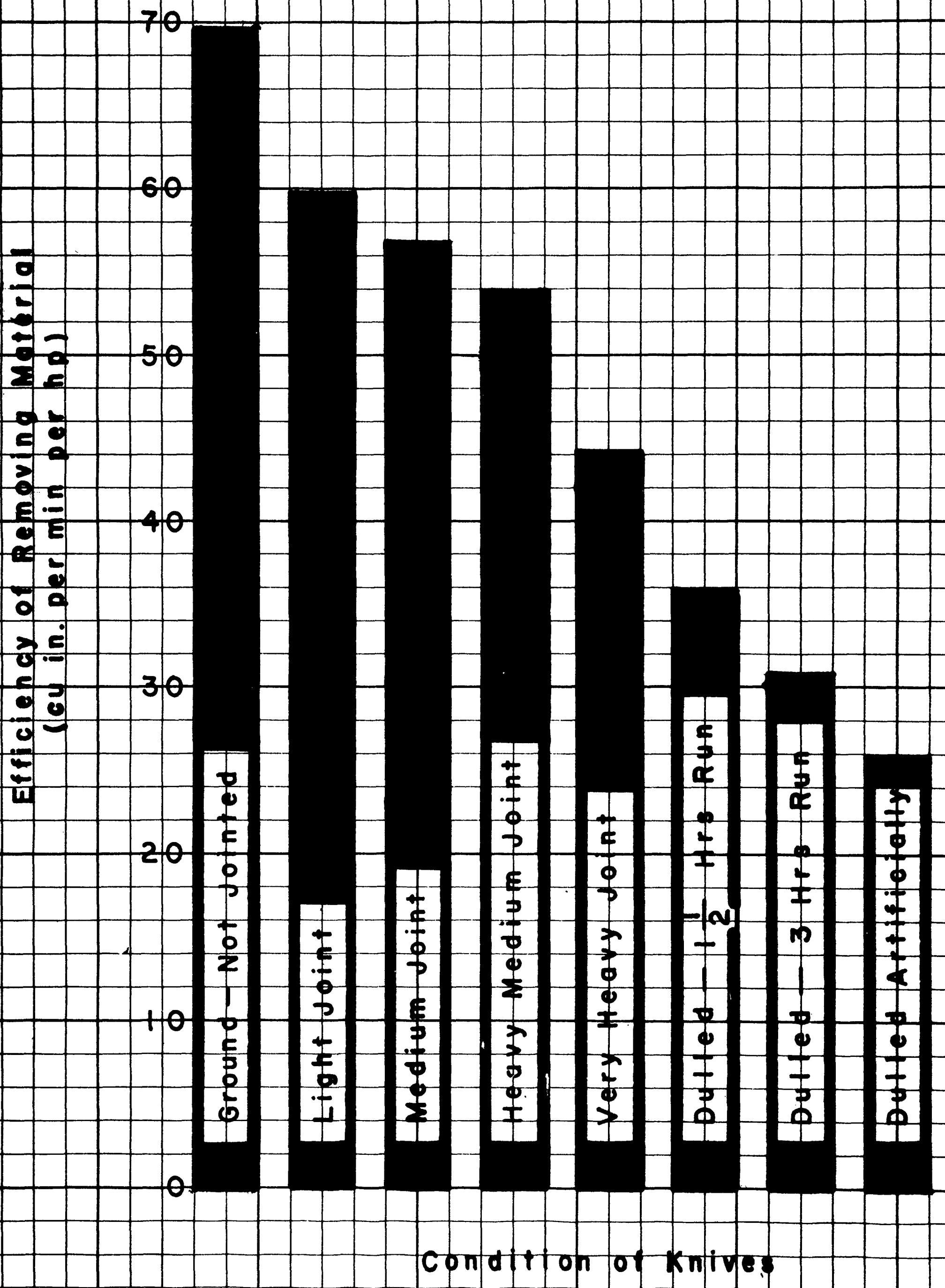
The sponsor suggested that a study be made to determine the effect of knife dulling on the power required to surface hard maple lumber, the aim of which was to provide information of a general nature which can be used in educating operators and supervisors on the importance of maintaining planer knives.

An empirical investigation was agreed upon since precise techniques for determining and controlling knife dullness would require considerably more basic research on knife sharpness than the sponsor felt was justifiable at this time.

As originally set forth, this study was to include determinations of cutterhead power under at least three knife conditions: a) knives ground but not jointed, b) knives ground, lightly jointed, and then partially dulled, c) knives dulled further until the work produced was unacceptable as finish

FIG. III-1 EFFECT OF KNIFE DULLING ON EFFICIENCY OF REMOVING MATERIAL.

Hard maple planed at 3600 rpm and 46 fpm with $\frac{1}{16}$ in. depth of cut.



planing. In addition to determinations made under these conditions, a corollary study was conducted to find whether or not dulling produced artificially would correspond to dulling resulting from normal wear in its effect on power.

In order to produce dulling with a minimum of effort and material, only a small section of the knives was used. A space was blocked off which was just sufficient for a 6-inch-wide specimen to pass through.

The lumber stock used was kiln-dried hard maple. Before use the stock was conditioned in a controlled temperature-humidity room to an equilibrium moisture content of approximately 8 per cent. The stock was cut into 35 specimens 6 x 48 x 1-1/4.

Power determinations were made under three sets of conditions. The first was made with knives newly ground but not jointed. The second group of determinations was obtained after the knives had been artificially dulled. The third group was made after the knives became dull through actual planing of lumber.

The method of determining power was the same as used in Parts I and II of this report, using an Esterline-Angus AW recording wattmeter. Efficiency was computed in cubic inches per minute per horsepower by the procedure presented on page 8 of this report.

For this entire study a head speed of 3600 revolutions per minute and a feed of 46 feet per minute were used. The depth of cut was .062 inch.

A. Knives Ground, Not Jointed. In Part I of this report, page 27, attention was called to the uniformity of results obtained for equal cuts with unjointed knives from one run to the next. It was also found that the average value for 12 specimens of the type described above did not differ significantly from the value for a much larger sample. On the basis of this experience the 35 samples available for this experiment were divided into three groups; two groups of 12 each and one group of 11.

For the determinations made with unjointed knives, all three groups of specimens were run, and although the final average for this condition represents all 35 specimens, each group was averaged individually and checked against the average of the whole. Only small variations were observed among the groups, between the individual group averages, and the average of all 35 specimens.

As would be expected, the highest efficiency was obtained with the newly ground, unjointed knives; the power values correspond very closely to those obtained in previous studies on hard maple. The results are shown graphically in Fig. III-1, page 43.

B. Artificially Dulled Knives. To make an exact study of the relation of dulling to power, it would be necessary to have some fairly accurate method of producing measurable degrees of dulling, or at least of measuring dulling produced by planing. Jointing the knives is one method of producing a form of knife dullness. Since the amount of jointing can be controlled fairly well and measured with reasonable accuracy, four determinations were made with knives jointed in successive stages, from light to very heavy.

The width of the land produced by jointing varied considerably from point to point on the knife and from one knife to another; however, when only a short section of the knife is considered, the effect of these differences is minimized. The jointing land width was measured at three points on 1/8-inch section of each knife by means of a low power microscope of the type commonly used for Brinell hardness readings. An average width was determined for each knife and an average for all of the knives.

There seemed to be a rough correlation between the average width of the joint line and the power required -- an increase in width giving an approximately proportional increase in power required. The results shown in Fig. III-1, page 43, represent the efficiencies for various-width joint lines, ranging from an average of .004 inch for the light joint to .026 inch for the heavy joint.

Even when the knives were heavily jointed, it was observed that there was still a fairly keen cutting edge formed by the land created in jointing and the face of the knife. When the knives deteriorated through usage, however, it was found that a land is created as in jointing but also that the cutting edge is rounded off and chipped out. To simulate these conditions artificially, the heavily jointed edge was honed with the face of an oil stone turned to an angle of about 45 degrees with the face of the knife. In addition to this a coarse grinding wheel was rotated by hand over the joint line at about 45 degrees to the line of the knife. The cutting edge resulting from this procedure was "duller" than would normally be found even in cases of poor maintenance, and the power results (Fig. III-1) show that this treatment gave the lowest efficiency of any of the conditions studied.

C. Knives Dulled by Planing. It is difficult to describe the amount of dulling which occurs as a result of cutting. Hours of run are perhaps the best means, but this will vary considerably depending upon the nature of the material being planed and the distribution of the wear over the length of the cutterhead.

For this experiment the intentional dulling was confined to 1/8-inch length of the knives. The knives were freshly ground and then given a medium joint. Miscellaneous stock, including some rough hard maple planks and several rough-hewn railroad ties of a medium density tropical species, were planed under average conditions of feed speed and depth of cut. The ties had been stored on the ground, and no attempt was made to clean off the abrasive matter which clung to them. This, undoubtedly, somewhat accelerated the deterioration of the knives. When planing the stock, some time was required for adjusting the machine and lugging stock, so the machine time does not represent continuous planing.

After a period of one and one-half hours the first power determination was made. This showed a drop of about 50 per cent from the peak efficiency with unjointed knives and a drop of about 30 per cent from the efficiency obtained with medium jointed knives. After planing for an additional one and one-half hours, a second power determination was made. This showed a further drop in efficiency of about 10 per cent. The cutting efficiency under these conditions is compared with the sharp and artificially dulled knives in Fig. III-1, page 43.

PART IV

THE EFFECT OF CUTTING VELOCITY ON POWER REQUIREMENT AND SURFACE QUALITY

Summary

The effect of peripheral cutting velocity on power and surface quality was considered in this study. Soft maple was planed under various velocity-feed combinations at three depths of cut.

A. Power. Using combinations of velocity and feed which produce a constant feed rate in inches per knife, efficiency of removing material was determined for 1/32-inch, 1/16-inch, and 1/8-inch cuts. It was found that efficiency of removing material was practically constant for any given depth of cut under these conditions. Efficiency of removing material increased with depth of cut, confirming the results of Part I (Fig. I-5, page 21).

The relationship between spindle speed and peripheral velocity for the Buss 4L planer are shown in Fig. IV-1, page 48.

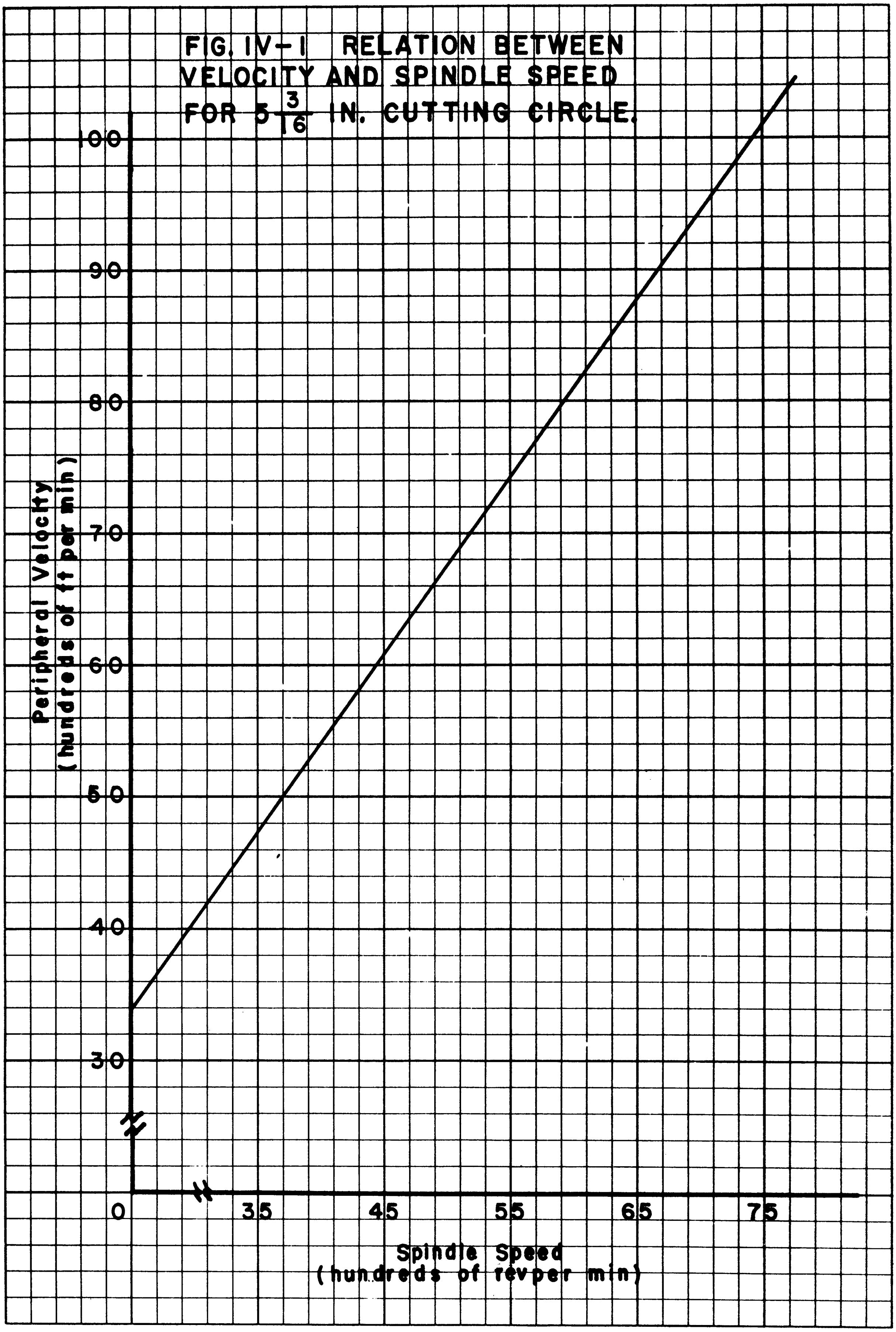


FIG. IV-1 RELATION BETWEEN VELOCITY AND SPINDLE SPEED FOR $5\frac{3}{16}$ IN. CUTTING CIRCLE.

B. Surface Quality. After the stock was machined under the various conditions of velocity, feed, and depth of cut, each piece was individually inspected for machining defects. In general, the severity and frequency of defects decreased as the depth of cut decreased and the velocity increased (Fig. IV-2, page 50). Chip marks were the most prevalent defect, with chipped grain being second. Fuzzy grain and torn grain occurred only in minor amounts on the species studied.

Discussion

The aim of this study is to show the effect of cutting velocity on the power required to plane soft maple and on the quality of the surface produced. Efficiency of removing material was determined for four combinations of feed and speed and for three different depths of cut. Surface quality of the stock planed under the various conditions was analyzed by the method described in United States Department of Agriculture Technical Bulletin 824[2] and by supplementary means.

Studies of velocity and its effect on power and surface quality are particularly significant in the light of the trend in recent years to increase the spindle speeds of woodworking machines. Two major factors have led to higher cutterhead speeds: First, it is usually believed that the number of cuts per inch of stock travel is a criterion of the quality of the surface. In order to maintain the number of cuts per inch under high production feed rates it is necessary to rotate the cutters faster or to add more cutters, the more practicable method usually being faster rotation. Second, experience indicates that higher cutting velocities produce better surfaces in most cases where the same ratio between feed and speed can be maintained. This is particularly true when part or all the cutting is against the grain.

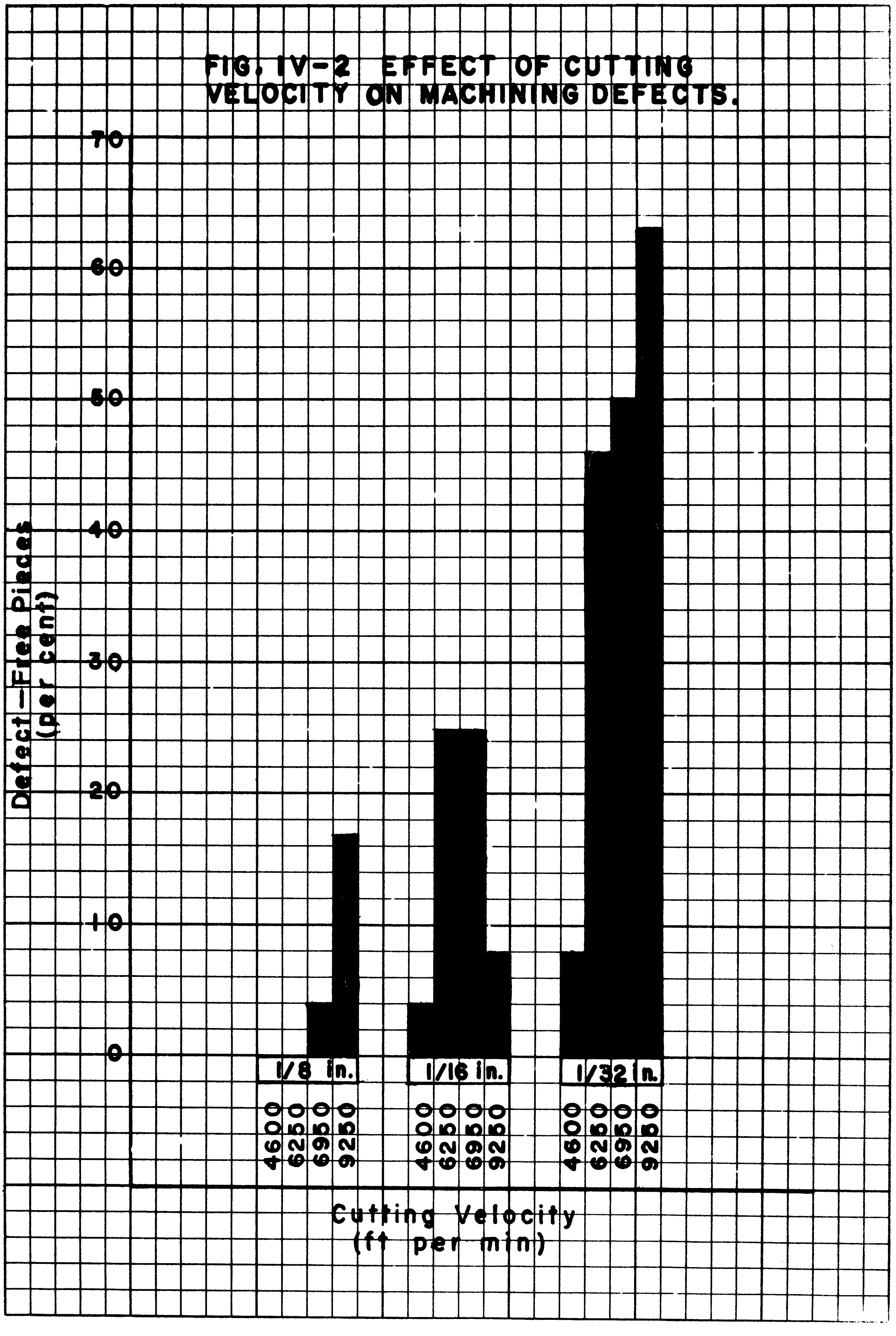


FIG. IV-2 EFFECT OF CUTTING VELOCITY ON MACHINING DEFECTS.

Because of the continuing trend to increase cutting velocities, it is important to know just what machine users receive for increased initial machine cost and the greater power required when high velocities are used. It should be established whether or not the more complex equipment required for high-velocity cutting pays its way in terms of greater production and better quality. Although the question cannot be completely answered in this preliminary study, it is believed that the results of this work will emphasize the significance of such information.

The physical equipment used for this study was the same as that described for the other parts of the investigation.

Kiln-dried soft maple which had been conditioned to an equilibrium moisture content of approximately 8 per cent was used. The specimens were sound boards accurately machined to 48 inches by 6 inches by 1-1/4 inches initial thickness. 36 such specimens were divided into 3 groups of 12 each. Two of these groups were selected to yield clear areas which were at least 36 inches by 4 inches; sound defects were allowed in the remainder of the piece. The third group was made up of pieces which contained a number of sound defects scattered throughout the piece.

The variable elements in this study were cutting velocity and depth of cut. The effect of both of these factors on power and surface quality was determined. Cutting velocity and its relation to efficiency of removing material was reported upon in Part II in terms of cutterhead speed. Since speed and velocity are proportional for any given cutterhead (see Fig. IV-1, page 48), the efficiency results based on the speeds used in Part II may be compared either directly or by extrapolation with the velocity results described here. This study differs from the cutterhead-speed study in that a constant ratio was maintained between velocity and feed rate. This kept the feed in inches per knife the same for all velocities, and it is assumed that this neutralizes the effect of the number of cuts per inch upon the quality of the surface.

Power values were determined for each specimen at each cutting velocity. These values were translated into efficiency, and the mean efficiency values for each velocity were compared with thosefor other velocities and with the actual or extrapolated results of Part II.

Each group of specimens was machined at a different position along the cutterhead. This minimized the effect of dulling. Each group was machined at depths of cut of 1/32, 1/16, and 1/8 inch and at the conditions of velocity and feed rate shown in Table IV-A.

TABLE IV-A

FEED-VELOCITY COMBINATIONS USED IN PART IV

Feed Rate	Idling Velocity		Approx. Vel. under Load	
fpm	fpm	rpm	fpm	rpm
34	4880	3590	4600	3400
46	6625	4880	6250	4600
51	7250	5325	6950	5100
68	9525	7000	9250	6800

The knives were ground and slightly jointed before determinations were made at each depth of cut. This meant that not more than 48 pieces were planed between grindings. Results of the preceding parts of this investigation show that dulling from this amount of cutting would have an almost negligible effect on power. The effect on surface quality should also be very slight.

The fact that the knives were jointed introduces some ambiguity into the results since there was no way of jointing the knives precisely the same amount each time. It was shown in Part III that the amount of jointing has considerable effect on power, and it is probable that there is also an influence on surface quality. Jointing is justified in this study, however, on the grounds that jointed knives are the usual practice in industry.

The direction of feed with respect to grain is an important factor both in relation to power and to surface quality. Chipped grain, which is one of the most troublesome defects in planing, is usually the result of planing against the grain. This trouble can be lessened on cross-grain stock by feeding in the more favorable grain direction. In industry, however, there is usually no selection of feed direction; therefore, for this study the direction of feed was chosen at random with respect to grain direction.

Power measurements were made by the same means as previously described in this report, using a recording wattmeter in the cutterhead motor circuit.

Surface analyses were made as follows. The 36-inch by 4-inch areas of the A and B specimens designated for analysis were examined for surface defects. Defects considered were chipped grain, fuzzy grain, torn grain, and chip marks, as defined under Terminology (page 5). A board containing any of these defects was not classed as "defect-free". With careful judgment an inspector determined whether or not any of these defects were present in the specimen, and the percentage of defect-free pieces was used as a measure of surface quality. Only the specimens of Groups A and B were considered in this evaluation since only these specimens had clear areas of the prescribed size. The frequency of occurrence and severity of the defect were tabulated. This method follows that used by the United States Forest Products Laboratory[3].

The specimens of group C were inspected for the same defects, and the occurrence of machining defects in relation to natural defects, such as knots and streak, was noted.

The inadequacy of this method of surface analysis is recognized. It is believed, however, that it is the most practicable method for evaluating surface characteristics at present. In order to illustrate more effectively the nature of defects which occur, photographs were made of the representative defects produced for each condition. These were made with the line of focus normal to the surface and with low-angle illumination (10 to 20 degrees). Two typical sequences are shown in Plates IV-A and IV-B, pages 55 and 56. Each of these figures shows a series of photographs of a given area of a sample piece after it has been machined under various conditions. Plate IV-A represents a piece which chip-marked badly. Plate IV-B represents a piece which showed a large degree of chipped grain in addition to chip marking. Further discussion of the effects illustrated here will be found in the discussion of surface quality (page 58).

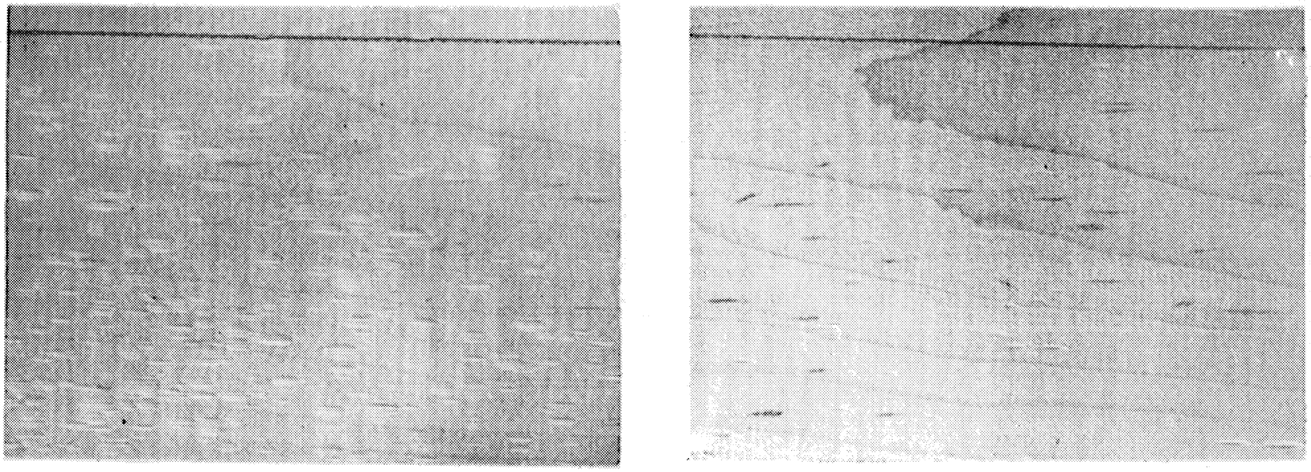
A. Relation of Velocity to Efficiency of Removing Material (Power). The cutterhead power required to machine each specimen under each of the 12 conditions of cutting velocity and depth of cut was determined from wattmeter chart readings. These power readings were used to determine the efficiency of removing material by using Eq 5, page 8.

The average efficiency of removing material for the specimens was determined for each of the 12 conditions and was found to be as tabulated below.

The average efficiency values verify the findings of Part II on the efficiency of machining soft maple at various feed rates and head speeds. In checking the tabulated figures at 1/16-inch depth of cut with the values read from the curves of Fig. II-2, page 31, it is seen that the differences are very small and are well within the range of experimental error.

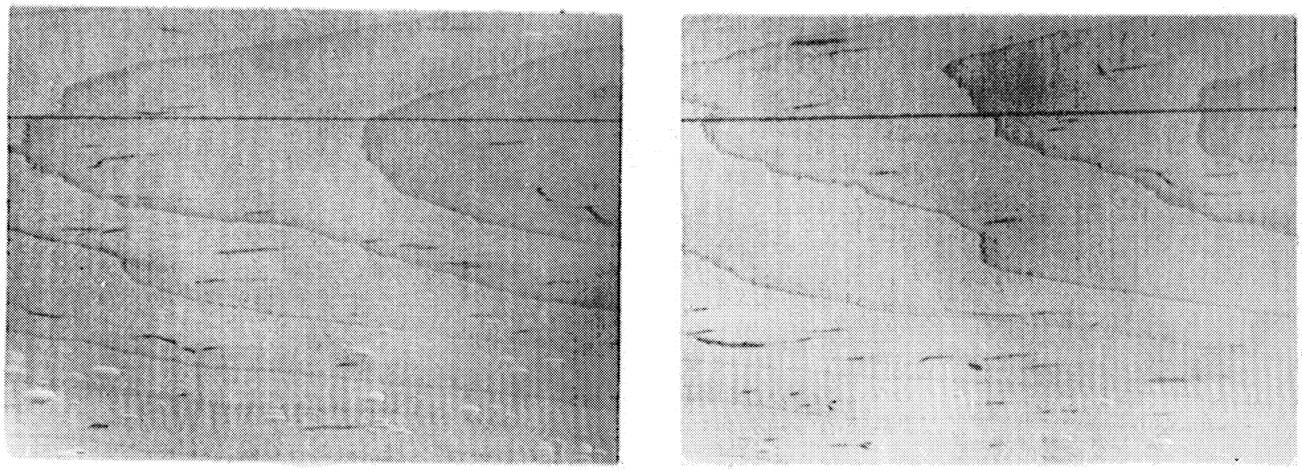
The tabulated values also verify the relationship between depth of cut and efficiency found in Part II, although no direct comparison could be

PLATE IV-A. A PORTION OF A SOFT MAPLE BOARD SHOWING MACHINING DEFECTS WHICH OCCURRED AT VARIOUS CUTTING VELOCITIES AND DEPTHS OF CUT.



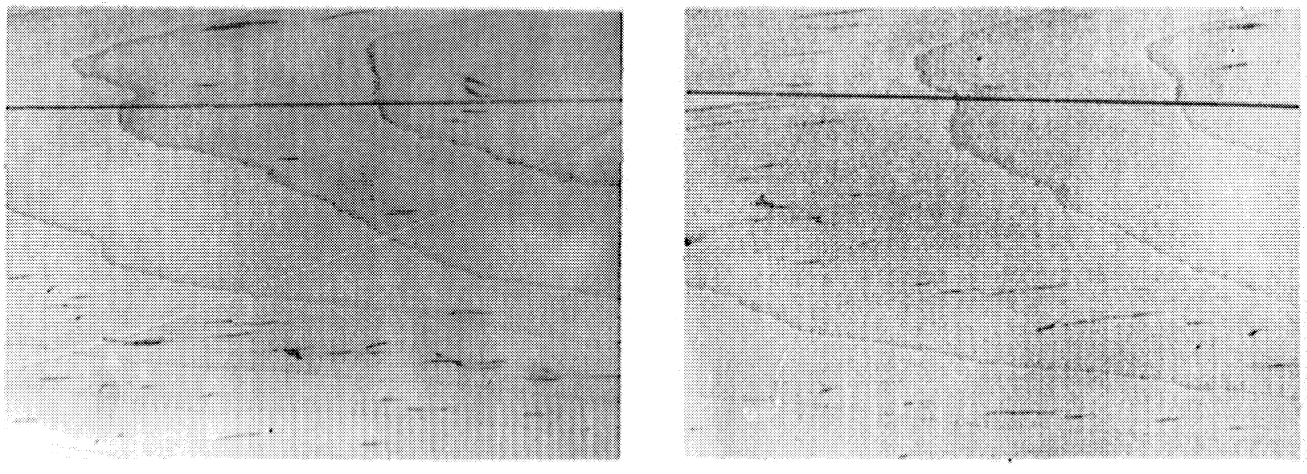
4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{8}$ in.



4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{16}$ in.



4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{32}$ in.

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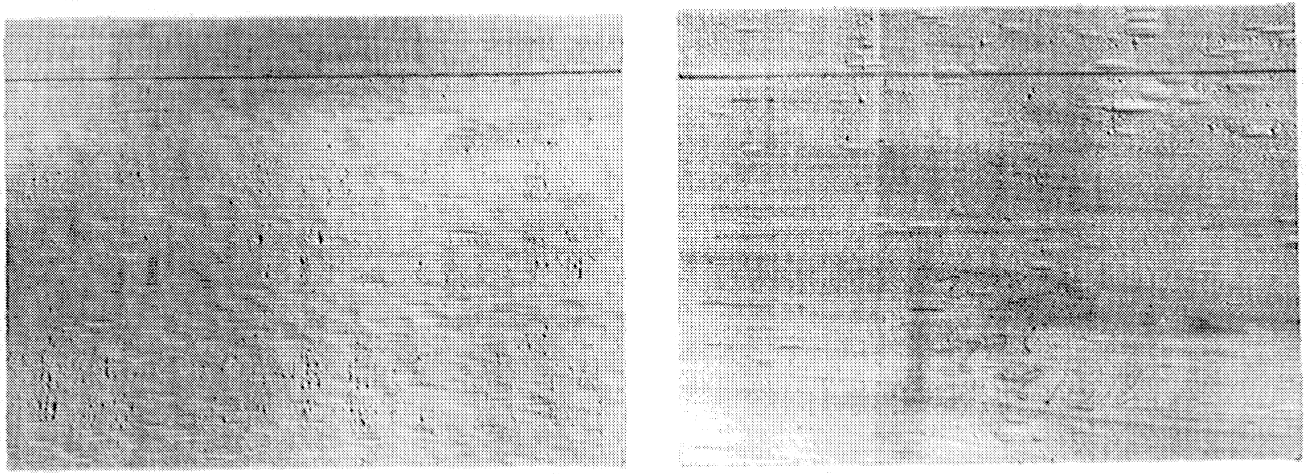
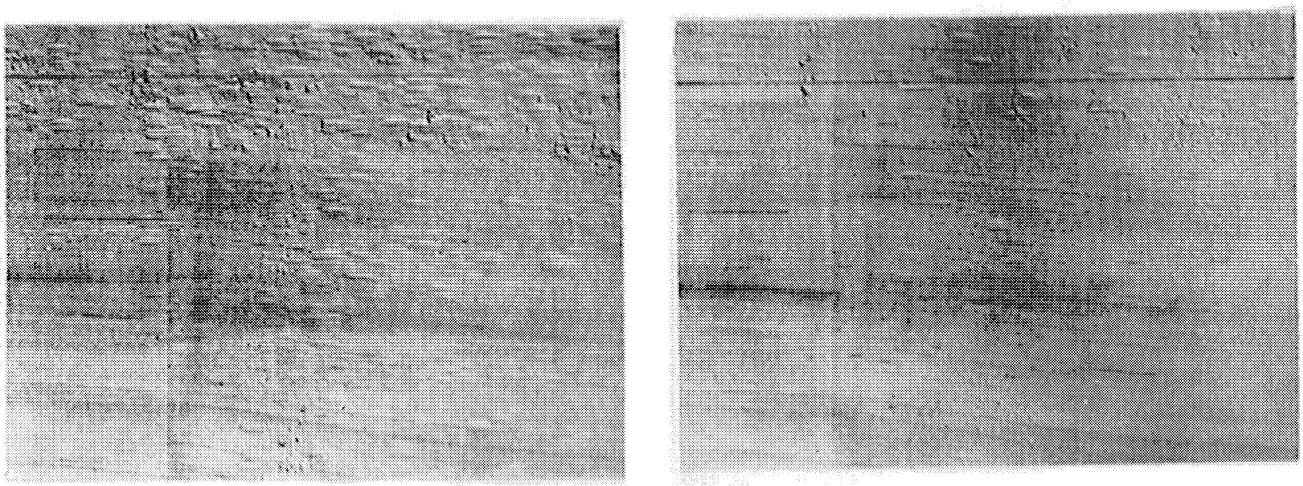
PLATE IV-B. A PORTION OF A SOFT MAPLE BOARD SHOWING MACHINING DEFECTS WHICH OCCURRED AT VARIOUS CUTTING VELOCITIES AND DEPTHS OF CUT.



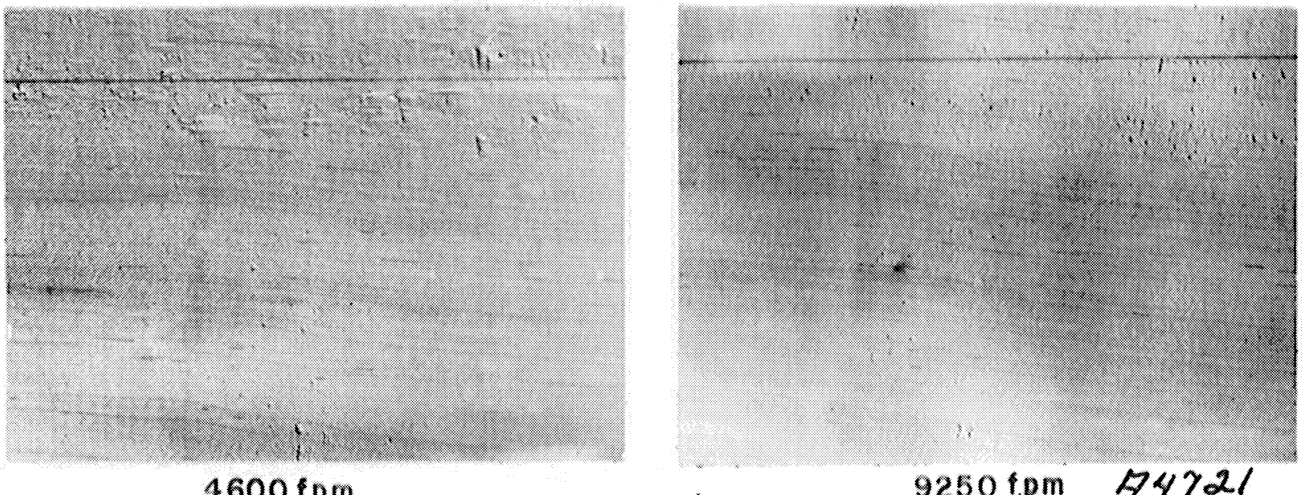
4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{8}$ in.



4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{16}$ in.



4600 fpm 9250 fpm

Depth of Cut = $\frac{1}{32}$ in.

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made because the conditions of machining were not identical. However, it is apparent from the figures given in Table IV-B that the efficiency of removing material increases with increasing depth of cut.

TABLE IV-B

AVERAGE EFFICIENCY OF REMOVING MATERIAL (CU IN. PER MIN PER HP)

	Feed-Velocity Combinations* Approx. Velocity under Load (fpm)			
	4600	6250	6950	9250
	Feed Rate (fpm)			
	34	46	51	68
Depth of Cut (in.)				
.031	72.97	68.41	70.43	70.03
.062	75.04	74.44	74.67	75.36
.125	81.86	83.12	96.08	81.61

* Feed rates and velocities chosen to give a feed of .030 in. per knife for each combination.

In analyzing the effect of cutting velocity on efficiency of removing material as tabulated in Table IV-B, above, it is apparent that there is no significant change in efficiency as the cutting velocity is increased when the ratio between head speed and feed rate is kept uniform. This means that the actual cutting can be done as economically at high speeds as at low speeds while producing the same surface from the standpoint of number of knife marks per inch. The tare-power requirement, however, is higher for higher velocities and increases approximately as the square of the increase in velocity, an important consideration in designing high-velocity machines. For example, doubling the idling velocity multiplies the tare power by 4. It should be possible in most cases, however, to justify the extra power required by the increase in production when higher velocities are accompanied by higher feed rates.

B. Relation of Velocity to Surface Quality. Since there is no accurate means of determining the quality of a wood surface, considerable ambiguity in these analyses was to be expected. But there was a remarkable consistency in the data in spite of the rather unprecise technique that had to be used, and this consistency seems to hold under several different methods of evaluation.

The initial estimate of quality was made on the basis of percentage of defect-free pieces. These percentages are shown graphically in Fig. IV-2, page 50. With one exception a constant improvement in quality can be seen as cutting velocity increases; the specimens machined at 9250 feet per minute and 1/16-inch depth of cut are the only contradiction. In this case the loss of defect-free pieces was largely the result of an increase in chipped grain, which may have been due to the human element involved in the inspection.

The percentage of defect-free pieces was low under most of the conditions. Apparently, the results of this study were somewhat below those reported by the Forest Products Laboratory. The two studies are not directly comparable, however, since the results described by the Forest Products Laboratory for soft maple represent an average of cuts made at four different cutting angles, two of which were more favorable than the 25-degree cutting angle used in this study. This difference may be sufficient to explain the discrepancy.

Chip marks were by far the most prevalent defects and disqualified many pieces that would otherwise have been considered "defect-free". Consequently, very close attention was paid to the factors which are usually believed responsible for chip marking, such as inadequate exhaust. The collection system was carefully checked; the draft was found to be better than average. These determinations were made with a draft of 4 inches of water on a water gauge at the pipe. When the draft was increased to 6 inches, there was only a slight decrease in the amount of chip marking.

Chip marking is explained by some investigators on the basis that certain woods do not sever cleanly as the knife leaves the cut, but instead break away from the surface near the end of the cut. The bundles of fibers which are attached to this type of chip tend to hook onto the knives, which carry the chip around into the cut. This theory further supposes that the chips of heavier woods have sufficient centrifugal force acting upon them to pull them away from the knife against the resistance of the hook[2].

In an attempt to distinguish the characteristics of chips of different species, chips were collected from soft maple pieces which chip-marked badly and from hard maple and basswood pieces which did not chip-mark under the same conditions of machining. These chips were carefully compared under the microscope. The type of hook did not seem to be particularly characteristic of the species, although there was some difference in their stiffness, with hard maple the stiffest and basswood the least stiff. Chips of hard maple tended to curl tighter than either of the other species. The soft maple and basswood chips appeared to be very similar in the amount of curl.

These observations did not seem to support the existing theories on chip marking; consequently, other possibilities were studied. One phenomenon which was especially interesting was the building up of an electrostatic charge on the surface of dry pieces (approximately 6 per cent) when they passed through the planer. This charge was sufficient in some cases to attract a number of small chips when the board was held a half inch or so above the pile of chips. This leads to the speculation that perhaps the chips are attracted to the surface in planing and are pressed into the surface by successive knives. There was some indication that the electrostatic effect was particularly strong with soft maple, but these few trials were not sufficient basis for any conclusions.

The brief study of chip marking described here has not disproved the presently accepted explanations of this problem, but it has stimulated further thought, and it is believed that some of the accepted theories of the causes of this defect may be subject to question. Further experimentation along this line, including a study of the airflow around the cutterhead, should be of considerable value. These findings indicate that the subject of chip exhaust requires further intensive investigation.

Next to chip marking chipped grain was the most numerous defect. This occurred rather uniformly under all conditions, and the effect of velocity and depth of cut on the frequency of occurrence is not very well defined. It is probable that grain direction has the greatest effect upon chipped grain. With a larger sample some definite pattern might be discernible for the velocity-depth of cut effect.

Plates IV-A and IV-B show two typical pieces after they have been machined under various conditions. The improvement in chip marking with greater velocities and shallower cuts is well illustrated. It can also be seen that the relationship for chipped grain is not so distinct.

A few pieces showed fuzzy or torn grain, but the percentage was almost insignificant when compared with the two major defects.

When the number of defect-free pieces produced proved to be so small, a complete evaluation could not be made on this basis. Consequently, a system was devised to rate defects on the basis of severity as well as frequency. In the inspection of the specimens after each planing, defects were described in degree as being very light, light, medium, or heavy. These ratings were based both on concentration of the defect per unit area and the depth of the defect, bearing in mind the amount of sanding which would be required to remove it.

The descriptions obtained in the above manner were assigned weighted values as follows:

Very light defect	1 point
Light defect	2 points
Medium defect	3 points
Heavy defect	4 points

The "defect points" for each type of defect were obtained for the entire sample. When tabulated according to the depth of cut and velocity, as in Table IV-C, page 62, these "defect points" show a remarkably clear pattern.

It can be seen that there is a consistent drop in the chip-mark defect rating, both due to increase in velocity and to depth of cut. This corresponds closely to the trend in the percentage of defect-free pieces and was the controlling factor in that percentage.

When evaluated by this system, chipped grain did not show a much more definite relationship to the conditions than when considered on the basis of frequency of occurrence. At 1/8-inch depth of cut the best velocity appeared to be 7250 feet per minute; at 1/16 inch, 6625 feet per minute; and at 1/32 inch, 9525 feet per minute. Chipped grain was in general somewhat less severe with deeper cuts.

Fuzzy grain occurred in only 6 of the 288 surfaces analyzed, and when weighted, these six defects totaled only 9 defect points. The average severity would be "very light" to "light".

There was only one instance of torn grain in the 288 surfaces analyzed.

The total defect ratings for each velocity condition closely paralleled the percentage of defect-free pieces with a general downward trend

TABLE IV-C

DEFECT RATINGS FOR A SAMPLE OF 24 SPECIMENS*

	Depth of Cut 1/8 inch				Depth of Cut 1/16 inch				Depth of Cut 1/32 inch			
Cutting Velocity	4880 fpm	6625 fpm	7250 fpm	9525 fpm	4880 fpm	6625 fpm	7250 fpm	9525 fpm	4880 fpm	6625 fpm	7250 fpm	9525 fpm
Chip Marks	89	84	73	50	64	49	34	35	53	6	4	0
Chipped Grain	25	19	13	23	25	10	26	36	42	33	33	24
Fuzzy Grain	0	0	4	2	3	0	2	0	0	0	0	0
Torn Grain	0	0	0	0	0	0	0	0	2	0	0	0
Raised Grain	0	0	0	0	0	0	0	0	0	0	0	0
Total Ratings	114	103	90	75	92	68	62	71	97	39	37	24

* High scores represent more defective surfaces.

in the severity of defects with increased velocity and decreased depth of cut.

Several tentative conclusions can be drawn from the results of this analysis of surfaces. It is significant that when evaluated in several different ways, these results seem to substantiate in a general way the other known experimental findings. Although this study has covered only a limited selection of conditions which should be investigated, it has shown that there is considerable promise in this approach to surface improvement.

It can be concluded that under these conditions surface quality as a whole improves with increased cutting velocity. It also improves with decreased depth of cut within the limits of this study. These same conclusions were stated by the Forest Products Laboratory for soft maple and for all the sixteen other species tested, except basswood.

Although depth of cut and velocity apparently have an important effect upon surface quality, it should not be concluded that these are the only or necessarily the most important conditions which need to be considered. Factors such as knife angles, moisture content, and knife sharpness are known to be extremely significant, and it is probable that many of the physical characteristics of the wood itself influence surface quality.

There is an increasing realization in the industry that surfaces are extremely important in the bonding and finishing of wood. Consequently, it is believed that a more comprehensive investigation of the effect of velocity on surface quality would be valuable. Such a study could also be expanded to include the effect of cutting angle on the surfaces of the most-used species. Further research along these lines should yield information from which optimum planing conditions could be specified.

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