Analysis of the Wood-Cutting Process

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AN ANALYSIS OF THE WOOD-CUTTING PROCESS

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PREFACE

The need for technical information on wood machining has been indicated by growing industrial interest in research in this area. In developing technical data, several leading manufacturers have taken advantage of the facilities available through the Engineering Research Institute of The University of Michigan to sponsor substantial research projects concerning the machining of wood with saws, surface planers, and coated abrasives.

These research projects were conducted in the University's Department of Wood Technology, where they stimulated a study of the basic principles of wood machining. The following analysis of the factors and relationships that control the wood-cutting process is a direct outgrowth of research conducted under industrial sponsorship.

In the course of this study of wood machining, it has been necessary to seek the advice and assistance of others at The University of Michigan. To Professor Stephen B. Preston (Department of Wood Technology) sincerest gratitude is expressed for his unlimited aid in all phases of the work. Without his scholarly and graciously accorded cooperation, it is doubtful whether this investigation could have been carried out successfully. Acknowledgment is also made of the immeasurable assistance given by Professor Lester V. Colwell (Department of Mechanical Engineering), whose achievements in the field of metal-cutting provided a wealth of knowledge applicable to the machining of wood, and who made available the necessary instrumentation. Warmest personal appreciation is expressed to Professor Alan A. Marra (Department of Wood Technology) for his scholarly help and friendly encouragement throughout the investigation and preparation of the manuscript. For making it possible to conduct the research in conjunction with academic obligations, the help of Dean Stanley G. Fontanna (School of Natural Resources) is gratefully acknowledged.

Acknowledgment is made of contributions to the initial phase of the research by Professors W. W. Gilbert (formerly, Production Engineering Department) and L. A. Patronsky (formerly, Wood Technology Department); of the encouragement given by Dean Emeritus S. T. Dana and Professors F. E. Dickinson and W. Kynoch (all of the School of Natural Resources); and of the help of the Engineering Research Institute, particularly that of Dr. R. G. Folsom, Director, and Dr. B. A. Uhlendorf, Editor, through funds and editorial services which have made this publication possible.

Norman C. Franz

Ann Arbor, Michigan
November, 1957

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INTRODUCTION

Wood has served man for untold centuries. This unique material has been exploited constantly to provide such basic necessities as shelter, warmth, food, weapons, and tools. It is difficult to imagine another material of such diverse utility or which has had equal importance in the evolution of mankind. Being a renewable natural resource, the impact of wood on the development of man promises to be augmented as the reserves of other resources continue to dwindle.

One of the important characteristics of wood that has permitted it to be of great versatility is the ease with which it can be worked with tools. It is this characteristic which allowed primitive beings to fashion wooden items with crude implements and which has helped wood to maintain a competitive position against contemporary substitute materials. However, the relative ease of machining wood has not stimulated much development in this area, while progress in the machining of competing materials has been very significant. This has resulted in the rejection of wood for many applications, since the advantage of wood's machining ease has been nullified by technological progress in other fields.

It is unfortunate that the machining of wood is one of the most neglected fields of forest products research (1), since it is probably one of the most important considerations in wood utilization. From the time a tree is felled until it reaches the final stage of manufacture, machining is a major phase of the process, whether the means be a saw, planer, pulpwood chipper, veneer cutter, or particle mill. While the apparent progress in the machining of wood during the past century may seem great, an examination of developments shows that the real progress has been in fields other than wood machining. Actual knowledge of the wood-cutting process has not increased appreciably; it has been possible only to profit from advances in other fields which have provided cheap electrical power, alloyed and sintered cutting-tool materials, and high-speed machinery (2).

It cannot be denied that much valuable information on the machining of wood has been acquired through practical experience in the absence of complete understanding of the process. This means of obtaining knowledge is slow, however, and it has been demonstrated clearly that progress in any field is materially accelerated by sound technological research that offers an understanding of the fundamental concepts involved. The recent spectacular advances in chemistry, electronics, and nuclear physics are direct effects of the procurement of basic knowledge in these areas.

It follows that the paucity of basic information on the wood-cutting process precludes the probability of outstanding advances in wood machining. In order to surmount this obstacle, a research effort of considerable magnitude is required. The work described herein is a contribution to the establishment of an understanding of the fundamental aspects of wood machining.

This research endeavors to establish what takes place when wood is machined with a cutting tool and pursues the factors controlling the identified phenomena. It is at once apparent that the many facets of wood machining constitute a subject much too comprehensive to be treated adequately in a single work. Therefore, the study presented is directed primarily to a consideration of aspects associated with the machining of wood parallel to the grain. It is expected that much of the information and incidental data can be expanded, and will lead to interpretation of other wood-machining procedures.

REVIEW OF THE LITERATURE

Machining of Wood

A substantial amount of literature pertaining to wood machining has been published (3), yet paradoxically little research has been done on the subject (1). Infrequent papers have been released concerning the technical aspects of machining wood, and of these but a few bear on the subjects considered in this investigation.

Studies on the feed and cutter-head power requirements of rotary planers have been conducted by Bobbe (4) at Dresden, and later by Sekiguchi and Hasegawa (5) at Tokyo. Other investigators (6, 7, 8) have subsequently examined the factors influencing power demands, but none have attempted to explain the results obtained.

The Swiss worker Köberle (9) investigated static tangential cutting forces by loading a knife free to rotate about an axis until it removed a chip of given thickness. This exploratory work stimulated Kivimaa (10) in Finland to make a very noteworthy study of the cutting forces in wood machining. By feeding carefully controlled wood samples radially into a revolving knife, and measuring the tangential and radial forces during cutting by means of a pendulum dynamometer, he was able to detect the influences of numerous variables.

The phenomenon of chip formation is noted briefly in the above work by Kivimaa, but is not the object of any study. Chip formation is also treated in general terms in a survey publication issued by the British Forest Products Research Laboratory (11). Photographic studies of the wood-cutting process have been reported by Patronsky (12), Franz (13), and Hoyle and Cote (14) in the United States.

Machining of Metals

In contrast to wood machining, the machining of metals has been the subject of much learned basic research, and numerous scholarly publications on the topic have appeared. Recent work in the field has added many titles to an already impressive bibliography of metal-cutting prepared by Boston (15). Since the literature contains much information that can be applied to the machining of wood, a few of the more relevant publications are included below.

It has been pointed out by Ernst (16) that in cutting metals three basic types of chips are formed: Type 1, the discontinuous chip; Type 2, the continuous chip; and Type 3, the continuous chip with built-up edge. Merchant (17, 18) has presented a mathematical analysis of the geometry, mechanics, and plasticity conditions governing the formation of the continuous chip, and with Field (19) has similarly analyzed the discontinuous chip. Piispanen (20) has developed nearly identical analyses of chip formation in the course of independent work in Finland. The continuous chip with built-up edge is discussed in a study of friction between the chip and tool by Ernst and Merchant (21), and in a paper by Prianishnikoff (22).

The mechanics and geometry of the orthogonal* cutting process have been adequately examined by Merchant (23). In an analysis of the milling process, Martellotti (24, 25) has described the geometry of rotary cutting.

The value of photomicrography as a research tool in metal-cutting has been demonstrated by Boston (26). Elaborating on this

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*Cutting nomenclature is defined in a following section of the text.

approach, Ernst (16) employed motion picture photography to observe the phenomena associated with the cutting process. In experiments by Field and Merchant (19), photographic methods were used for simultaneous correlation of chip formation and the forces exerted on the cutting tool. The measurement of tool forces has received considerable attention, and various types of dynamometers for this purpose have been described (27, 28, 29).

The investigations of the metal-cutting process provide a plausible foundation for research in the machining of wood, since many of the underlying principles are common to both materials. While important differences in machining are to be expected, it is apparent that an understanding of the wood-cutting process may be accelerated in development by advantageous use of the vast amount of information accrued on metals. Further, it is indicated that the study of chip formation and its controlling factors, an approach of proved success in metals, is a logical starting point for basic investigations on the machining of wood.

NOMENCLATURE

In current practice, considerable confusion exists in the various descriptive terms applied to wood machining. Terminology relating to tool geometry is particularly chaotic, being encumbered by ambiguities. A definitive treatment of machining nomenclature is therefore an essential antecedent of discussions pertaining to the wood-cutting process. The terminology adopted for use herein is defined below, with geometrical relationships shown in Figures 1, 2, and 3.

α — cutting angle; the angle of the tool face measured from a perpendicular to the direction of tool travel.

β — clearance angle; the angle between the back of the tool and the work surface immediately behind the cutting edge.

d — depth of cut; distance from original work surface to surface generated by cutting edge.

ρ — angle of tool force resultant; the angle whose tangent is equal to the normal tool force divided by the parallel tool force.

t — chip thickness; thickness of chip before removal from work piece.

w — chip width; width of the undeformed chip.

μ — coefficient of friction between the tool face and the chip.

F — friction force; force component acting along interface between tool and chip.

F_n — normal tool force; force component acting in direction perpendicular to parallel tool force and surface generated.

F_p — parallel tool force; force component acting in direction parallel to tool motion relative to work piece.

N — normal friction force; force component acting normal to tool face.

R — resultant tool force; the resultant of parallel and normal tool-force components.

V — cutting velocity; velocity of tool relative to work piece.

Orthogonal cutting — machining condition in which the cutting edge is perpendicular to the direction of relative motion of tool and work piece and generates a plane surface parallel to the original work surface.

Rotary cutting — machining condition in which the tool rotates about an axis, making intermittent contact with a work piece moving tangentially to the path described by the tool.

Feed per knife — in rotary cutting, the amount the work piece advances in the interim between successive contacts of one or more rotating tools.

Additional terms of infrequent occurrence are defined where they appear in the text.

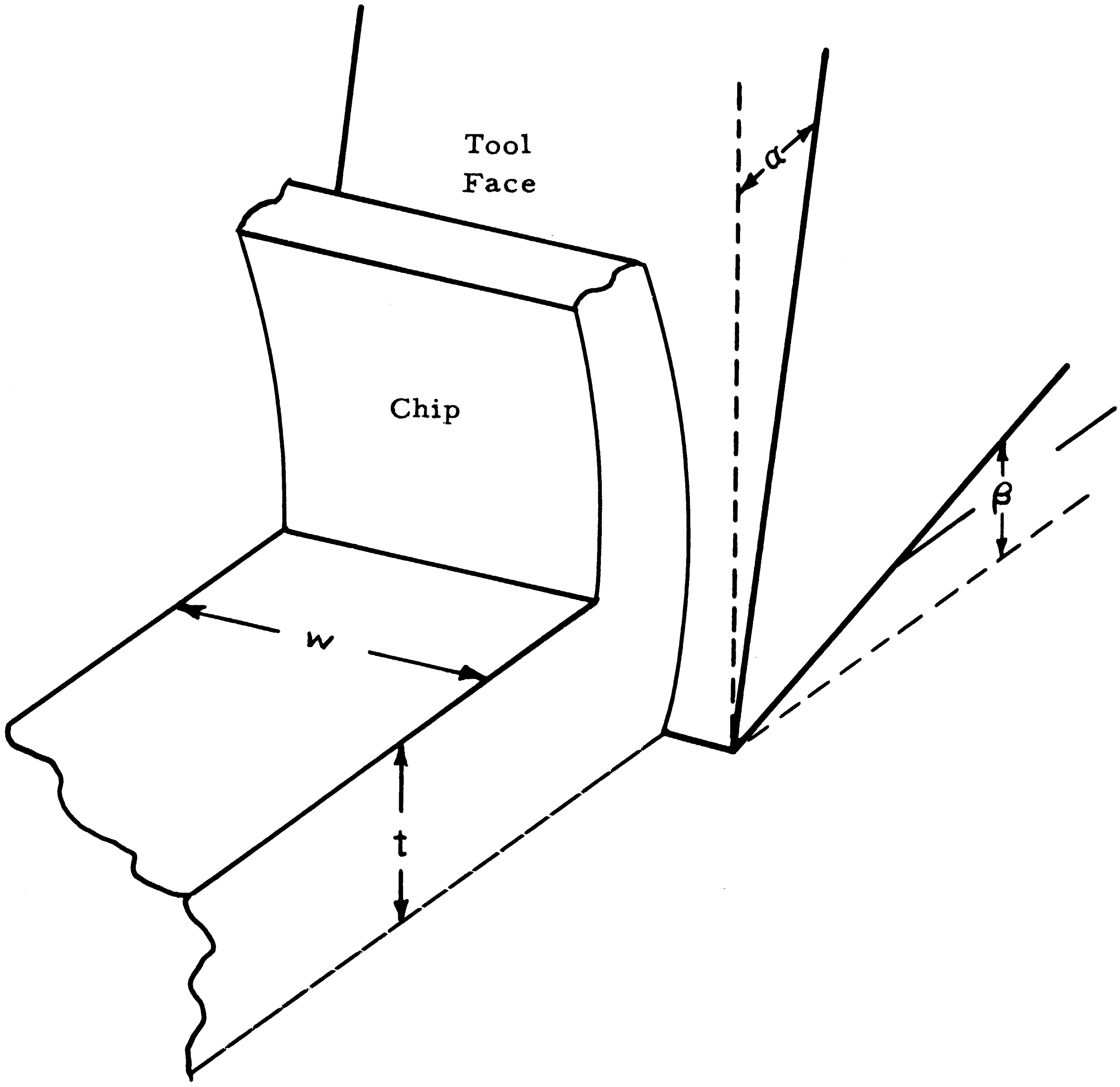


Fig. 1. --Geometry of orthogonal cutting

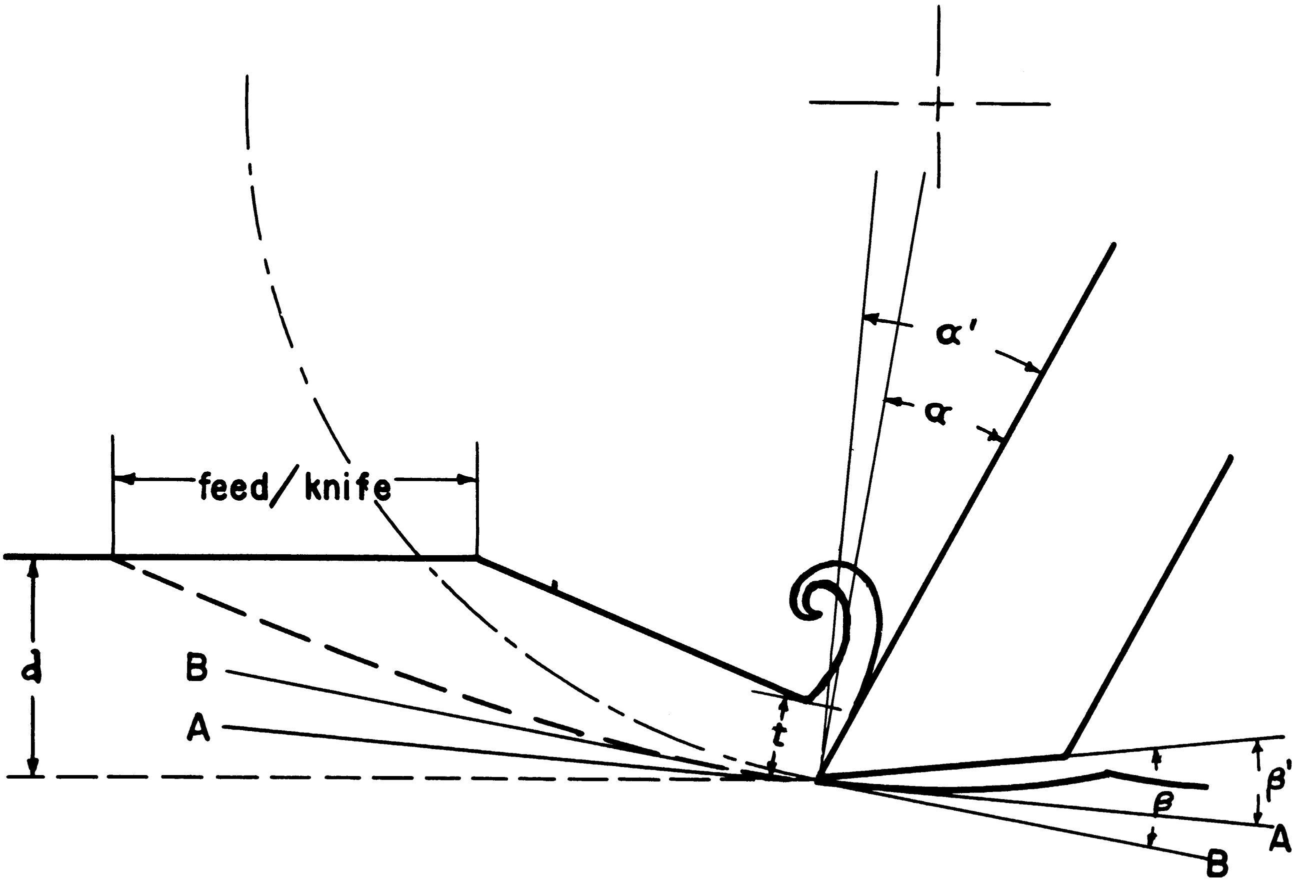


Fig. 2. --Geometry of rotary cutting. Line A - A, tangent to tool path; Line B - B, tangent to cutting circle; α, apparent cutting angle; α', actual cutting angle; β and β', apparent and actual clearance angles, respectively; t, instantaneous chip thickness; d, depth of cut.

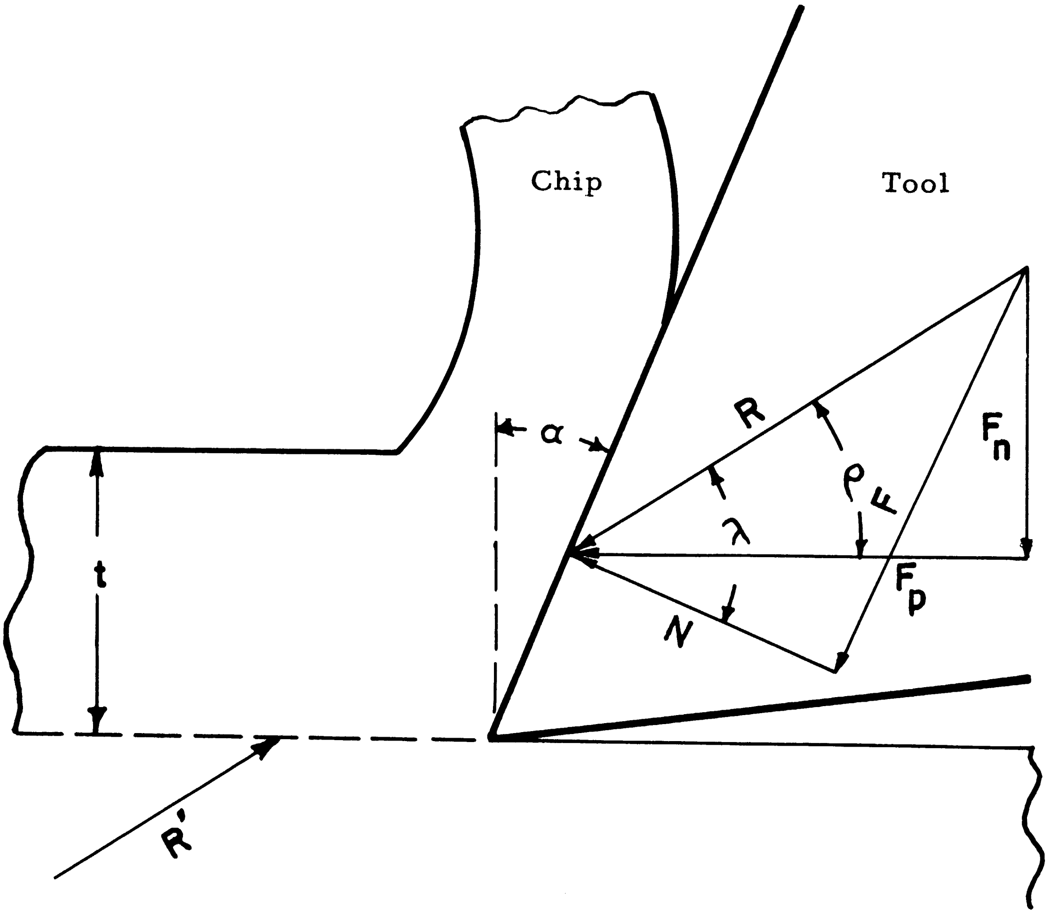


Fig. 3.--Force relationships in orthogonal cutting. See text for definition of nomenclature.

DEVELOPMENT OF THE STUDY

Photographic Studies

Examination of past research efforts in wood machining clearly demonstrated that the lack of fundamental information precluded the possibility of developing empirical or theoretical data that could be utilized to full advantage (30). It therefore appeared that proposed academic research in the machining of wood could most profitably be directed toward the establishment of basic concepts relating to the cutting process.

A logical research approach was suggested by the literature on metal-cutting, in which studies on the formation of the chip have proved to be of primary importance. It seemed plausible that a similar treatment of wood machining would be expected to give equally valuable information if suitable investigative techniques could be established. A series of developmental experiments was thus deemed appropriate to determine the applicability of metal-cutting methods, and to provide qualitative information on the process of chip formation in wood machining.

An initial study of conventional rotary cutting was made on a vertical-spindle shaper. Using well-known principles of microflash photography, it was possible to observe chip formation at any desired instant during machining at various sets of conditions. Cutting velocity, feed per knife, and depth of cut were readily controlled by appropriate devices to enable photographic comparison of effects on chip formation.

The use of high-speed electronic flash photography provided a convenient means of observing the wood-machining process at cutting velocities up to 25,000 feet per minute. Clear images of the knife and sharp delineation of the accompanying chip were obtainable, but due to inherent characteristics of the microflash source, it was not possible to photograph a sequence on the removal of a single chip. Since the events taking place at various points on the tool path were necessarily recorded as observations on different individual chips, analytical treatments were confounded by the introduction of natural variations in the wood being machined.

Recognizing the above limitations in technique, a concurrent study of the cutting process was initiated using an 8 mm. high-speed motion picture camera. With film speeds up to 14,000 frames per second, this device permitted an apparent thousand-fold magnification of time when photographs of chip formation were viewed at normal projection speed. The continuity of observation provided by motion photography enabled close examination of the wood-cutting process, from which it was determined that the mechanical failures developing in the chip during removal could be detected with adequate image magnification.

The degree of magnification applicable to motion studies of rotary cutting was seriously restricted by the size of the observation field required to include all of the tool path. In order to secure motion photomicrographs of reduced subject areas, it was essential to consider a situation where the tool remained stationary and the work moved. Orthogonal cutting, which lends itself to this approach with simplicity, was therefore used for minute study of chip formation in a manner similar to that described by Ernst (16).

Since orthogonal machining is attended by practical limitations of cutting velocity, care was taken to detect possible associated aberrations. Chip formation during rotary cutting was observed at peripheral velocities ranging from 100 feet per minute up to 20,000 feet per minute using the photographic methods already described. A parallel study of chip formation in orthogonal cutting included speeds ranging from nearly static conditions up to 81 feet per minute.

The above visual studies of the wood-cutting process proved helpful in establishing a program for a more intensive study of chip formation. The results and conclusions drawn from this phase of preliminary experiments are discussed in a following section of the text.

Power and Force Studies

During photographic studies of the rotary cutting process, it was deemed advisable to record data on the power required for machining under various conditions. This was accomplished by use of a proprietary recording watt-meter wired to the spindle drive motor. Net power required for cutting was defined as the difference between the gross power recorded and the tare power necessary to turn the spindle when not under load. Adjustment of data to compensate for electrical losses was made in accordance with the motor manufacturer's specifications.

Measurement of the forces exerted on knives during rotary cutting was not considered practical in preliminary studies of limited scope. In a study of chip formation during the cutting process, average force determination as presented by Kivimaa (10) has little advantage over power measurement, since instantaneous forces are obscured. On the other hand, procurement of data on instantaneous forces in rotary cutting becomes difficult as normally associated machining velocities are reached. Further, the analysis of data is confounded by the varying geometrical and mathematical considerations inherent in the curved tooth path of the process (24, 25). The obstacles thus confronting any tenable analysis of rotary cutting forces made such an attempt seem premature.

Many of the restrictions on force measurement during rotary cutting can be eliminated in a consideration of the orthogonal cutting process. The relatively stable mathematical and geometrical relationships of this machining method lend themselves to expedient analysis, and the lower cutting velocities normally attendant are helpful in force studies where instantaneous values are sought. Equally important, the constant conditions of orthogonal cutting permit observation of force patterns developed during chip formation.

For the above reasons, the measurement of forces associated with wood cutting was limited to a treatment of orthogonal conditions. A tool dynamometer similar to that described in the major study was used to determine force components normal and parallel to the path of the cutting edge. Electrical translation through a recording analyzer resulted in a continuous plot of both components of force. These graphic representations could then be correlated with simultaneous motion pictures of the cutting process, thus making it possible to observe the behavior of force variations with respect to stages of chip formation.

Findings of Preliminary Studies

Examination of the rotary cutting process reveals that chip formation apparently takes place in two phases. Typically, when machining parallel to the grain under conventional conditions, an initial curled chip of ever-increasing thickness is formed as in Figure 4. Then, at a critical point on the cutting path, rupture of the wood occurs some distance in advance of the cutting edge as illustrated in Figure 5. Since wood failures in the first instance are within the path described

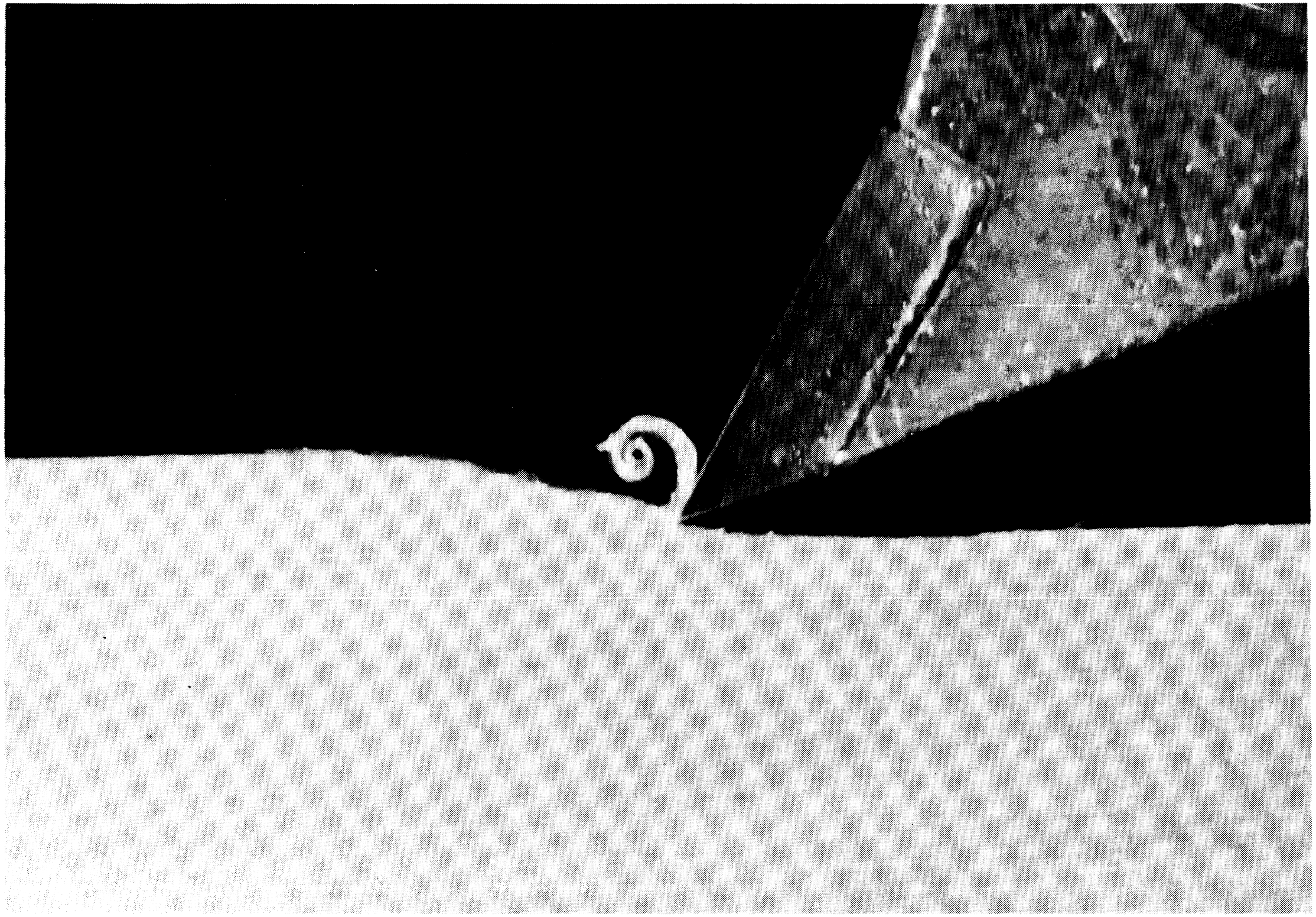


Fig. 4. --First phase of chip formation in rotary cutting

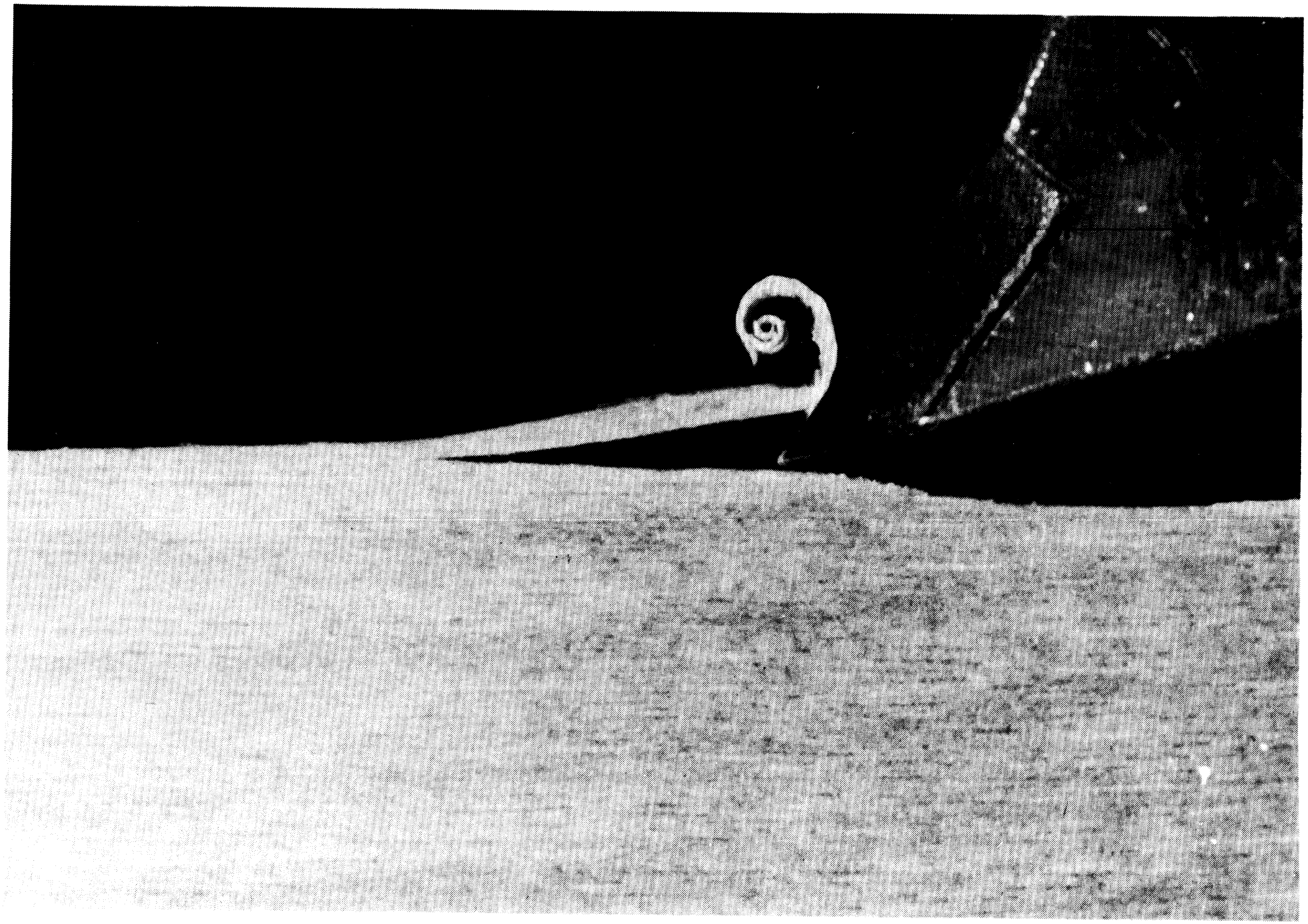


Fig. 5. --Second phase of chip formation in rotary cutting

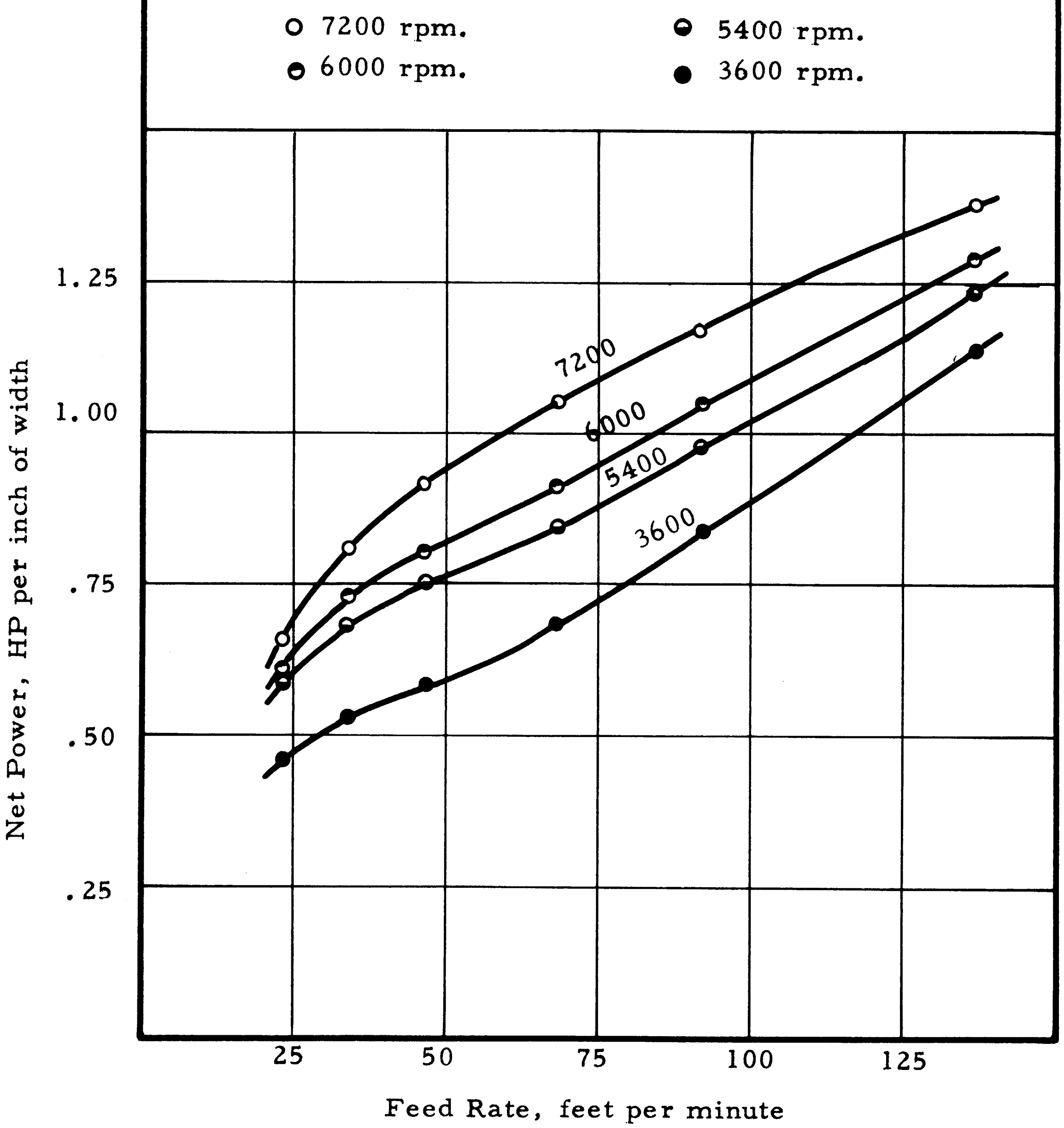
by the tool edge, the resulting surface on the work piece may be expected to be generally good. In the second phase, however, external failures leave an irregular surface which persists on the final work surface unless removed by successive chip formation.

It is commonly recognized that the grain orientation of wood largely determines the quality of surface obtainable in a machining operation. Under adverse conditions the probability of a poor surface is increased by the tendency of splitting failures in the second chip phase to follow planes of weakness in the wood and extend beyond the tool path. It was observed that the severity of this condition is greatly influenced by the position on the cutting path at which transition between the two chip phases occurs. Quite logically any postponement of the change reduces the extent of splitting failures.

As would be expected, the chip phase transition is retarded by decreasing the thickness of the chip removed through the reduction of feed per knife or depth of cut. Reduction of the knife cutting angle had a similar effect as did an increase in the wood moisture content. It was observed, however, that the response to changes in cutting conditions varied markedly among wood species, and further, that the character of the chip during the first phase of formation was often altered by factors that influenced the point of transition.

The modulation of the process of chip formation in rotary cutting is reflected by power requirements. Cutter-head power demand plotted as a function of average chip thickness gives a characteristically sigmoid curve as exemplified in Figure 6, where feed per knife is the controlling variable. It appears that such a curve may represent a summation of values for each of the two phases of chip formation, where power requirements display an exponential relationship to chip thickness in the first phase and a linear relationship in the second phase. It follows that at small chip loads the major volume of material is re-

Fig. 6.--The effect of feed rate and cutter-head rotation on power in rotary cutting. Sugar maple; 8.0 per cent moisture content; four-knife head; depth of cut 1/16 inch.



moved prior to transition in formation, and power is depicted as associated with the initial chip phase. Then, as chip thickness is increased, the amount of material included in the first phase apparently approaches a limiting point, and an increasing proportion of the wood is removed by the second chip phase which affects power demands accordingly.

Visual study of the process of chip formation in orthogonal cutting revealed close similarity to the events taking place in rotary cutting. This holds, since orthogonal cutting may be considered to be a special case of rotary cutting where the angular velocity of the tool is zero. The machining conditions thus stabilized by orthogonal treatment permitted minute examination of the chip formation phases identified in the rotary process. It was observed that chip formation could be distinguished most accurately according to types, the first phase including several such classifications, with the second containing but one. These types of formation tend to parallel those described for metal-cutting (16), but are distinctive due to the anisotropism of wood. Comment on the various types of chip formation is deferred, since the subject is considered more appropriately in later discussion.

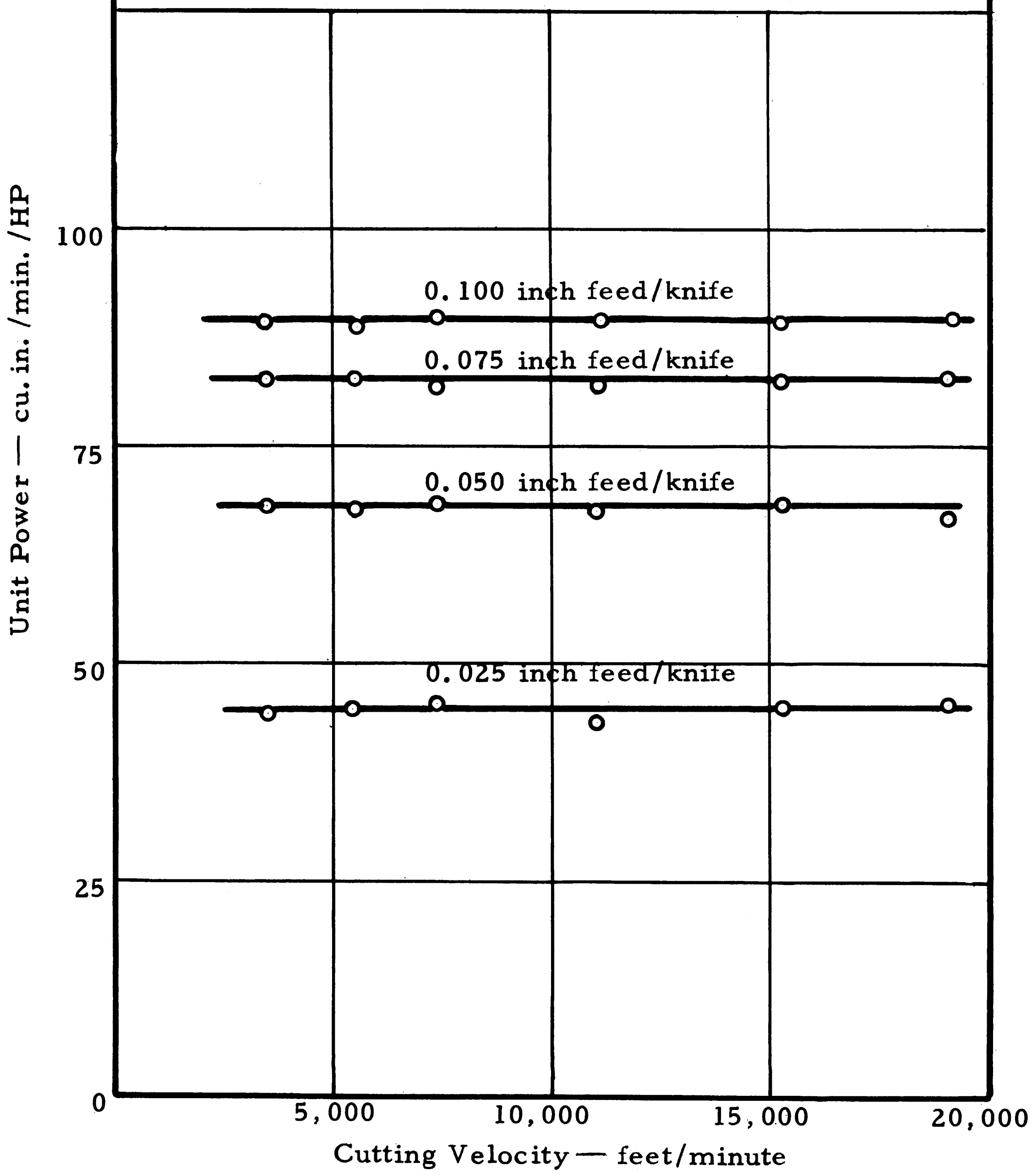
Of considerable significance was the observation that each of the various chip types manifests a characteristic quality of surface on the work piece. This conforms to findings in the machining of metals, but in wood the surface variations appear much more diverse. All the commonly recognized machining defects attributable to the cutting process can be traced to specific types of chip formation. Equally well, the absence of defects can be identified with chip type. Thus, it is implied that the quality of machined wood surfaces can be predetermined by control of the process of chip formation. This premise is part of the underlying philosophy of the approach taken in this research.

Instantaneous tool forces recorded during orthogonal cutting indicated substantial correlation with wood properties, machining geometry, and the process of chip formation. Both force magnitude and chip type were seen to be contingent on interrelationships of wood properties and cutting geometry, while patterns of force development along the tool path were found to be dependent on the type of chip formation existent. In accord with the process of chip formation, which was observed to vary from a continuous event to one of cyclical nature, tool forces ranged from stable values to those of violent fluctuation but uniform amplitude. Hence, it is suggested that the cutting process may be controlled by altering force relationships determined from machining geometry.

Visual studies of the wood-cutting process disclose no discernible variation in chip formation as a result of changes in cutting velocity, so long as all other factors remain constant, and truly dynamic conditions exist. As static conditions are approached, it was noted that alteration of the cutting process gradually takes place and often results in changes of chip type. This behavior presumably reflects a reduction in certain wood mechanical properties as rates of strain approximate zero.

The findings of visual examinations are corroborated by studies of velocity effects on power in rotary machining, and on forces in orthogonal cutting. It may be assumed that any appreciable change in the cutting process due to velocity would be reflected by unit power requirements and force levels. However, as exemplified in Figure 7, no evidence of change in unit power requirements is seen over the range of velocities considered, and even an expected small chip acceleration effect appears negligible. Similar results were obtained in force measurements, which displayed congruity at all but near-static conditions.

Fig. 7.--Relation of unit power requirements to cutting velocity in rotary machining. Depth of cut 1/16 inch; hard maple at 8.0% moisture content.



The above preliminary experimentation was used to establish a point of origin for more intensive study of the wood-cutting process. From the data accumulated, it was apparent that an approach paralleling that used for metal-cutting was sound, despite gross differences in work piece properties and the significantly greater cutting velocities associated with practical wood machining.

PURPOSE AND SCOPE

Preliminary investigations of the wood-cutting process provided significant information leading to an understanding of what happens when wood is machined. Further, initial studies were invaluable in the development of suitable research techniques, and defined the areas of machining that offered greatest opportunity for application of intensive study.

Exploratory research demonstrated that two broad corollaries exist for the machining of wood with a cutting tool. First, the energy required for cutting and the characteristics of the surface generated are dependent on distinguishable types of chip formation. Second, the recognized types of chip formation are determined by interrelationships of wood properties and cutting geometry which govern tool-force development. Hence it may be postulated that cognizance of the factors which control chip formation, and establishment of the interactions of those factors, should lead to a means for predetermining the results of a given machining operation. Following the above reasoning, the purpose of this research is two-fold: (1) to extend the knowledge of chip formation gained in preliminary studies, (2) to study the factors and relationships that determine the various types of chip formation.

It is obvious that any attempt to attain the listed objectives is confounded by numerous variables, some of which were considered in the preliminary phases of research. Thus, the magnitude of the subject is beyond the comprehension of a single project, and limitations of scope must be imposed to meet practical qualifications as well as to avoid results that defy analysis by virtue of their complexity.

Acknowledging the restrictions necessary, this research was held to a consideration of orthogonal cutting parallel to the grain of the wood at low velocities. The influences of wood properties on the cutting process were studied principally by varying the species and moisture content of the work piece. Simultaneously, the interactions of cutting geometry were investigated by varying the thickness of the undeformed chip and the cutting angle of the tool.

While the selection of orthogonal cutting at low velocities is admittedly unrealistic in view of common woodworking practice, it was felt on the basis of preliminary investigations that information obtained from this approach would be applicable to conventional rotary cutting at high velocities.

EXPERIMENTAL PROCEDURE

Design of Experiment

Orthogonal cutting at a velocity of 3.5 inches per minute was determined to be particularly well suited for an investigation of the wood-cutting process. While representing a marked departure from practical applications, which typically employ rotary cutting at peripheral velocities in the order of 5,000 to 10,000 feet per minute, the selected conditions were considered fully defensible and correlative. As noted in previous discussion, the orthogonal cutting method may be considered to be a special case of rotary cutting. Further, preliminary experiments showed that cutting velocity is inconsequential in wood machining, a conclusion that is corroborated by Kivimaa (10).

The experimental techniques used for study of the variables and relationships controlling chip formation were similar to those described by Field and Merchant (19). This required that tool-force components normal and parallel to the cutting path be correlated with the events associated with formation of the chip. The photographic equipment and tool-force system used for simultaneous determinations are discussed in detail under appropriate headings later in the text.

A total of 378 different machining conditions, with three replications in each, were included in experiments concerning the interactions of factors determined to be of major importance in the cutting process. Orthogonal cutting parallel to the grain at a velocity of 3.5 inches per minute was used in all cases. The following variables were included:

(1) Three species; sugar pine (Pinus lambertiana Dougl.), yellow birch (Betula alleghaniensis Britt.), and white ash (Fraxinus americana L.).

(2) Three moisture contents; 1.5 per cent, 8.0 per cent, and saturated, based on oven-dry weight.

(3) Seven chip thicknesses; 0.002, 0.005, 0.010, 0.015, 0.020, 0.025, and 0.030 inch.

(4) Six cutting angles; 5, 10, 15, 20, 25, and 30 degrees.

The above species, representing a moderately resinous coniferous wood, a diffuse-porous hardwood, and a ring-porous hardwood, all of commercial importance, were selected for their wide range of physical and mechanical properties. Equally important, each is typically free of unusual or confounding characteristics, and proved available in adequately sized pieces displaying straight grain, uniform growth, and flat-sawn surfaces. The three moisture contents at which the woods were machined encompass extreme as well as a popular moisture condition. The levels chosen provided a simple means of altering the mechanical properties of each species, which vary in their response to moisture change (31). On the basis of preliminary investigations, the chip thicknesses and cutting angles used for this study gave ample coverage of these machining variables.

Supplemental to the study of interactions listed above, more limited consideration was given to friction between the chip and the tool face by varying the surface roughness of the latter. Sugar pine at 8.0 per cent moisture content was machined parallel to the grain at 3.5 inches per minute using three tool bits with 20 degree cutting angles and uniform geometry, but with face roughnesses varied through grinding with abrasive wheels of different characteristics. Four depths of cut were employed, including 0.005, 0.010, 0.020, and 0.030 inch.

In contrast to all other experiments in which machining was limited to cases where the wood grain paralleled the tool path, a brief examination of cutting with and against the grain was appended to the principal studies to gain additional information on the process of chip formation. Cutting angles of 10, 20, and 30 degrees were used to machine sugar pine of 8.0 per cent moisture content at 0.005, 0.010, and 0.015 inch depths of cut. Tool travel was in opposite directions to a grain angle of 5 degrees, referenced with respect to the cutting path.

Simultaneous data on the process of chip formation and associated tool forces were collected in the foregoing experiments. These data are presented and discussed in subsequent portions of the text.

Preparation of Wood Specimens

Investigation of the influence of wood properties on the machining process made close control of all test specimens mandatory, since heterogeneity would confound results and preclude accurate analyses. It was therefore necessary to impose judicious restrictions on the selection of material in the three species studied, the preference of which has been discussed in considerations of experimental design.

In order to minimize variations in wood properties, the following precautions were taken: (1) only defect-free, straight-grained wood of uniformly moderate growth was used, (2) all specimens of a given species were taken from a single band of growth rings, (3) specimens for mechanical properties tests and machining experiments at a given moisture content were side-matched, (4) sets of specimens to be conditioned to various moisture contents were end-matched.

Carefully selected stock of sugar pine, yellow birch, and white ash, meeting the above requirements and of adequate size to provide all of the specimens desired, was procured in the air-dry condition. Three end-matched sections were cut from each of the original pieces, as in Figure 8, and their relative orientation noted. Wood grain alignment radial and tangential to the axis of growth was determined for each section by means of a pivoted scribe commonly used for such purposes, and the ends of the specimens marked to indicate the positions of five specimen blanks, as shown in Figure 8. The blanks were band-sawed from the material allowing some surplus for subsequent machining, and the groups from each section accordingly removed for conditioning to the three moisture-content levels prescribed for study.

Specimen blanks to be conditioned to 1.5 per cent moisture content were placed in an air-circulating oven which maintained a dry-bulb temperature of 120 degrees Fahrenheit, and a wet-bulb temperature of 70 degrees Fahrenheit. The dry-bulb temperature was raised gradually from room conditions over a period of several days in order to avoid possible damage to the wood from too rapid drying. Individual specimen blanks were considered to be at equilibrium when no weight loss was discernible after an interim of 48 hours.

A constant-temperature and humidity room was used for conditioning the group of specimens from each species that was designated to be used at 8.0 per cent moisture content. Held at a dry-bulb temperature of 75 degrees Fahrenheit and a relative humidity of 45 per cent, specimens were considered to reach equilibrium moisture content when no weight change was noted after an interval of one week.

The specimen blanks to be tested at saturated moisture conditions were submerged in water at room temperature for an extended period. When the material lost all bouyancy, it was presumed that the interior portions were above the fiber-saturation point.

When the wood specimens had apparently reached their respective equilibrium moisture conditions, random samples were taken from each group and checked for moisture content by accepted oven-

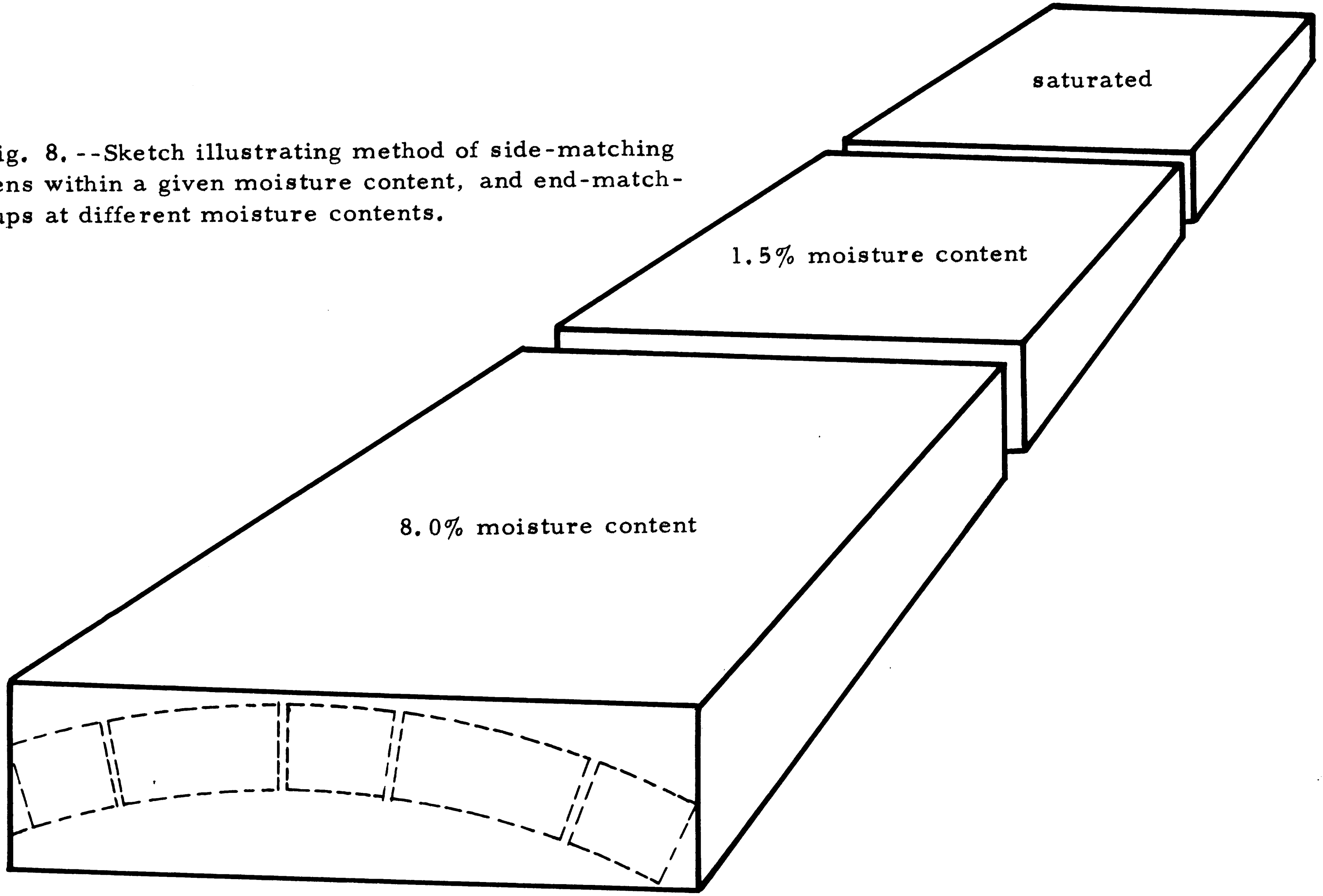


Fig. 8.--Sketch illustrating method of side-matching specimens within a given moisture content, and end-matching groups at different moisture contents.

drying techniques (32). Following this, the blanks were jointed and planed to a rectangular cross section one inch across the growth rings and one or two inches in the tangential direction. In the planing operations, tolerances were held to .001 inch, and machine feed pressures were kept at an absolute minimum to avoid injury to the wood surfaces. The finished blanks, each presenting surfaces that were truly radial or tangential to the growth rings, and of uniformly straight grain longitudinally, were then cut transversely to obtain specimens for machining studies and the determination of wood properties, as in Figure 9.

The wood samples to be used for machining were divided into three parts paralleling the growth increments, each being a sample of the inner, central, or outer portion of the band of growth under consideration. The samples were carefully machined to a thickness of 0.250 inch, plus or minus 0.001 inch, and further divided into three-inch lengths. One edge of each specimen was split off with a dull knife to produce a reference edge exactly parallel to the wood grain, and the remaining edge was machined to give uniform width. Radially matched specimens from each of the three growth zones were affixed to a backing strip for convenience in handling, and the resultant work-piece unit, shown in Figure 10, was held at appropriate moisture conditions until used.

It will be noted that the specimens to be machined were derived to present a radial surface to the tool. This was considered essential, since seasonal variations in a given annual growth increment would be detrimental to control of wood properties in tangential face machining, particularly with depths of cut small in comparison with the yearly growth accretion. While wood rays introduce a confounding factor when machining on a radial surface, the species selected for study contain a relatively small volume of narrow, interspersed rays of inconsequential physical influence.

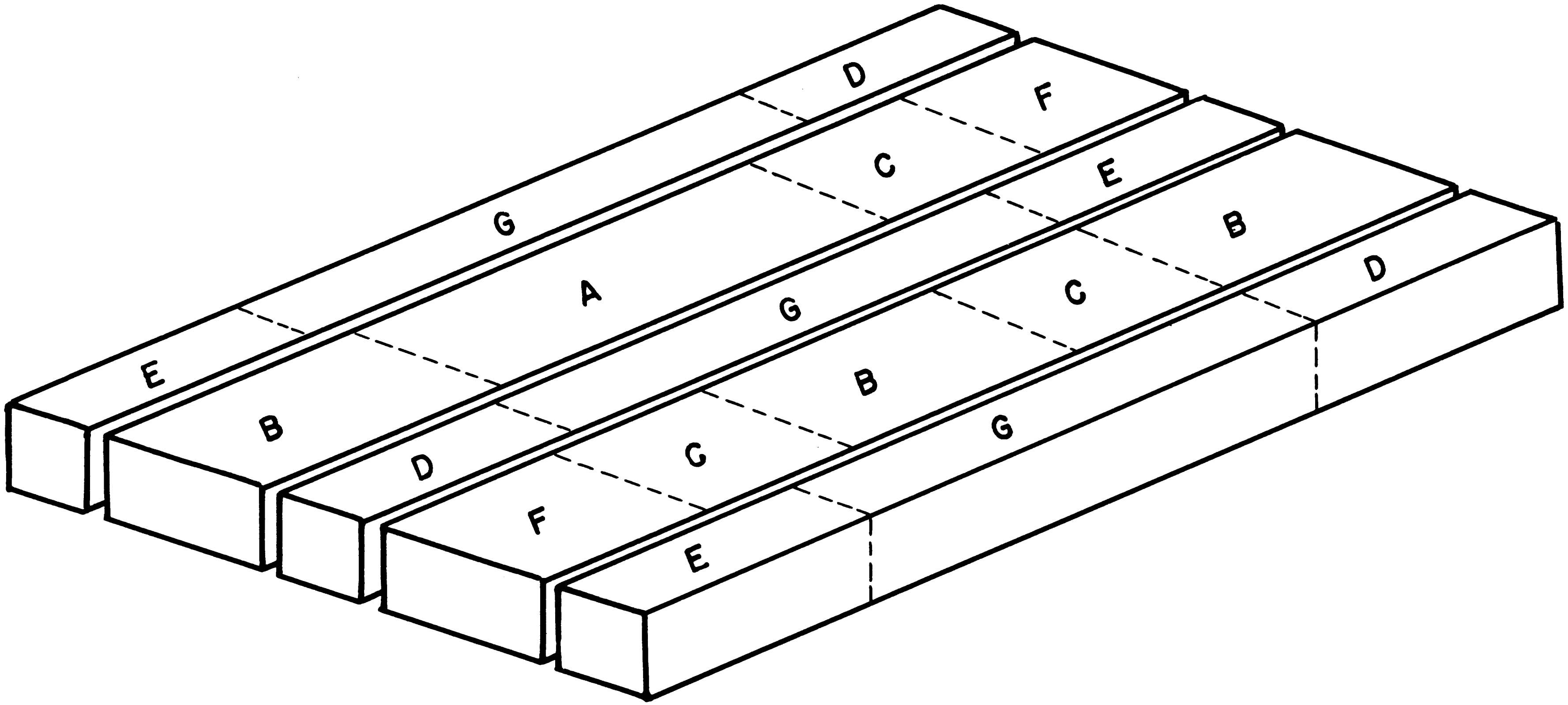


Fig. 9. --Sketch of specimen blanks showing manner in which machining and mechanical properties test specimens were derived. A, machining specimens; B, cleavage; C, shear; D, compression parallel to grain; E, compression perpendicular to grain; F, tension perpendicular to grain; G, bending.

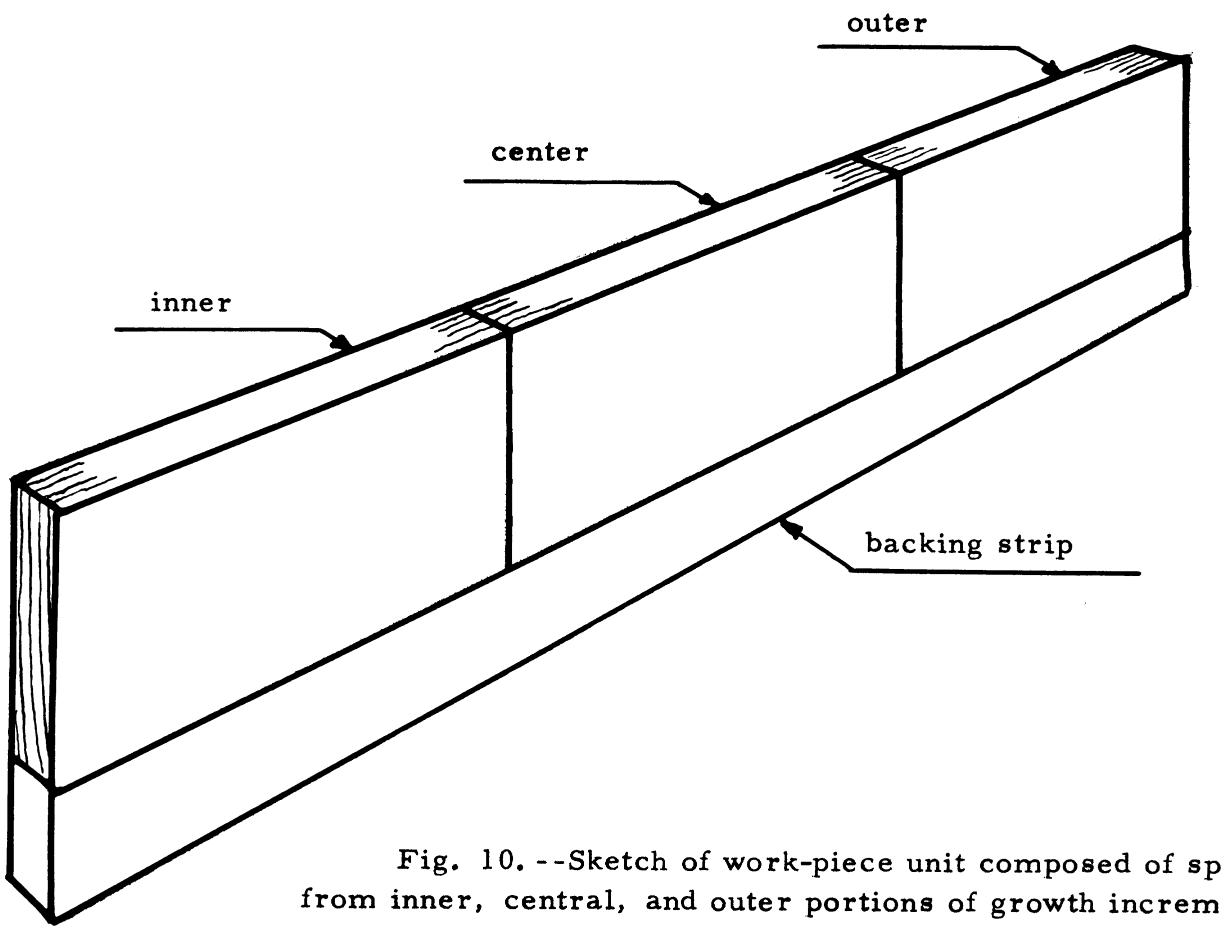


Fig. 10.--Sketch of work-piece unit composed of specimens from inner, central, and outer portions of growth increment.

The surfaced wood samples remaining after the preparation of the above machining specimens were manufactured into mechanical-properties test specimens as indicated in Figure 9. Specimen preparation was in accordance with accepted standards (32), except that certain dimensional reductions were imperative with the limited amount of available material. The two-inch square cross section specified for testing in cleavage and shear parallel to the grain, and tension perpendicular to the grain, was reduced to one inch in width while retaining the standard depth and length. Determinations of all other mechanical properties were based on specimens one inch square and of length consistent with critical dimensional proportions in appropriate cases; the test pieces were designed to assure loading in a direction tangential to the annual growth rings.

Determination of Wood Properties

It was evident from preliminary experiments that the machining characteristics of a given wood are largely governed by dynamic mechanical properties. It was also apparent that severe stress concentrations must develop in regions of the work piece near the cutting edge, and that complex, combined stresses are imposed by the tool. These considerations limit the applicability of conventionally determined static properties in an analysis of the cutting process. Conventional mechanical tests (32) were used, however, since no other means of determining wood properties have been developed to provide more satisfactory data.

As pointed out in discussion of the methods used for specimen preparation, modification of test-piece size was mandatory with the limited amount of material available. This deviation from standard dimensions was considered of minor importance, since appropriate adjustments were made to maintain specimen proportions, and rates of strain during testing were appropriately reduced as required (31). In all cases where loads were applied perpendicularly to the grain of the test piece, the direction of application was tangential to the growth rings. This insured that the stress planes of specimens used for the determination of wood properties were comparably oriented with those under consideration during machining.

The various moduli and stress values associated with wood mechanical properties were derived from test data by means of recognized standard procedures (32). The methods and computations involved are too widely comprehended to warrant explicative comment.

Tool-Force Determination

The determination of instantaneous tool forces induced during orthogonal cutting necessitated the development of a system for the detection and recording of loads imposed normal and parallel to the cutting path. This was most satisfactorily accomplished by methods similar to those which have been proved in research on the machining of metals.

The system devised for force measurement employed a two-component tool dynamometer in conjunction with a recording strain analyzer, Figures 17 and 18. During machining, forces exerted against the tool bit held in the dynamometer cause the latter to be stressed as a short cantilever beam, resulting in slight deflections normal and parallel to the tool path. Two electrical resistance strain-gage bridges translate the deformation, and the signal for each component is fed to a proprietary two-channel strain-analyzing instrument which interprets tool forces in terms of pen deflection on a moving chart. Through calibration of the system, tool-force components can be computed from their respective oscillograph records.

In Figure 11, the dynamometer constructed for this investigation is pictured with the cutting bits which were inserted to vary tool geometry. The design of the dynamometer is patterned after a similar metal-cutting research device which was applied in preliminary force studies on wood, but which proved inadequately responsive. The rapidly fluctuating tool forces associated with wood machining, with only five or ten per cent of the magnitude found for comparable cutting conditions in steel, necessitated design modifications to increase the sensitivity of the otherwise satisfactory prototype. Based on exploratory work, the dynamometer for this study was required to be responsive to 0.05 pounds change in force values of either component. Further, deflection of the tool bit at the center of loading was limited to 0.001 inch under application of 100 pounds.

Design details of the aluminum-alloy tool dynamometer developed to meet the above specifications are shown in Figures 12 and 13. The unique construction was found essential to obtain adequate rigidity with sufficient strain at the gage locations to provide the desired sensitivity. From the circuit diagram of the strain-gage bridges mounted on the ribs of the dynamometer, it will be noted that the device is self-compensating for temperature changes, torque, and deflection normal to that measured by each bridge. Tool bits, ground to prescribed specifications and of snug fit, were mounted in the off-center hole at the end of the instrument with the cutting edge on the dynamometer axis. Held in place with a set screw, the tool bits were supported by an extension of the dynamometer body to insure rigidity. The entire measuring device was fixed in position for machining as described in a following treatment of cutting methods.

The strain-gage bridges of the dynamometer were each connected to electronic amplifying units, which in turn transmitted

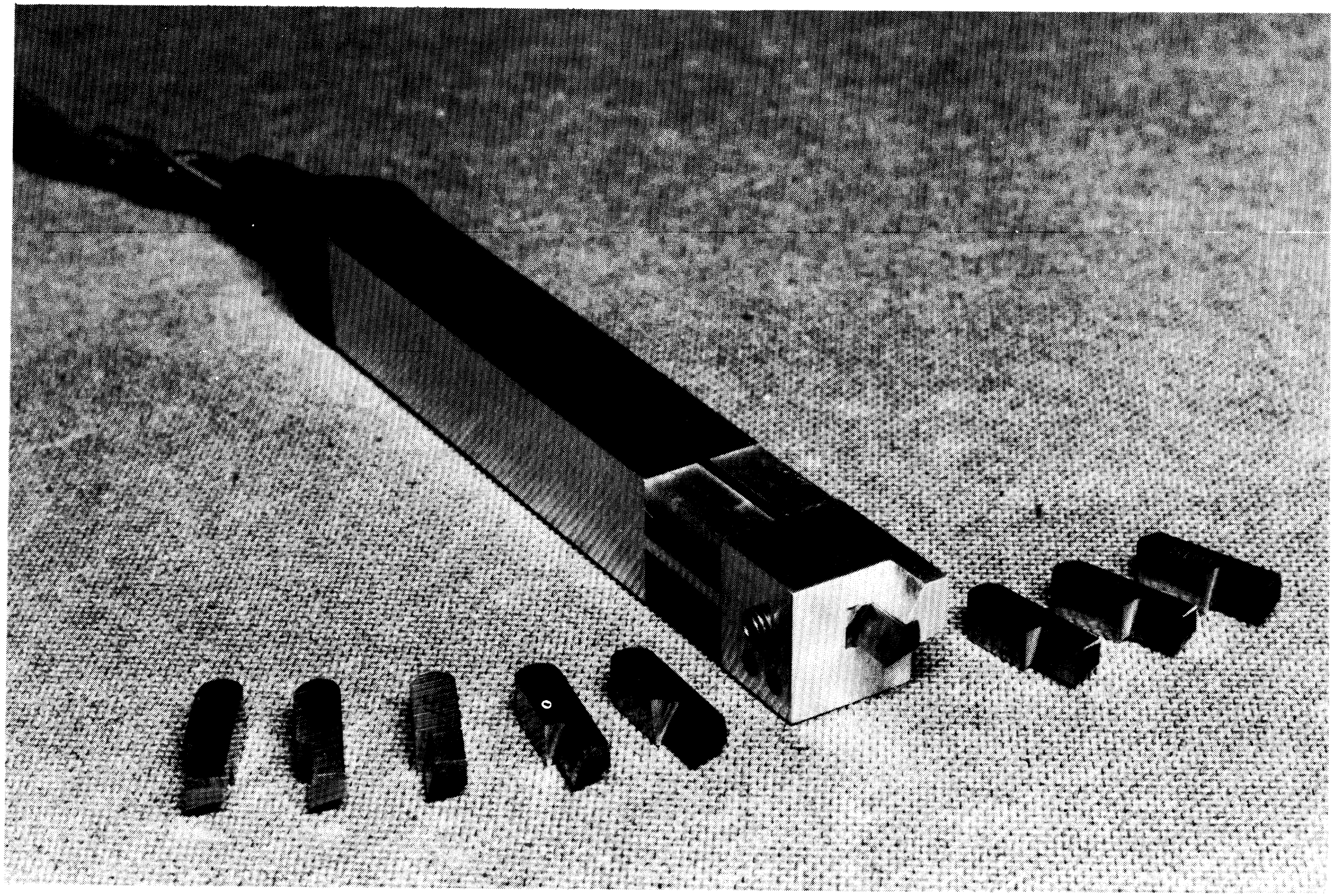


Fig. 11.--Two-component dynamometer for measuring instantaneous tool forces, and interchangeable bits used to vary cutting angle and roughness of the face of the tool.

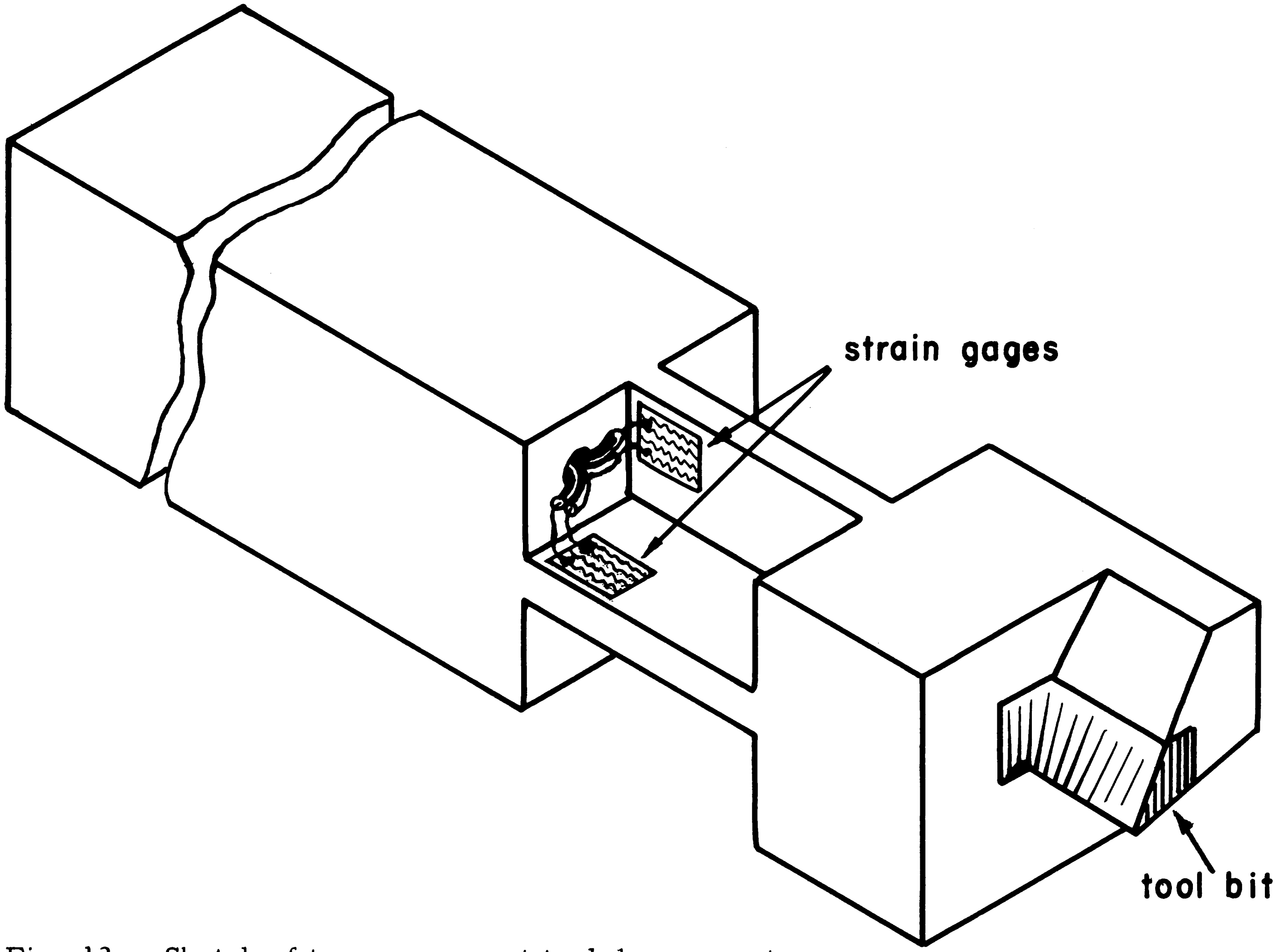
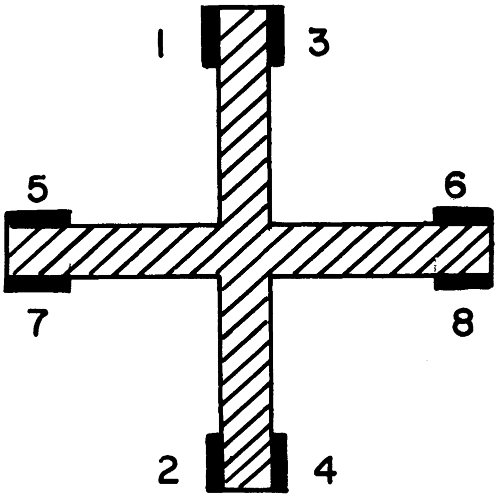
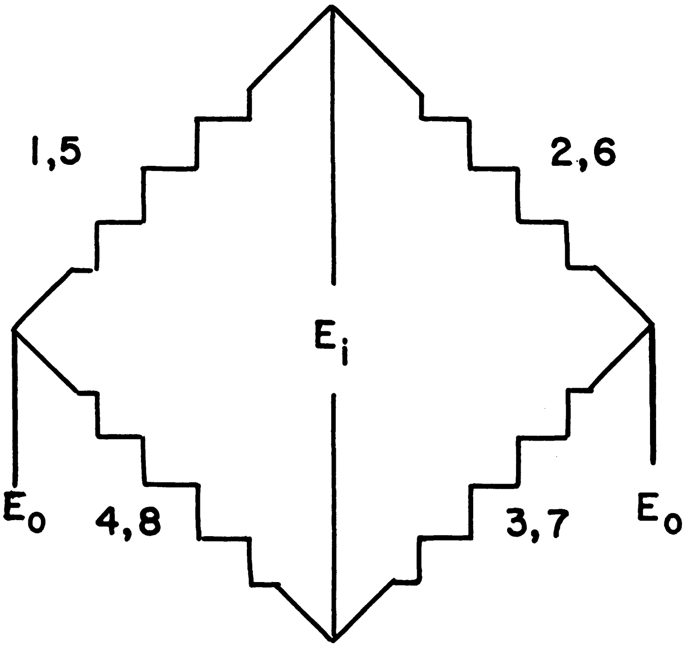


Fig. 12. --Sketch of two-component tool dynamometer



Location of strain gages on cross section through dynamometer.



Circuit diagram for strain-gage bridges of dynamometer.

Fig. 13.--Application of strain-gage bridges in design of two-component tool dynamometer.

signals to a two-channel oscillograph where tool forces parallel and normal to the cutting path were simultaneously recorded in terms of pen deflections on a graduated moving chart. Through calibration of the system, instantaneous tool-force components were readily determinable from the oscillograph record.

Calibration of the tool dynamometer was accomplished by mounting the device with the line of action of the component under consideration along a vertical axis A series of weights were suspended from a reference point on a dummy tool bit, each resulting in an oscillograph-pen deflection in response to the applied load. Adjustment of the gain of the amplifying unit permitted the selection of a convenient relation between force and pen deflection, which was then referenced for subsequent use by means of an internal calibrating circuit. The second measuring component was treated similarly, and the data from both calibrations were plotted as in Figure 14. It will be noted that pen deflection is a linear function of the applied force in each case.

Although preliminary experiments had attested that cutting velocity has no appreciable effect on the wood-cutting process, a treatment of the subject was felt advisable to detect possible errors in tool-force measurements due to attenuation by the mass of the dynamometer or peculiarities of the strain-analyzing instruments. Since attenuation by either would be expected to vary with the frequency of force changes, the characteristics of the system were ascertained by altering cutting velocity. In a randomized sequence of cuts on sugar pine at 8.0 moisture content, tool-force measurements were taken at cutting velocities of 0.8, 1.7, 3.5, 7.5, 14.5, and 24.5 inches per minute. Force determinations proved constant for all velocities, indicating that the measuring system was uniform in response and negligibly attenuating at the frequencies considered. The data, which have been assembled with the results of other tool-force experiments, are presented in Table 16.

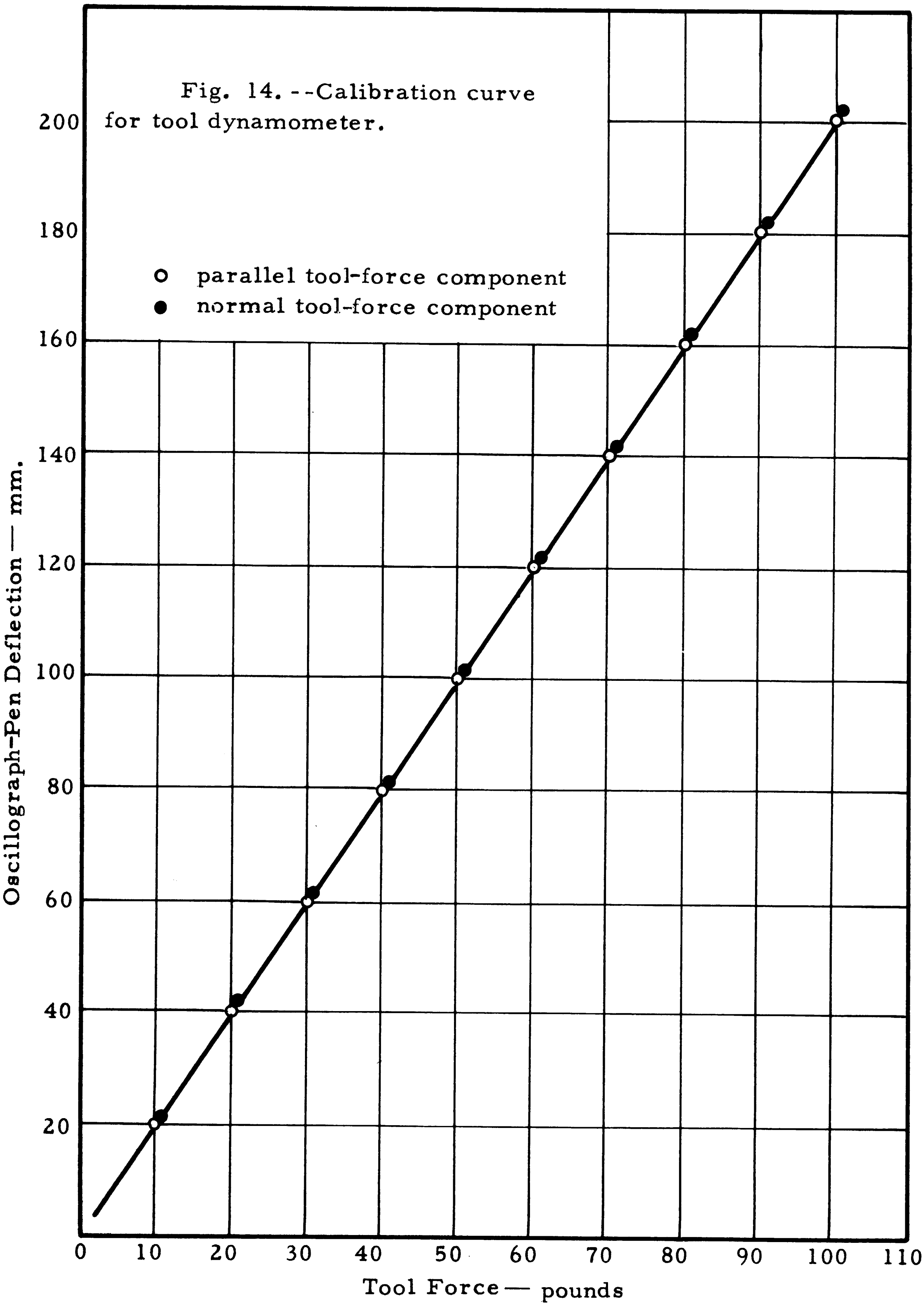


Fig. 14.--Calibration curve for tool dynamometer.

Cutting Tools

Investigation of the machining effects of cutting angle and roughness of the face of the tool was facilitated by use of interchangeable tool bits mounted in the previously described dynamometer. The bits, illustrated in Figure 11, included a set of six which were identical except for cutting angle, and a set of three in which face roughness was the only variable. A clearance angle of 15 degrees was used in all cases, this being a value which appears to be adequate without an adverse effect on the strength of the cutting edge (10).

The tool bits were wet-ground to approximate shape from polished high-speed steel blanks, five-sixteenths of an inch square. A finishing operation in a universal cutter grinder achieved the specifications given in Figure 15. Root mean-square roughness of the tool face in the direction perpendicular to chip flow was 7 to 12 microinches in the set of bits in which cutting angle was varied. In the set treating face roughness as a variable, values of 5 to 6, 14 to 16, and 25 to 28 microinches root mean-square roughness were obtained by use of grinding wheels with differing characteristics. A slight burr remaining on the cutting edge after grinding was removed by careful honing by hand on a hard Arkansas stone, which was allowed to contact only the clearance surface of the tool.

All prepared cutting edges were examined microscopically to make certain no imperfections were present. An inspection of angular relationships of the tool bits revealed a maximum error of 0.2 degree.

Photographic Analysis

The value of photographic observation of the wood-cutting

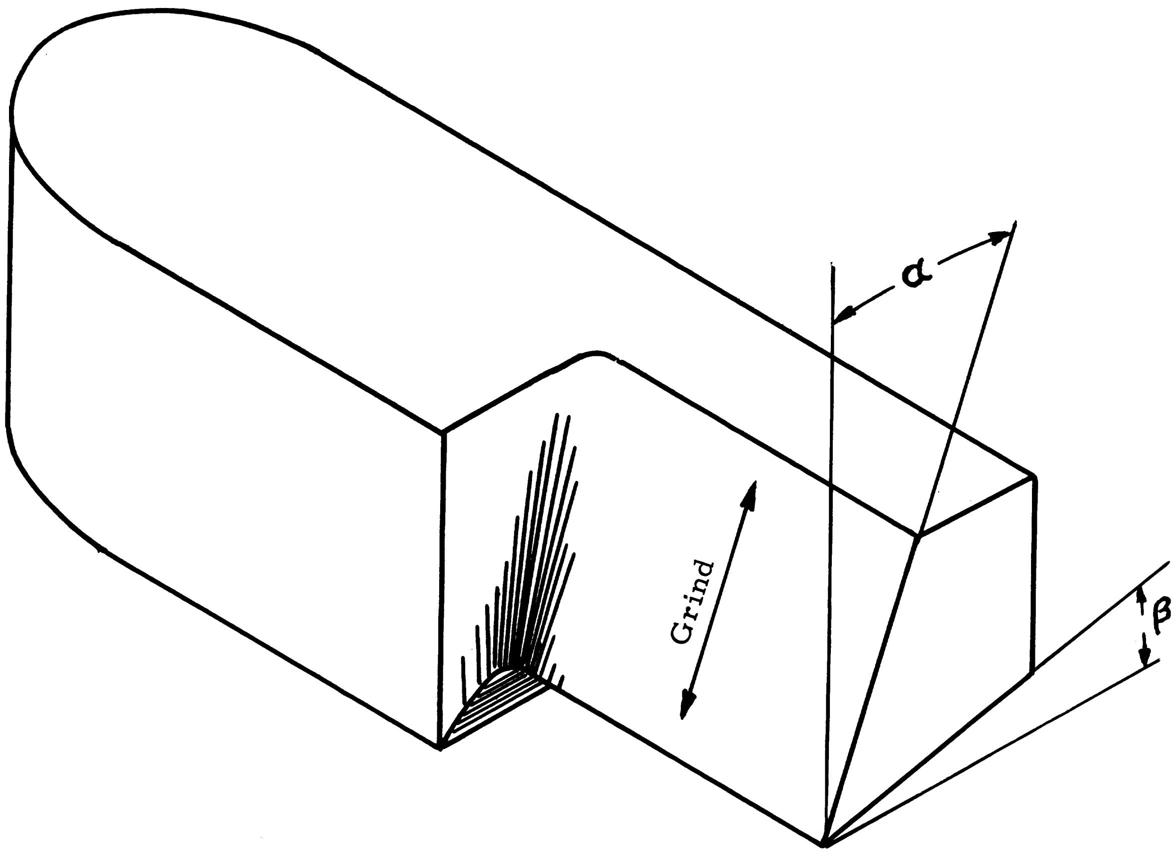


Fig. 15.--Sketch of tool-bit specifications. Cutting angle α varied to include 5, 10, 15, 20, 25, and 30 degrees; clearance angle held constant at 15 degrees. Grinding marks perpendicular to cutting edge.

process was clearly demonstrated in preliminary investigations. Motion picture photography, in particular, proved to be of unparalleled utility in determining the events taking place during chip formation. In exploratory studies, prior to procurement of convincing data on the null effects of cutting velocity, high-speed motion picture photography was an essential and exceptionally revealing research technique. It has, however, certain limitations when used for more extensive and critical applications. Immense quantities of film are consumed by high-speed cameras even at the lower frame exposure rates, resulting in prohibitive costs and serious restriction of the events included in a given sequence. Due to inherent characteristics of the optics employed in high-speed cameras, the film image often lacks the desired degree of resolution. Further, the intense light sources required for adequate illumination of the subject being photographed generate heat in such quantities that temperature and moisture control is difficult.

After it had been established that cutting velocity is not as consequential as commonly supposed, it was possible to consider motion picture photography with standard commercial equipment that eliminates the above inadequacies of high-speed facilities. Experimentation showed that excellent results were obtainable with ordinary techniques, and these were adapted for use as described in the following text.

A 16 mm. Kodak Cine Special Model II motion picture camera was used to photograph the process of chip formation. In order to obtain adequate subject definition, an f:2.7 anastigmatic lens with a focal distance of 63 mm. was mounted on the camera in conjunction with a lens extension tube system. The resultant film image was approximately 1.25X magnification, with each frame including a field about 0.25 inch by 0.35 inch at the subject. These conditions had previously been determined as optimum, giving sufficient projected image size and adequate observation area, as well as a suitable apparent rate of motion during viewing. An exposure rate of 24 frames per second proved appropriate for photographing orthogonal cutting at a velocity of 3.5 inches per minute.

Since the orthogonal cutting method is conveniently achieved by holding the tool stationary and moving the work, it was possible to mount the camera assembly on a rigid adjustable mechanism, as seen in Figure 16. A heavy, securely anchored drafting table served as the foundation of the device and provided a means of positioning the camera vertically. A cross-slide unit fastened to the table permitted lateral movement and focusing of the camera, which was mounted above a pivot joint on the slide assembly. Thus, angular and three-dimensional positioning of the photographic apparatus was readily accomplished.

High-incidence lighting, which had been found to give superior results in preliminary experiments, was used to illuminate the photographic field. A single 500-watt spot light placed about two feet from the subject provided sufficient light intensity to permit use of an f:11 lens aperture with Kodak Super-X film. In consequence, adequate depth of field was assured with the camera lens functioning at conditions of optimum theoretical performance, and the cutting process could be recorded on fine-grained film of high resolution.

Machining Methods

The method of machining used for this research was developed during preliminary investigations, and is patterned after a proved metal-cutting technique described by Ernst (16). For convenience in photographing the process of chip formation and measuring tool forces, orthogonal cutting was attained by holding the tool stationary and mov-

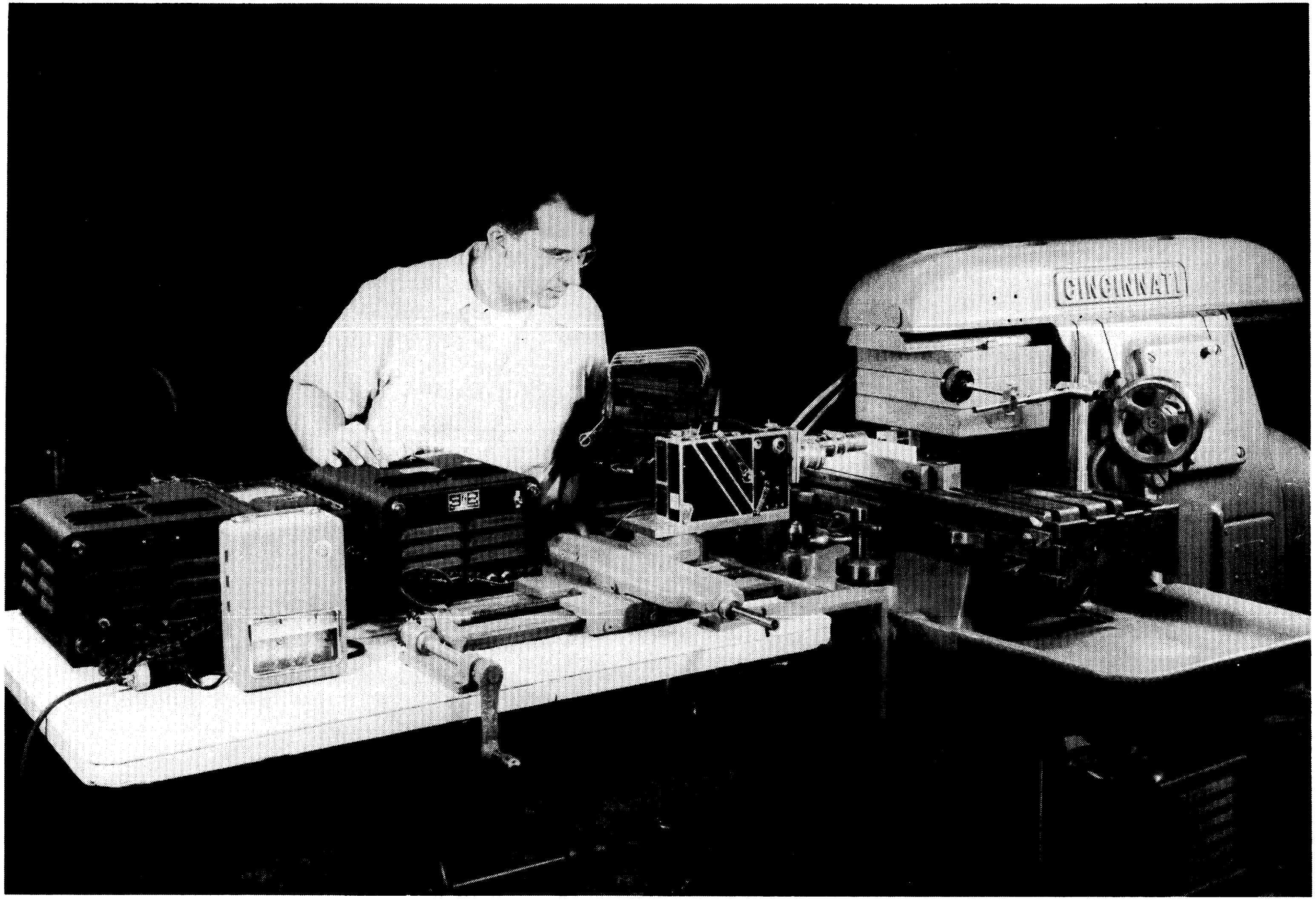


Fig. 16.--General view of experimental equipment illustrating photographic devices for recording the process of chip formation during machining.

ing the work. A milling machine was adapted for this purpose, as illustrated in Figures 16, 17, and 18.

Interchangeable tool bits, ground to the necessary specifications, were held in the tool dynamometer described previously. A heavy, accurately machined fixture attached to the frame of the milling machine was used to mount the dynamometer rigidly and align the tool edge precisely for truly orthogonal conditions. Design of the fixture allowed the dynamometer to be positioned axially to place the calibration loading point at the midpoint of the width of cut.

The wood specimens to be machined were securely held in a work-piece fixture mounted on the table of the milling machine. Accurate orientation of the assembly parallel to table travel assured constant reference between the work and the cutting edge. The cutting velocity was determined by the rate of table movement, which carried the work against the stationary tool bit. Depth of cut or undeformed chip thickness was controlled by vertical movement of the milling-machine table mechanism, the adjustment of which was within a few ten-thousandths of an inch by dial gage verification.

Effects attributable to possible changes in moisture content at the surfaces of wood specimens during machining were eliminated by appropriate control measures. At maximum moisture conditions, the wood surfaces were kept above the fiber-saturation point by wetting with a soft brush. When cutting specimens at 8.0 per cent moisture content, it was possible to maintain room atmospheric conditions at the corresponding relative humidity by the addition of water vapor. Moisture relations of the wood specimens at 1.5 per cent moisture content were held uniform by establishment of a suitable microclimate around the work. This was accomplished with a stream of desiccated air released from a series of orifices in close proximity to the work, as seen in Figure 19.

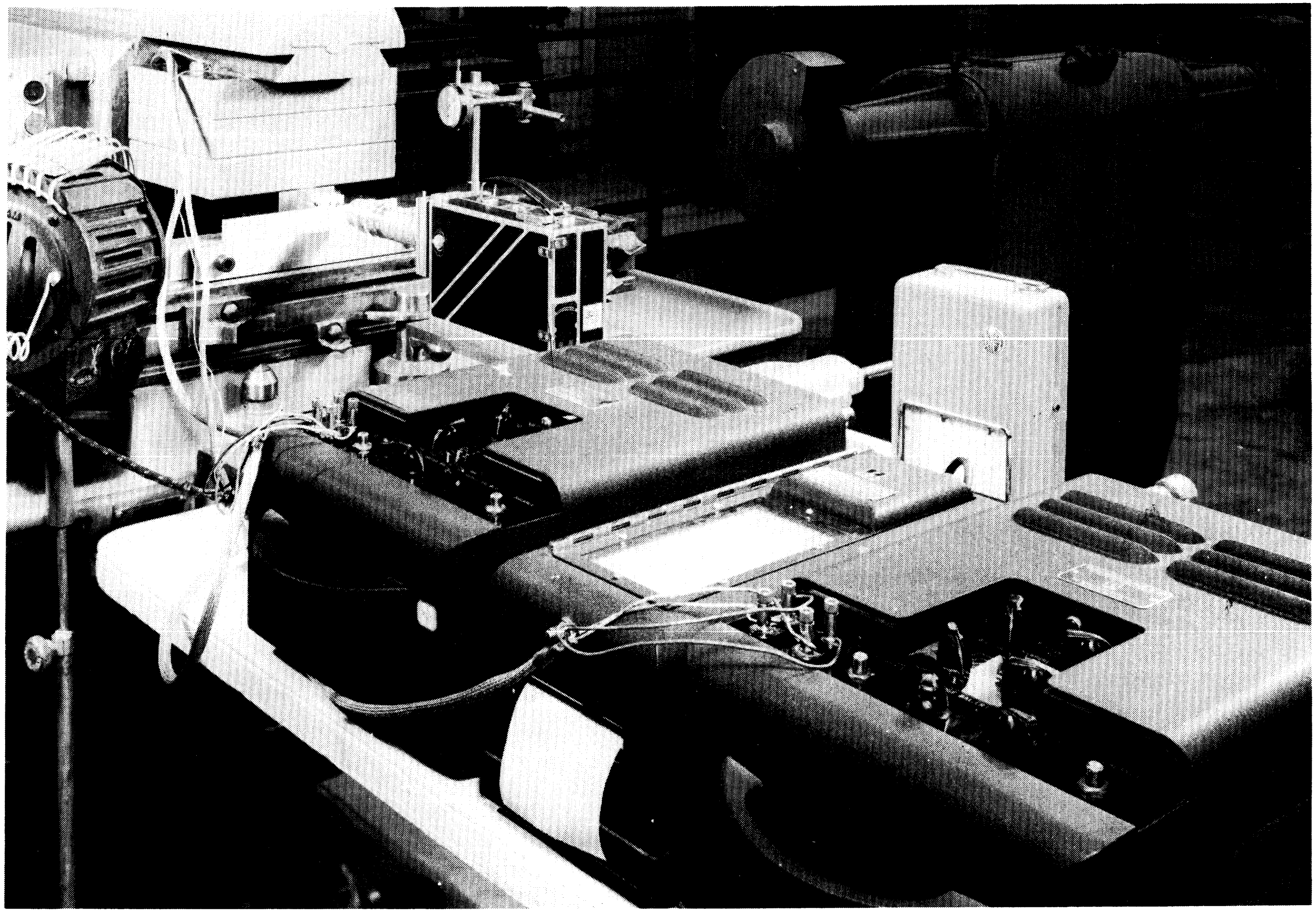


Fig. 17. --Experimental set-up used for study of chip formation. Strain analyzers in foreground; motion picture camera in center; work piece and dynamometer in background.

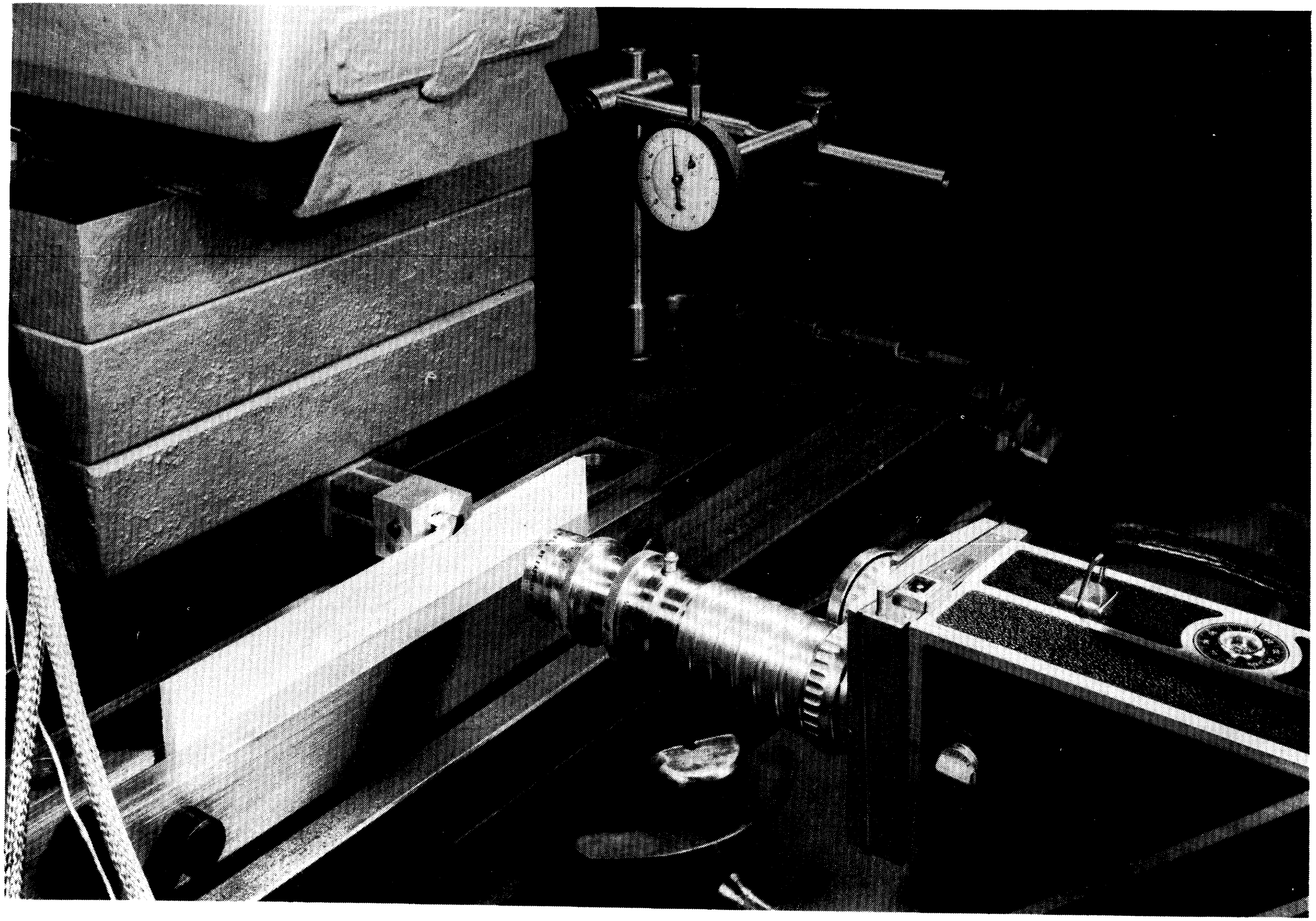


Fig. 18. --Close-up of machining operation showing the work piece, tool dynamometer, and motion picture camera used to correlate instantaneous tool forces with observations of chip formation.

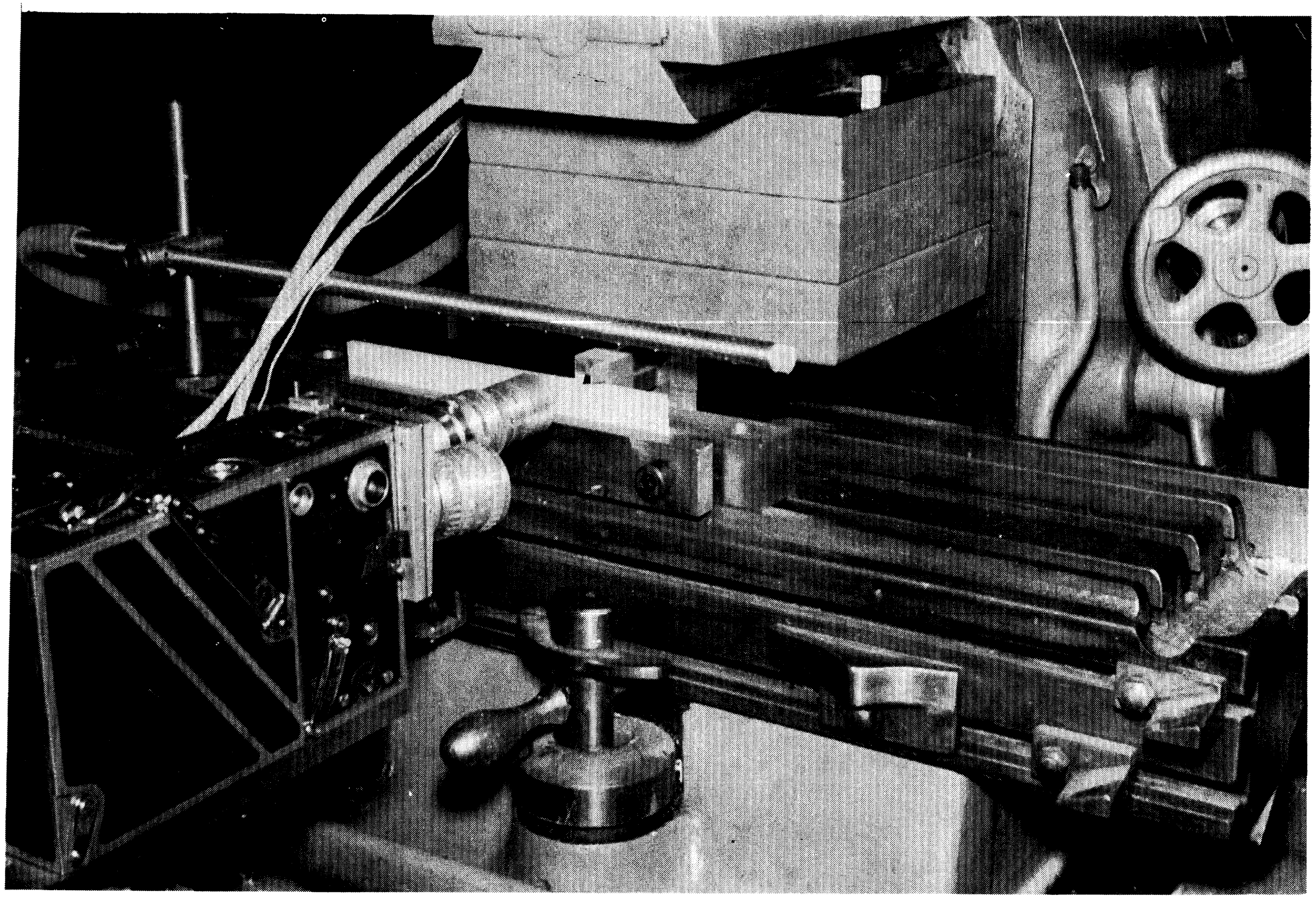


Fig. 19. --Air-bath device for controlling microclimate around work piece when machining woods at 1.5 per cent moisture content.

Prior to the collection of data for a given tool bit, several light preparatory cuts were made on the work piece. These established a true surface of good quality to be used as a starting point. Similarly, a reference surface was reestablished during a machining sequence if the quality of the generated surface was judged capable of exerting undue influence on the subsequent cut.

Each work-piece unit, consisting of three specimens of a single wood species at a predetermined moisture content, was machined at the seven depths of cut with each of six tool bits. Depth of cut was varied in sequence from lightest to heaviest, this being preferred over randomization to prevent the latter biasing the former through surface characteristics.

At each cutting interim the tool-force components parallel and normal to the cutting path were recorded by the two-channel analyzing system previously described. In the case of sugar pine at 8.0 per cent moisture content, simultaneous motion pictures were taken to enable correlation between force measurements and the events taking place during chip formation. At other species and moisture content conditions, most photographic study was omitted due to obviation by results of the above, and direct observation with a hand lens sufficed. The chips removed at the various cutting conditions were collected, and the characteristics of the accompanying machined surface noted for future reference.

In determining tool forces by experimental methods, it was considered necessary to obtain an estimate of the degree of control or variation that prevailed. An analysis of the procedures used indicated that the most probable sources of change variance were: (1) changes in wood properties as successive cuts were made in new areas of the work piece, (2) inaccuracies in the regulation of depth of cut by milling-machine table adjustment (3) discrepancies in wood-grain alignment when positioning work in table fixture, (4) influence of work-piece surface characteristics in advance of the cutting tool.

In evaluating the first three factors above, simultaneous study was made by taking ten successive cuts in the standard work-piece unit of three specimens, which was repositioned after each cut, and on which a new reference surface was established each time. All other factors were held constant according to normal operating procedures. In the case of the fourth source of machining variation, no experimental consideration was deemed necessary, since the influences are obvious. Rather, every effort was made to eliminate possible effects during experiments by reestablishing a reference surface if quality appeared questionable. This was readily accomplished by using a series of light cuts, since when machining parallel to the grain the surface defects are invariably slight.

The results of the above experiment showed that the control of machining variables was very precise. Excellent repeatability is seen in the data presented in Table 17, which have been assembled with other tool-force experiments as a matter of convenience.

INTERPRETIVE TECHNIQUES

Observation of Chip Formation

Interpretation of the process of chip formation through photographic and direct observation was founded primarily on similar work in the field of metal-cutting (16) (26), and on information obtained in a series of preliminary studies. Visual methods enabled positive identification and classification of chip types present in the machining of wood parallel to the grain. The evolution of specific chip types was examined closely for the development of wood failures in the chip during formation. The nature of the failures was then used to identify the wood properties responsible for surface generation, control of chip type, and the development of forces on the cutting tool.

While interpretation of the observed events during machining is admittedly prone to subjective coloration, it is felt that awareness of such tendencies minimized any possible bias. Deductions on chip type were based on accepted analogous conclusions for metals, and were supported by universally recognized characteristics of wood behavior. The interpretation of wood failures during machining was grounded on available information on rupture in wood (31), which also is prominent in surface quality considerations.

In addition to surveillance of the process of chip formation, photographic records were used for mensuration that would have been difficult or impossible by direct methods. The geometrical aspects of wood failure in the chip were readily determined with a transparent protractor placed on the projected chip image. Knowing the magnification of the projection, dimensional calculations were made to ascertain the prolongation of rupture in the work piece.

Oscillograph Data

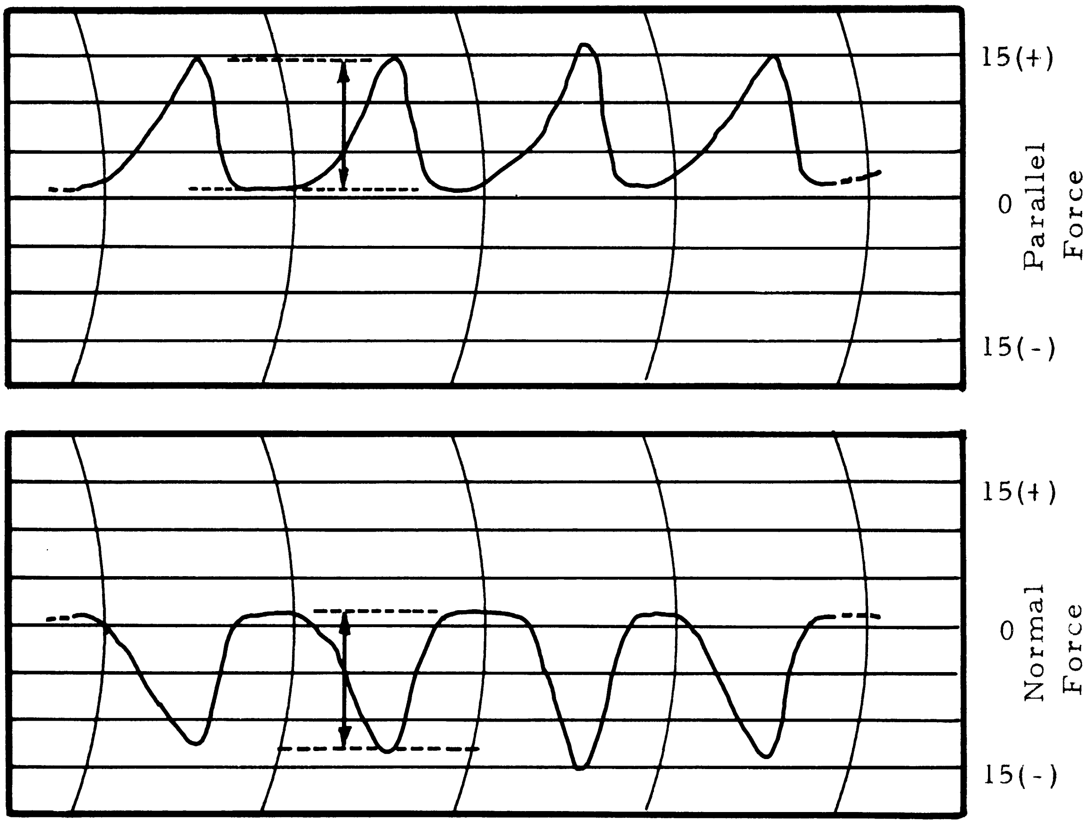
The normal and parallel components of tool force were measured with the calibrated system described previously. As recorded by the oscillograph, instantaneous forces often displayed great fluctuations of a cyclical nature which could be correlated with the formational process of the accompanying chip type. While the average force value was considered adequate for the work of Kivimaa (10), and can be associated with power requirements, such treatment of tool forces is useless to the study of chip formation. In order to relate the formation of a chip with force development during cutting, only instantaneous considerations are valid.

Minute evaluation of instantaneous force development during a single cycle of chip formation appeared premature in this research, since the utility of such data was in doubt. On the basis of accrued information, it was reasoned that the most significant instantaneous force values were those that represented maxima. It had been noted that the attainment of extreme force values closely coincided with the occurrence of wood failure in the chip. Thus, while the general pattern of force behavior was of great interpretive value, a salient feature for the determination of relationships controlling chip formation was seen to be force peaks.

Oscillographic records showed rather surprising homogeneity of force development under a given combination of cutting conditions. With cyclical chip formation, congruous patterns of uniform amplitude were repeated. When chip formation was a steady event, forces remained essentially constant with a minor wave form occasionally superimposed. In all cases, consideration was limited to tabulation of the maximum instantaneous values recorded during machining, the averages of which are presented in following text.

Visual averaging by means of a transparent straight edge was used for force determination when levels remained relatively constant. This method was shown mathematically accurate for cyclical patterns as well, if the frequency of peak development was in excess of twenty per inch of tool travel Below this frequency, it was necessary to evaluate force peaks individually and take an arithmetic average. Although a separate determination was made for each of the three workpiece units cut under a given set of conditions, differences were found negligible and a single value was derived for each force component.

In extracting values from oscillograph charts, all readings of pen deflection were made to the nearest 0.25 mm. Since attenuator tap selection on the strain analyzer had made it possible to keep pen deflection between 10 and 15 mm. in most instances, final force figures may be considered to be within approximately two per cent of the true observed value. Exception is found where force values are less than five pounds, in which case there was no electrical attenuation, and direct readings were made to the nearest sixteenth part of a pound. A sample of the form used for tabulating oscillograph chart readings is shown in Figure 20, which includes representative data for calculating force information.



	Normal Force	Parallel Force
Gross	-13	14.5
Tare	+ 2	1.5
Net	-15	13
Attenuator Factor	x 2	x 5
Lines	-30	65
Pounds	- 7.5	16.2

Fig. 20. --Sample Determination of Tool Forces

RESULTS AND ANALYSIS OF OBSERVATIONAL STUDIES

Chip Formation

Analysis of the wood-cutting process through photographic and direct observation substantiated preliminary findings on the presence of distinctive types of chip formation. As would be expected from the anisotropic nature of wood, the chip types identified were not entirely analogous to those recognized in metal cutting (16). However, certain similarities were seen, and it appears advantageous to treat chip formation in the machining of wood in a manner conforming to the conventions established for metals.

Three basic types of chip formation, with variations, were distinguished in this study. Arbitrary designation of the three classifications was made according to the most nearly comparable chip type recognized in metal-cutting, except that one of the types identified for wood includes the related metal-cutting chip as a variation. When machining wood parallel to the grain, or at small angles to the grain, chip formation may be classified as follows:

Type I, formed when cutting conditions are such that the wood splits ahead of the tool by cleavage until failure in bending as a cantilever beam occurs, as seen in Figure 21.

Type II, which results when wood failure in the chip is along a line extending from the cutting edge to the work surface, as in Figure 22.

Type III, occurring when tool forces cause compression and shear failures in the wood ahead of the cutting edge, as indicated in

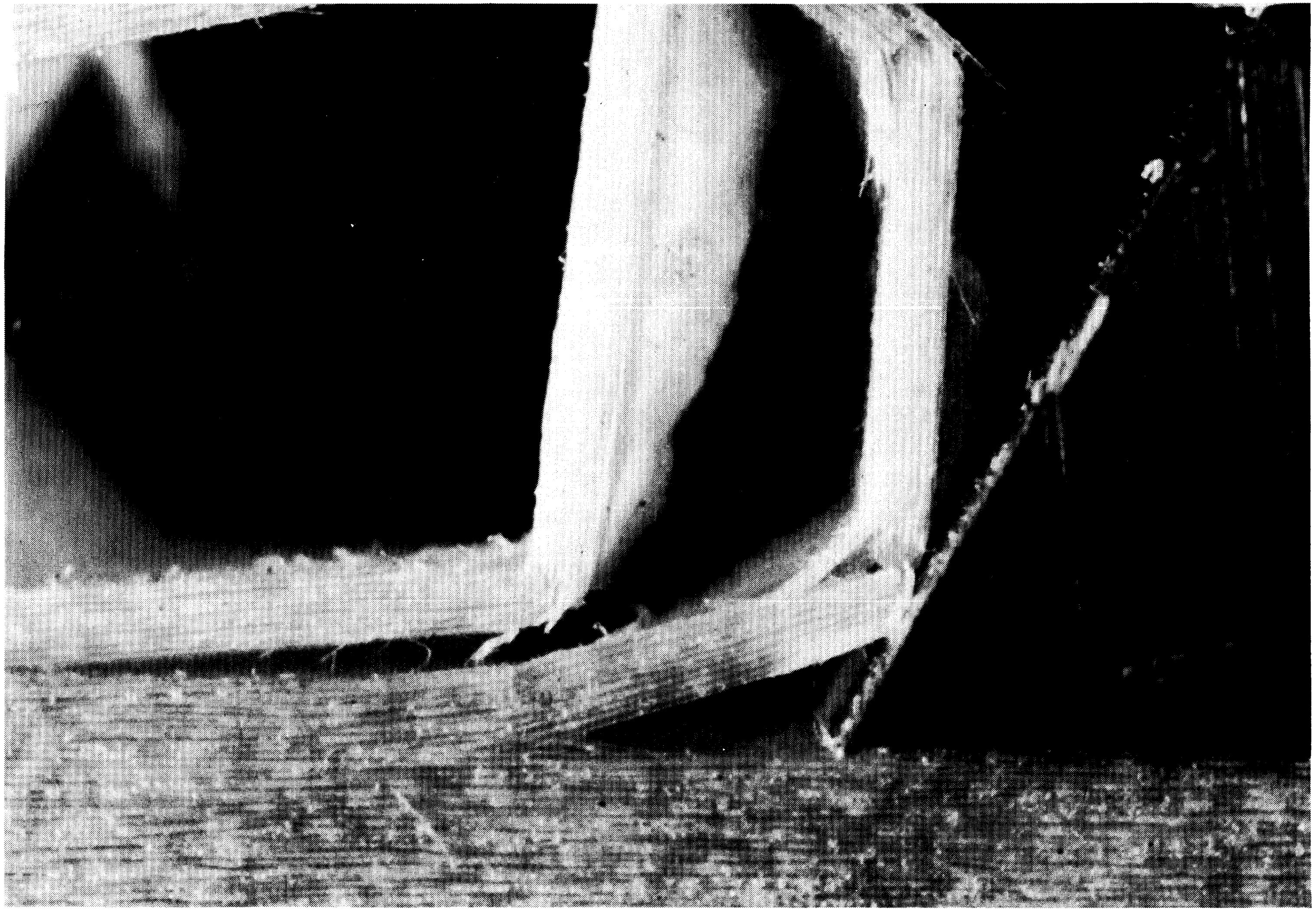


Fig. 21. --The Type I chip, showing splitting ahead of the tool edge and failure of chip as a cantilever beam.

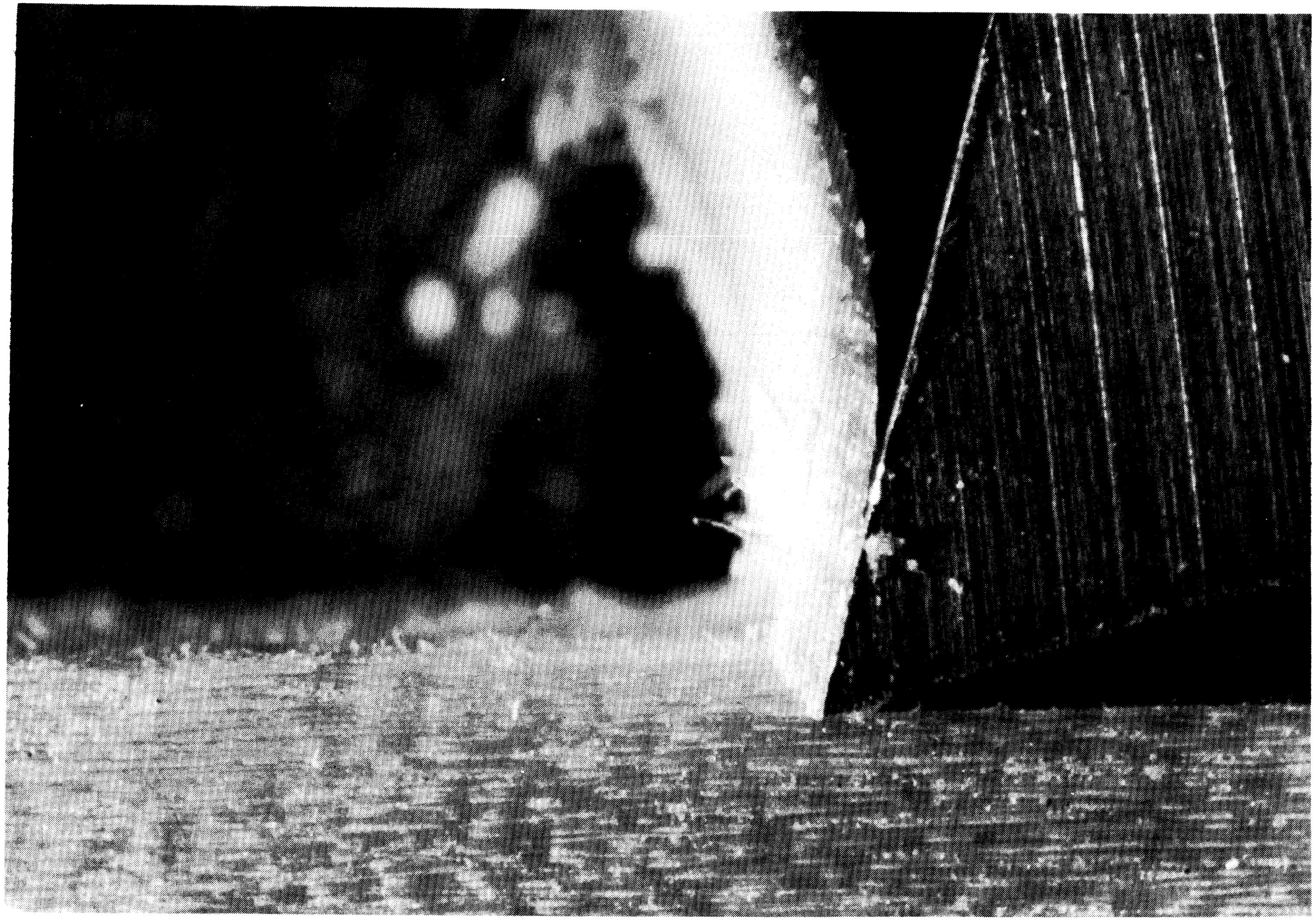


Fig. 22.--The Type II chip, showing wood failure along a plane extending from the tool edge to the work surface.

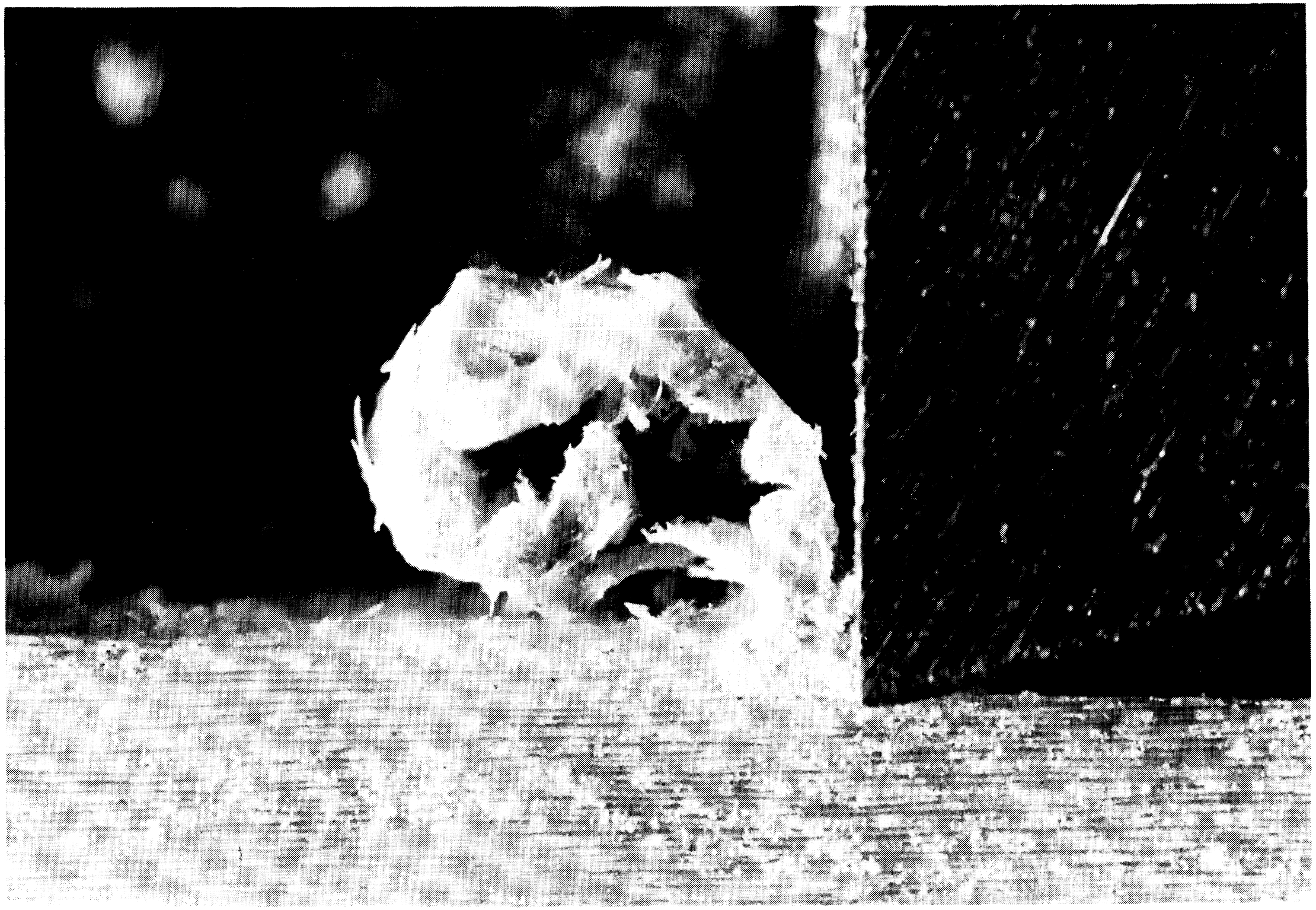


Fig. 23.--The Type III chip, showing compression of the wood ahead of the tool.

in Figure 23.

The above types of chip formation, which are treated in detail during subsequent discussions, were seen to be distinct, with no appreciable transitional tendencies. Thus, chip formation at any instant fell into a specific category uncomplicated by intermediate phases. Under critical machining conditions, the threshold between types of chip formation was indicated by alternate production of each, apparently in response to minute fluctuations in wood properties. In certain cases, it was observed that the separate types of chip formation appeared in regular sequential combinations dependent on peculiarities of the cutting conditions. In all circumstances, the character of the chip and the qualities of the generated surface were directly related to the type or types of chip formation present.

As anticipated, chip formation proved to be correlated with interactions of machining conditions and wood properties. Figures 24, 25, and 26 illustrate the trends and diversity in chip forms obtained during orthogonal cutting parallel to the grain of the work piece. The chips shown in these photographs are classified in Tables 1, 2, and 3 according to the three basic types recognized above.

Chip formation was found to be unaffected by changes in cutting velocity from 0.8 to 24.5 inches per minute, and proved to be accurately reproducible at a given set of conditions. Friction between the chip and tool face was seen to influence chip formation, often being responsible for type determination where other factors are in critical relation. The foregoing are discussed further in a consideration of tool forces.

Type I Chip Formation

The formation of the chip designated as Type I, Figure 21, is seen to be a cyclical series of events. As the cutting edge advances

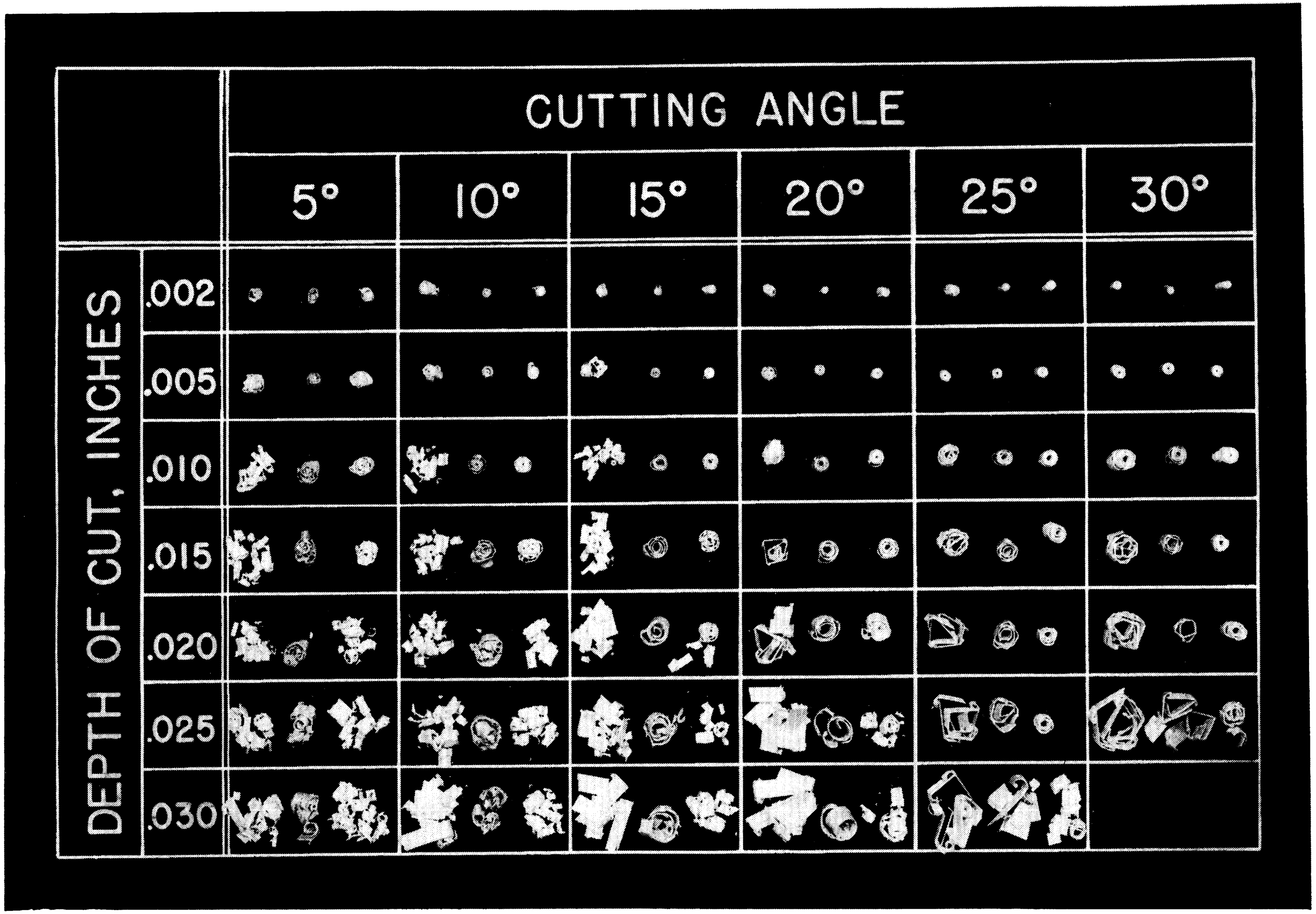


Fig. 24. --Chips removed from various wood species at 1.5 per cent moisture content. From left to right, the space provided for each combination of cutting angle and depth of cut includes chips of sugar pine, yellow birch, and white ash.

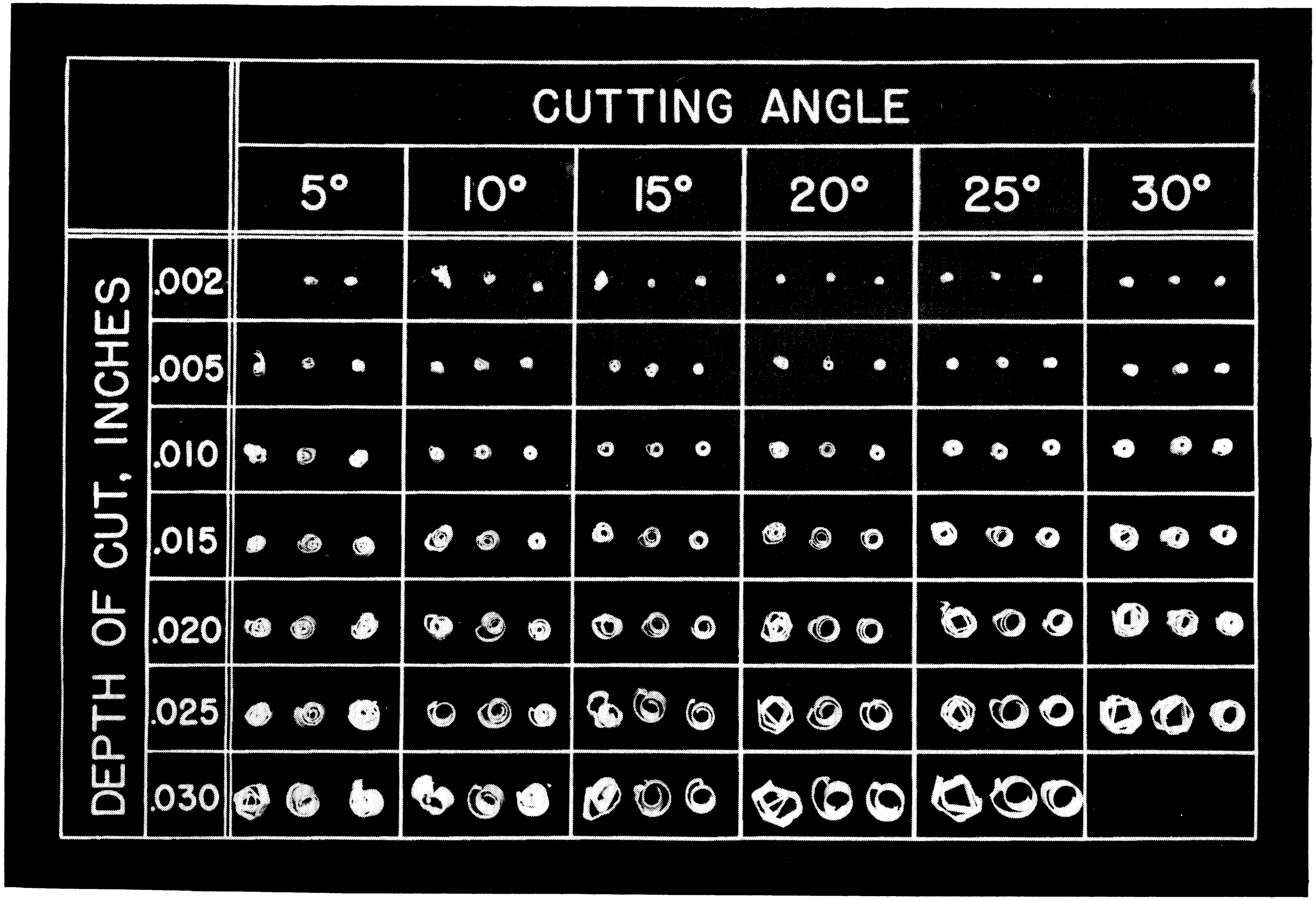


Fig. 25. --Chips removed from various wood species at 8.0 per cent moisture content. From left to right, the space provided for each combination of cutting angle and depth of cut includes chips of sugar pine, yellow birch, and white ash.

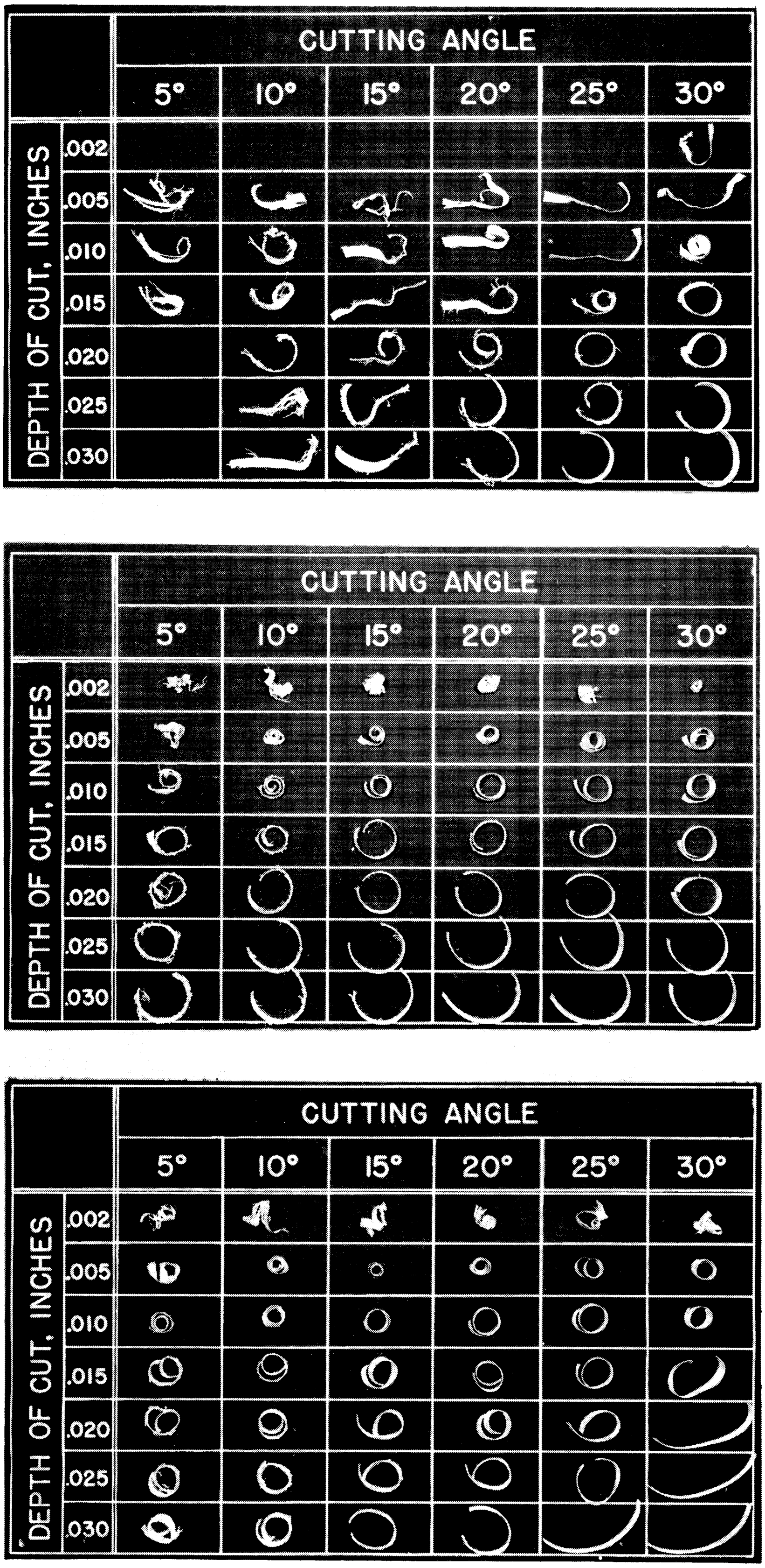


Fig. 26. --Chips removed from various wood species at saturated moisture conditions. From top to bottom, chips formed on sugar pine, yellow birch, and white ash are shown at each combination of cutting angle and depth of cut.

TABLE 1

RELATION OF TYPE OF CHIP FORMATION TO CUTTING ANGLE AND CHIP THICKNESS — SUGAR PINE AT VARIOUS MOISTURE CONTENTS*

Chip Thickness	Type of Chip Formation					
	Cutting Angle					
	5°	10°	15°	20°	25°	30°
	1.5 Per Cent Moisture Content					
0.002	III	III	II	II	II	II
0.005	III	III	II	II	II	II
0.010	III	III	III	I	I	I
0.015	III	III	III	I	I	I
0.020	III	III	III	I	I	I
0.025	III	III	III	I	I	I
0.030	III	III	III	I	I	-
	8.0 Per Cent Moisture Content					
0.002	III	II	II	II	II	II
0.005	III	II	II	II	I	I
0.010	III	II	II	II	I	I
0.015	III	II	II	I	I	I
0.020	III	III	II	I	I	I
0.025	III	III	III	I	I	I
0.030	III	III	III	I	I	-
	Saturated with Moisture					
0.002	-	-	-	-	-	II
0.005	III	III	III	III	II	II
0.010	III	III	III	III	III	II
0.015	III	III	III	III	III	II
0.020	-	III	III	III	III	II
0.025	-	III	III	III	III	II
0.030	-	III	III	III	III	III

---

*Where more than one type of chipformation was observed at the conditions listed in Tables 1, 2, and 3, only the predominating type is given.

TABLE 2

RELATION OF TYPE OF CHIP FORMATION TO CUTTING ANGLE AND CHIP THICKNESS — YELLOW BIRCH AT VARIOUS MOISTURE CONTENTS

Chip Thick-ness	Type of Chip Formation					
	Cutting Angle					
	5°	10°	15°	20°	25°	30°
	1.5 Per Cent Moisture Content					
0.002	III	II	II	II	II	II
0.005	III	II	II	II	I	I
0.010	III	III	II	II	I	I
0.015	III	III	III	I	I	I
0.020	III	III	III	I	I	I
0.025	III	III	III	I	I	I
0.030	III	III	III	I	I	I
	8.0 Per Cent Moisture Content					
0.002	II	II	II	II	II	II
0.005	II	II	II	II	II	II
0.010	III	II	II	II	II	I
0.015	III	III	II	II	I	I
0.020	III	III	II	I	I	I
0.025	III	III	II	I	I	I
0.030	III	III	I	I	I	-
	Saturated with Moisture					
0.002	III	III	II	II	II	II
0.005	III	III	III	III	II	I
0.010	III	III	III	III	II	I
0.015	III	III	III	III	I	I
0.020	III	III	III	III	I	I
0.025	III	III	III	III	I	I
0.030	III	III	III	III	I	I

TABLE 3

RELATION OF TYPE OF CHIP FORMATION TO CUTTING ANGLE AND CHIP THICKNESS — WHITE ASH AT VARIOUS MOISTURE CONTENTS

Chip Thickness	Type of Chip Formation					
	Cutting Angle					
	5°	10°	15°	20°	25°	30°
	1.5 Per Cent Moisture Content					
0.002	II	II	II	II	II	II
0.005	II	II	II	II	II	II
0.010	III	II	II	II	II	I
0.015	III	III	II	II	II	I
0.020	III	III	III	III	I	I
0.025	III	III	III	III	I	I
0.030	III	III	III	III	I	I
	8.0 Per Cent Moisture Content					
0.002	II	II	II	II	II	II
0.005	II	II	II	II	II	II
0.010	III	III	II	II	II	II
0.015	III	III	II	II	II	II
0.020	III	III	II	II	II	I
0.025	III	III	II	II	II	I
0.030	III	III	III	II	II	-
	Saturated with Moisture					
0.002	III	III	II	II	II	II
0.005	III	III	II	II	II	II
0.010	III	III	II	II	II	II
0.015	III	III	II	II	I	I
0.020	III	III	I	I	I	I
0.025	III	III	I	I	I	I
0.030	III	III	I	I	I	I

relative to the work piece at the beginning of a cycle, Figure 27-A, localized zones in the wood are compressed until the entire area of the undeformed chip cross section is in contact with the tool face. With additional movement, the wood ahead of the tool is strained, Figure 27-B, and immediately afterward the limiting cleavage stress in the wood is reached, causing rupture along the grain on a trajectory initiating at the cutting edge, Figure 27-C. As the chip moves up the tool face, the wood failure is extended until bending stresses in the chip become critical and failure as a cantilever beam results, as in Figure 27-D. The tool continues to deflect the chip until the face encounters the point of bending failure, which marks the beginning of another cycle. Repetition of the above sequence of events is evident in the character of the Type I chip, Figure 21, which consists of many jointed segments.

The length of chip segments is clearly dependent on the extent of cleavage failure before the wood ruptures in bending. Under certain machining conditions, particularly when the equilibrium moisture content of the wood approaches the fiber saturation point, continued deflection of the chip does not cause failure in bending. The chip is then free of segments, since formation is by a peeling split prolonged by movement of the chip up the tool face.

The nature of Type I chip formation suggests some of the factors that are conducive to its development. In the work piece, low relative resistance to cleavage in association with high stiffness and strength in bending would be expected to favor Type I chip formation. Heavy chip thickness, low coefficient of friction between the tool face and the chip, and negative normal tool forces attending a large cutting angle, are also indicated as positive factors. Further discussion of the various factors controlling chip formation is deferred for more appropriate consideration in following portions of the text.

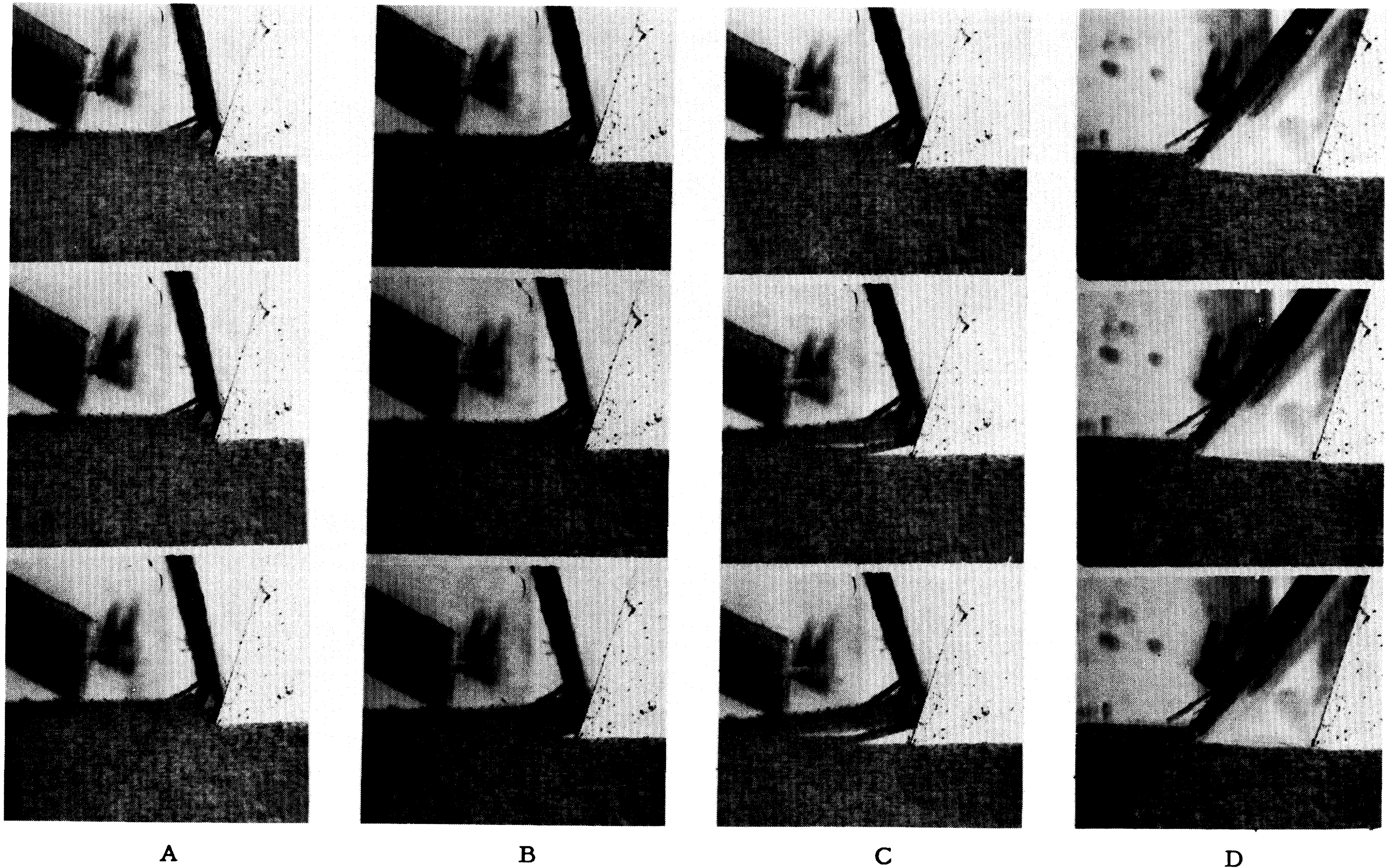


Fig. 27. --Development of the Type I chip. A, initial contact of the tool; B, straining of the work at instant before failure; C, splitting of wood ahead of cutting edge; D, failure of chip as a cantilever beam.

It is apparent that the surface generated during formation of the Type I chip is determined principally by the split that precedes the cutting edge, and the qualities of the surface agree with the nature of the wood failure. When the path of the tool is exactly parallel to the grain of the wood, and consequently the line of failure, the developed plane will approximate that described by the cutting edge. Any deviation of the grain, due to the inherent properties of wood, can be expected to alter surface propagation.

Supplemental observations of chip formation, which considered machining other than parallel to the grain of wood, showed that grain angle relative to the tool path is critical in the development of work surfaces with the Type I chip. When cutting against the grain, Figure 28, planes of weakness in the wood cause the splitting failure of the chip to extend divergent to the work surface, giving the chip added strength where the bending moment of the cantilever beam is greatest. This tends to aggravate splitting and retard failure of the chip in bending. Since wood failure during chip formation occurs below the path of the cutting edge, the resultant surface displays associated characteristics which typify the famili machining defect commonly termed chipped grain, Figure 29.

When cutting with the grain, Figure 30, the characteristic cleavage failure of the Type I chip initiates at the cutting edge and progresses convergent with the surface of the work piece. As soon as the split develops, the effective depth of cut becomes essentially zero. Movement of the tool relative to the work then produces a Type II chip of increasing thickness, the rate of increase being dependent on the angle of the preceding wood failure. At a critical chip thickness, formation converts to Type I, and the sequence of events is repeated. Figure 30 emonstrates the above combining of chip types, which produces a work surface of expected high quality.

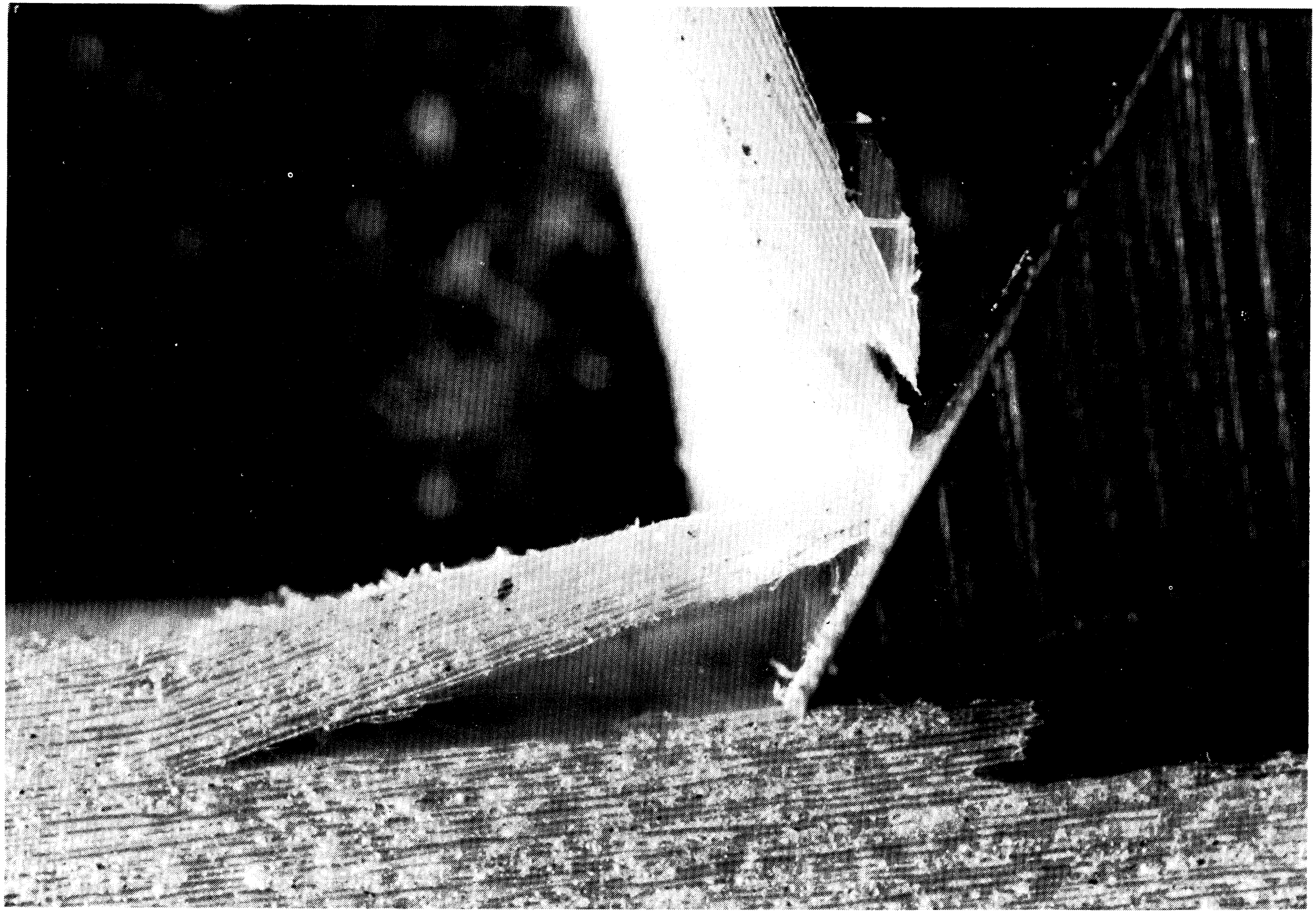


Fig. 28. --Formation of the Type I chip when cutting against wood grain making 5-degree angle with the tool path.

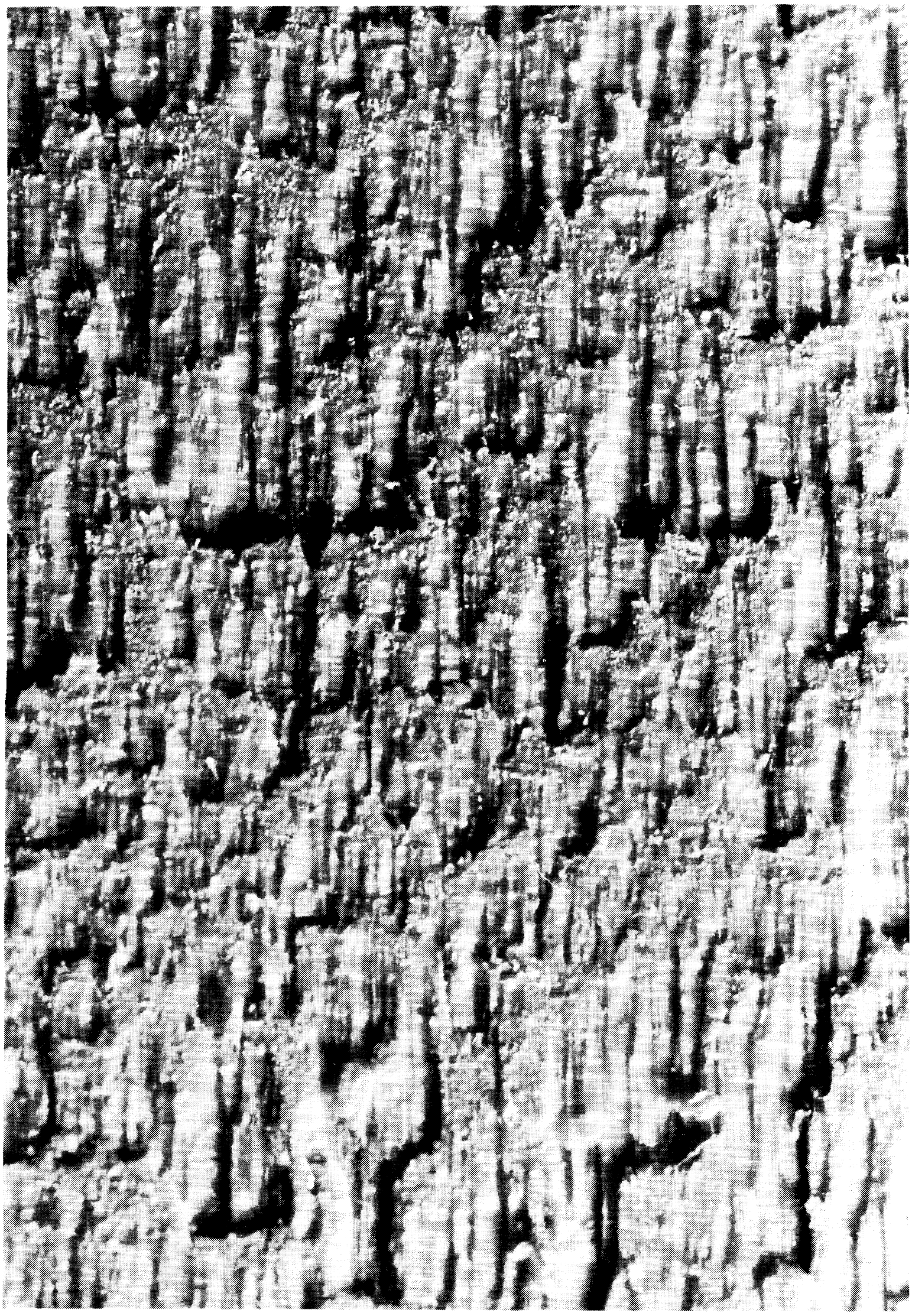


Fig. 29.--The defect 'chipped grain' on sugar pine, produced by Type I chip formation.

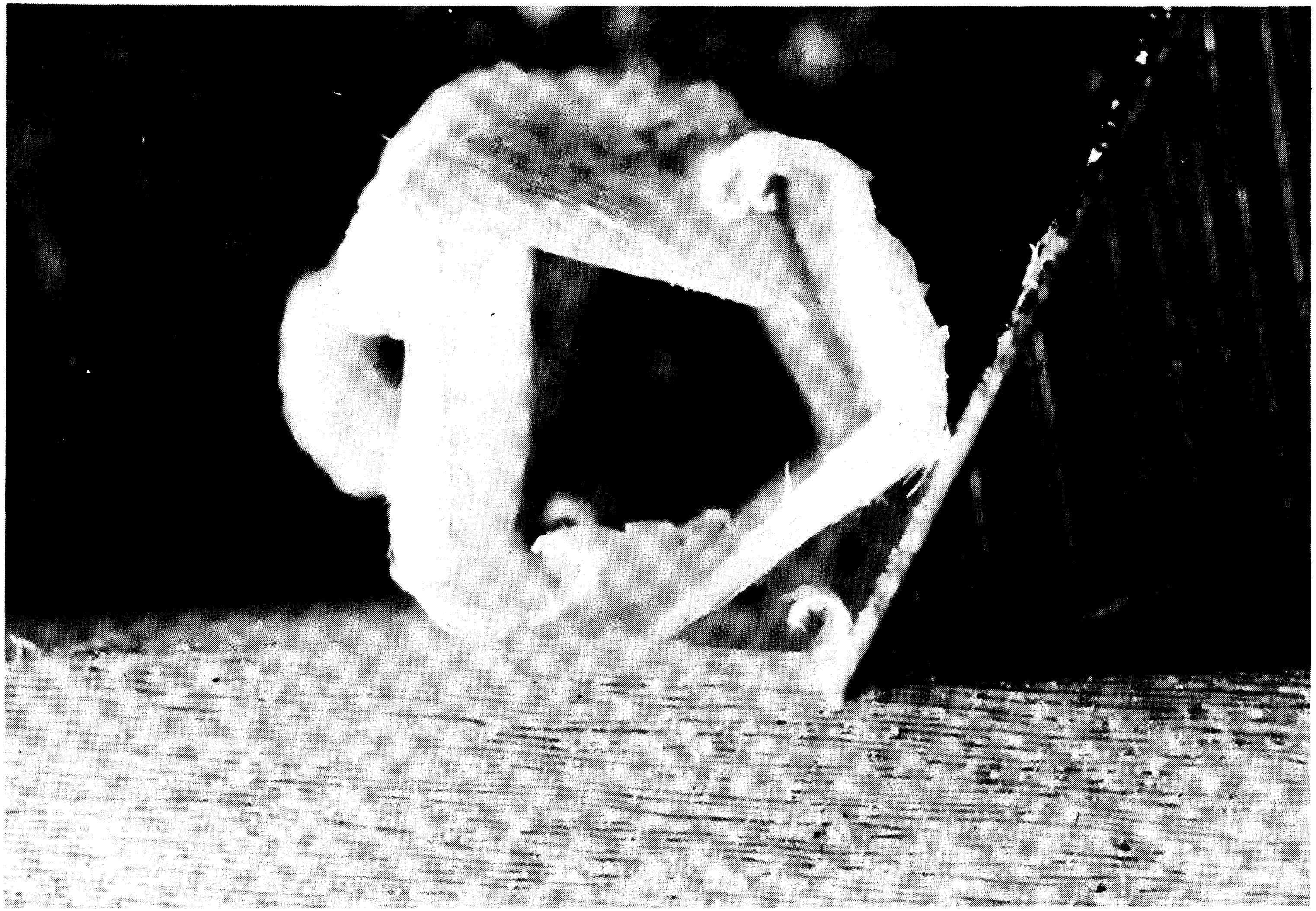


Fig. 30. --Chip formation when cutting with the grain, illustrating Type II chip formation in combination with Type I.

Type II Chip Formation

Within a limited range of machining conditions, cutting relationships favor the continuous development of wood failures in a plane extending from the cutting edge to the work surface ahead of the tool. Figure 22 illustrates this manner of chip formation, which has been classified as Type II. In the formation of the continuous Type II chip, relative movement of the tool along the cutting path strains the wood ahead of the tool face in compression and induces shearing stresses, which ultimately result in failure and compacting of the wood elements. The compressed material escapes upward along the tool face, allowing stresses to be transferred to adjacent intact portions of the wood in a relatively steady progression. The process thus resembles the development of a multitude of diagonal shearing failures commonly observed when wood is stressed in compression parallel to the grain.

As indicated in Figure 22, the character of the Type II chip reflects the uniformity of the machining process. The chip typically assumes the shape of a smooth spiral, the tightness of the involutions being dependent on the undeformed chip thickness. As depth of cut is increased, the radius of curvature of the chip becomes larger, Figures 24, 25, and 26 .

The quality of the surface generated by Type II chip formation is excellent, Figure 31, since the cutting edge limits wood failures and determines the resultant surface at all times. Type II chip formation therefore represents the ideal cutting process from the standpoint of surface quality, with the work piece left uniform and free of damaged wood elements. Supplementary investigations showed that equally good surfaces can be obtained with the Type II chip when cutting with or against wood grain that is at an angle to the tool path. The attainment of Type II chip formation requires critical adjustment of machining

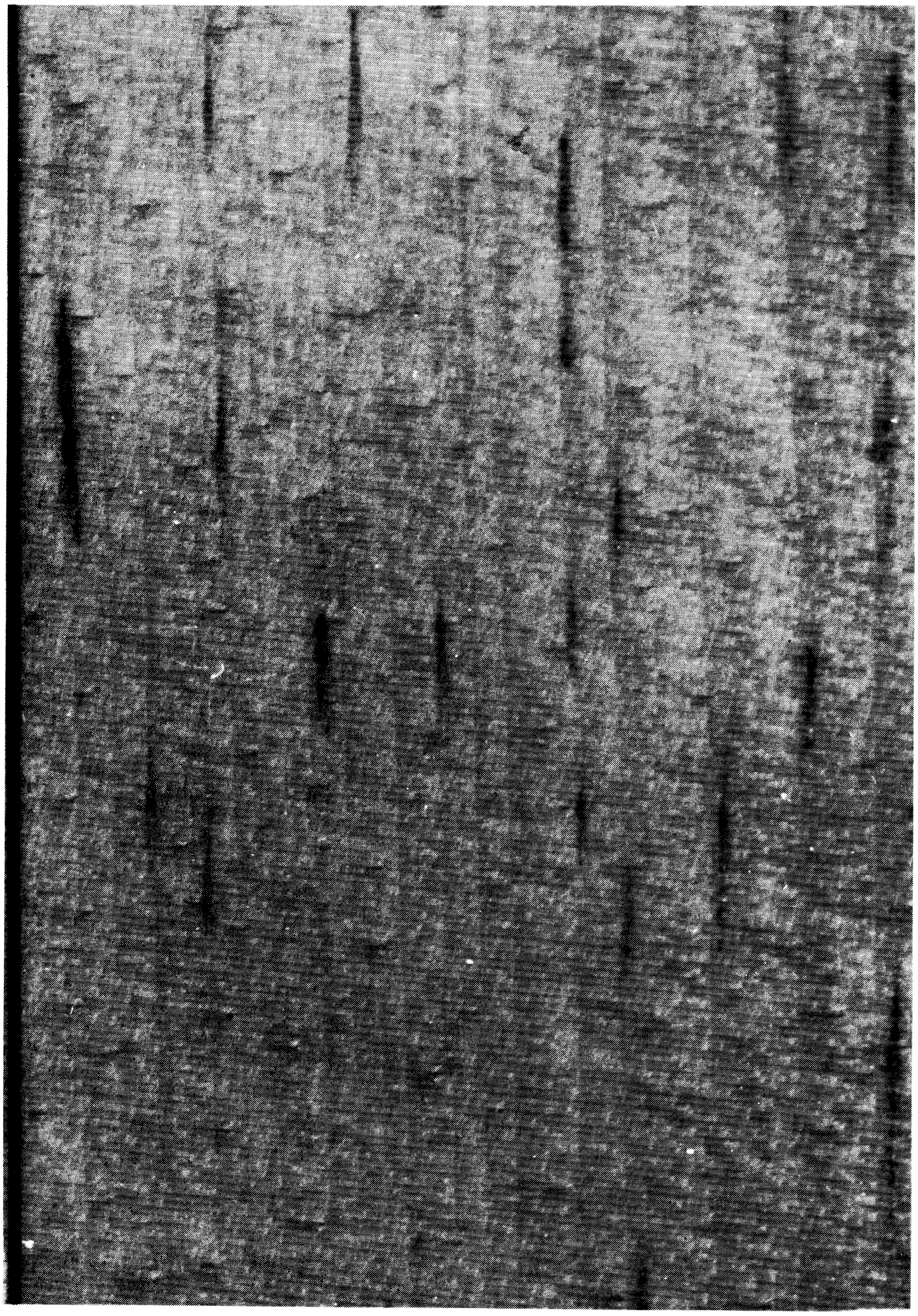


Fig. 31.--Photograph of defect-free surface on sugar pine, produced by Type II chip formation.

conditions when cutting against the grain, since wood properties obviously encourage formation of the Type I chip.

The formation of the Type II chip appears to be favored by the establishment of machining conditions medial to those of the Type I and Type III chips. Therefore, a careful balance in cutting relationships is necessary to assure Type II chip formation. This tends to prevail when chip thicknesses are small, and the wood being machined is prone to diagonal shear failures, although manipulation of tool geometry and the coefficient of friction between the tool and the chip permits extension of the restrictive wood factors.

Type III Chip Formation

Formation of the Type III chip occurs when machining conditions produce compression and shearing failures in the wood ahead of the cutting tool, as depicted in Figure 23. Like the formation of the Type I chip, formation of the Type III chip tends to be cyclical although entirely distinctive. Typically, at the beginning of a chip cycle the relative motion between the tool and the work piece causes the wood to be stressed in compression parallel to the grain. Further movement strains the wood until rupture in shear and compression takes place, Figure 32-A, and localized compacting of the wood results. This transfers stresses to undamaged areas, which fail in turn. Unlike the previously described types of chip formation, the ruptured wood does not flow freely up the tool face, but remains fixed and causes progressive compacting of the wood ahead of the tool, Figure 32-B, the zone being defined roughly by the grain of the work. Ultimately, the extent of the compressed material becomes critical, and buckling takes place, Figure 32-C. The chip is then free to escape upward, Figure 32-D, and the next cycle is started when the tool reaches the last failure line. As

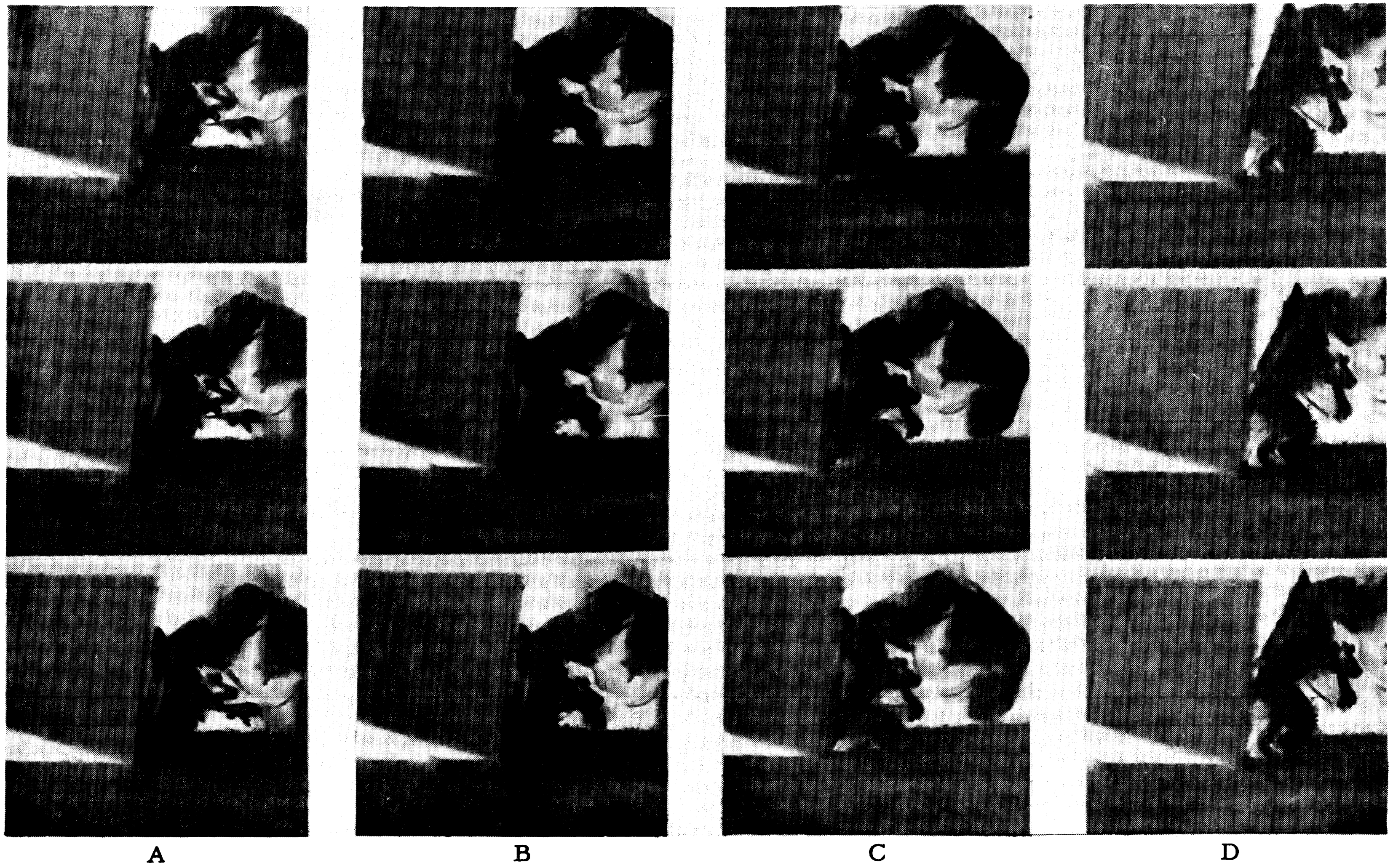


Fig. 32. --Development of the Type III chip. A, initial contact of chip by tool; B, progressive compression of wood ahead of the tool; C, buckling of compressed material; D, upward escape of chip.

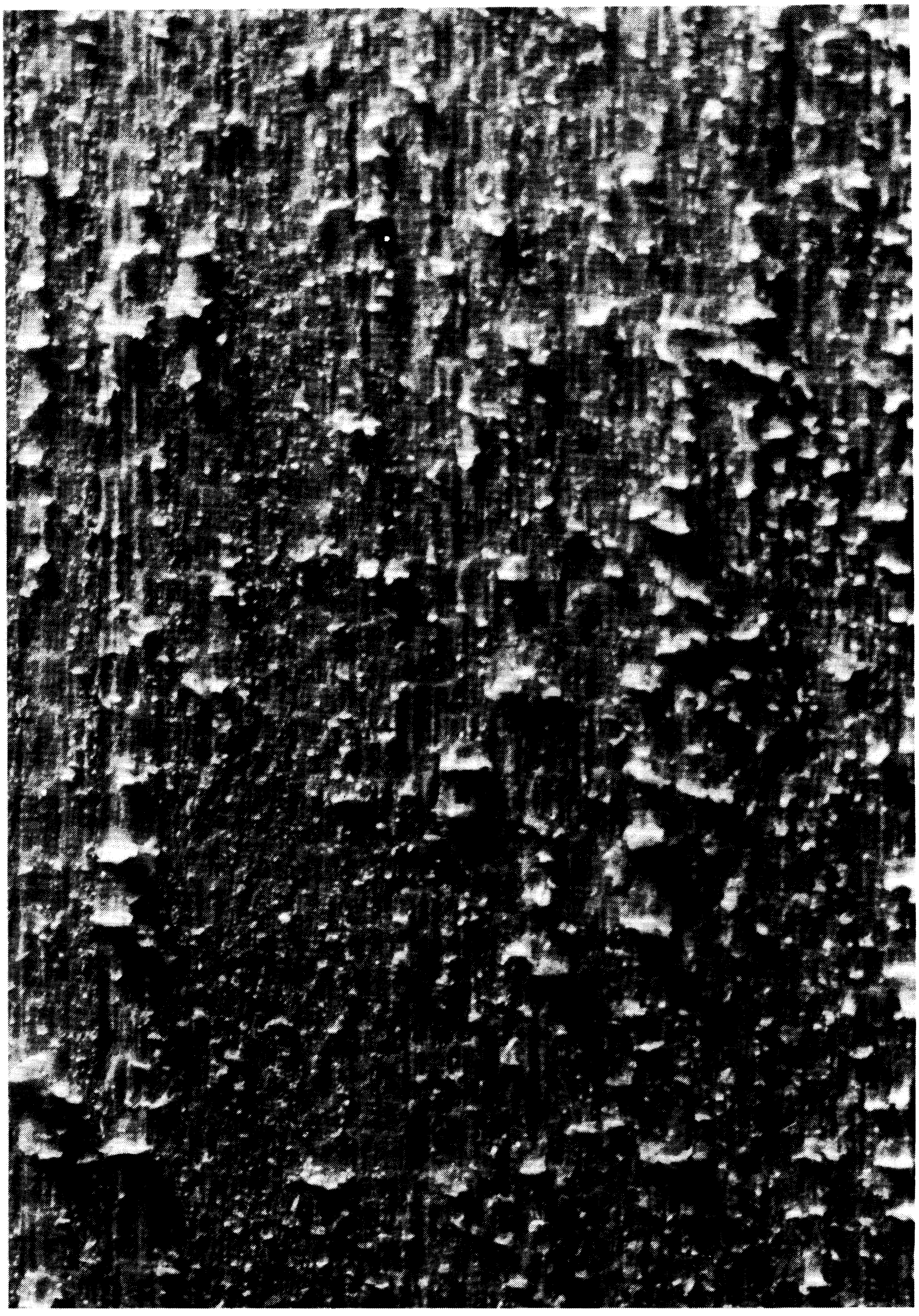


Fig. 33. --The defect fuzzy grain' produced by **Type III** chip formation on sugar pine.

seen in the figures, the chip produced by the above process is usually contorted in appearance.

Since the surface generated with the Type III chip is determined by wood failures ahead of the tool, which often extend below the tool path and pass under the cutting edge, the ruptures remain prominent on the work. This results in a work surface exhibiting many loosely attached bundles of damaged wood elements, Figure 33, and produces the machining defect commonly described as fuzzy grain.

Under certain machining conditions, particularly when negative cutting angles are employed and the friction between the chip and the tool face is seemingly great, a modification of the Type III chip is observed which is directly analogous to the Type III chip described for metal cutting. As illustrated in Figure 34, a built-up edge of compacted wood substance develops on the tool face near the cutting edge, apparently due to stress distributions and high specific pressures. Movement between the tool and the work increases the mass adhering to the tool, which acts as a false edge with a large cutting angle. When the size of the built-up edge becomes critical, or it induces formation of a secondary Type I chip, the resultant instability permits the mass to escape upward, after which the cycle is repeated.

Formation of the Type III chip with or without a built-up edge was observed to be coincident with the use of very small or negative cutting angles. It is apparent that a high coefficient of friction between the chip and the tool face also would favor this type of chip formation, and be essential to the development of a built-up edge. Dull cutting tools are seen to be particularly suited for establishment of a pseudo-edge by virtue of geometrical considerations, since a rounded edge has in effect a compound cutting angle which becomes negatively large at the tool extremity.

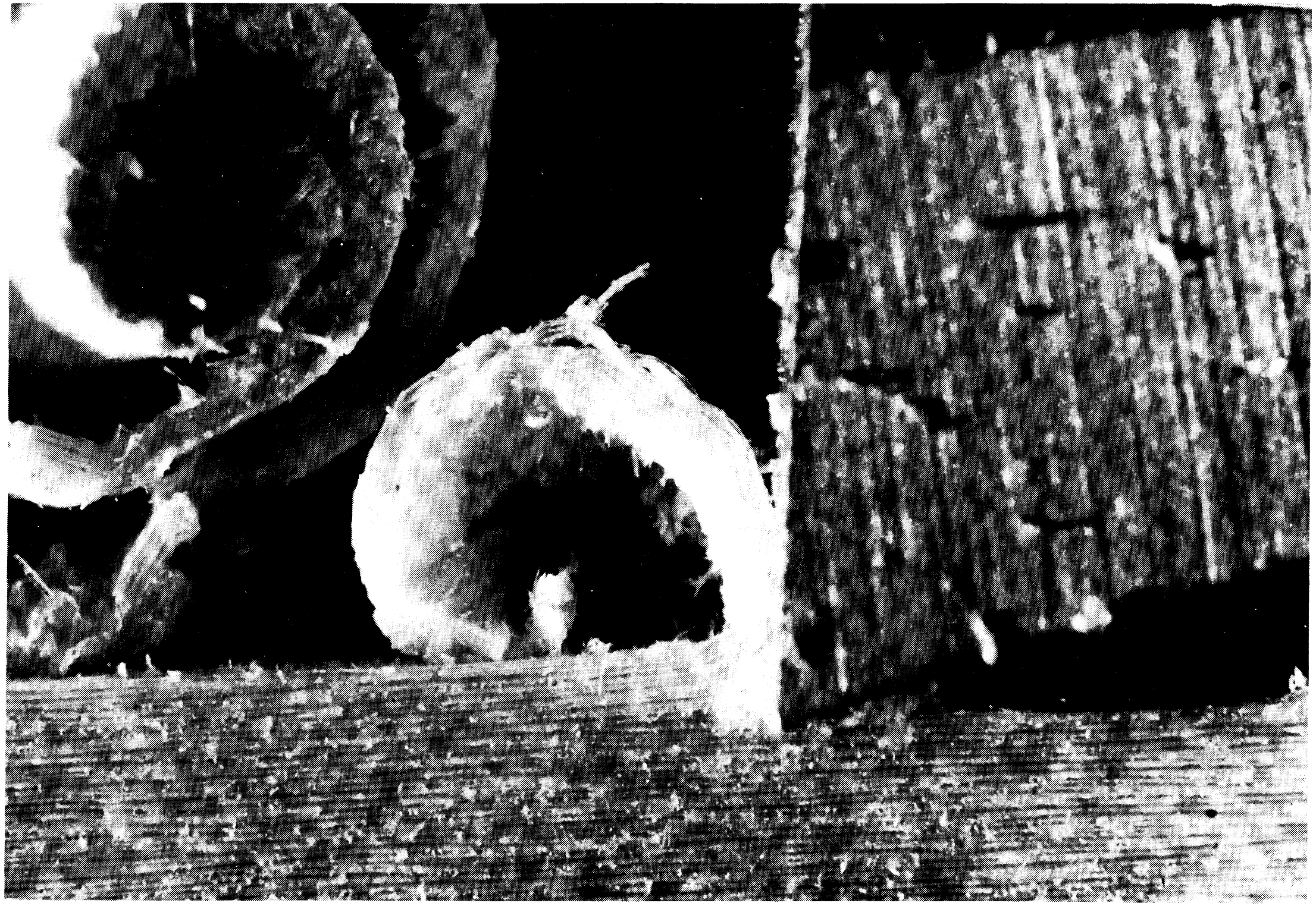


Fig. 34. --The Type III chip with built-up edge of compacted wood.

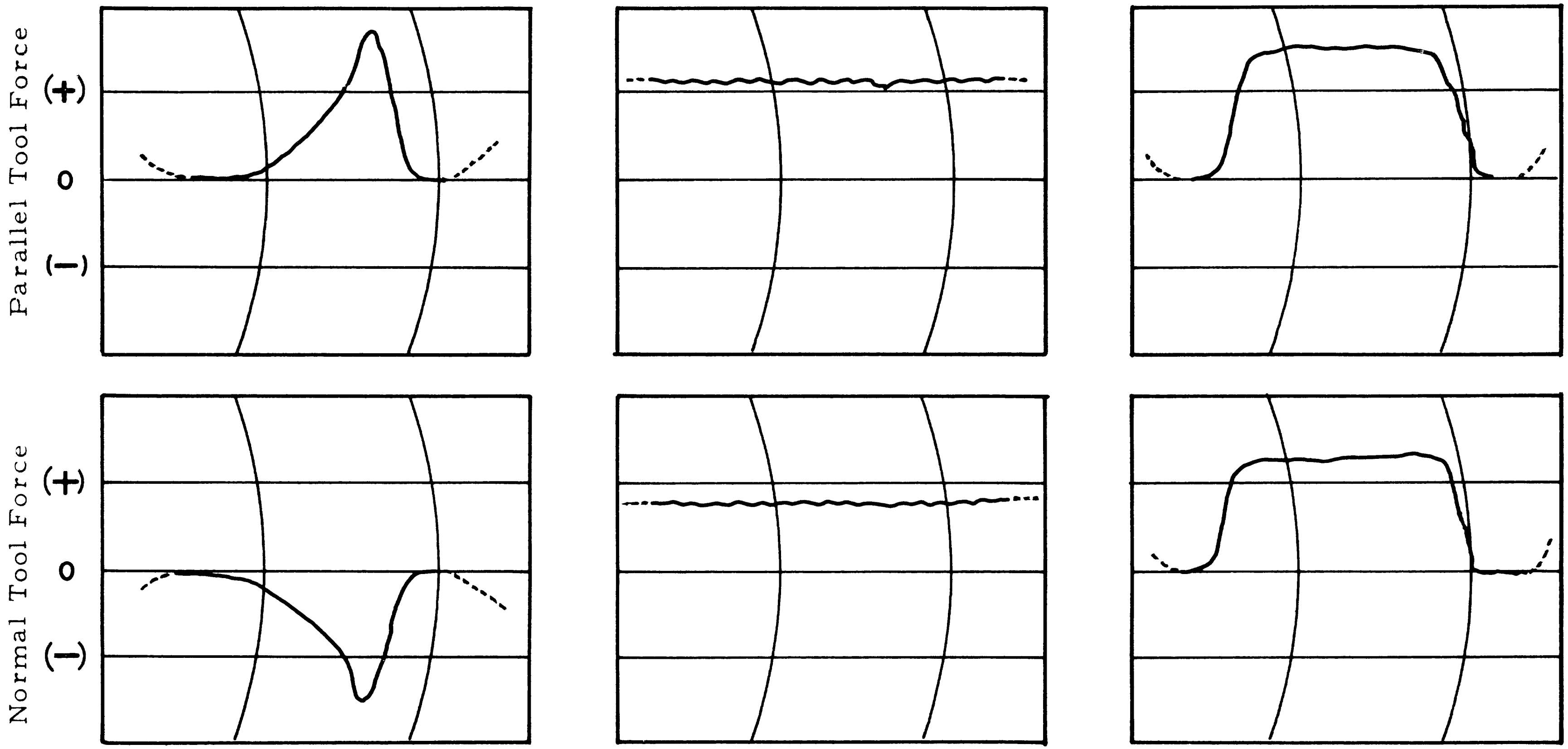
RESULTS AND ANALYSIS OF TOOL-FORCE STUDIES

Force Patterns

Oscillograph records of tool-force components parallel and normal to the cutting path verified perliminary observations on the presence of discernible patterns in the development of instantaneous force values. Further, it was evident that the nature of force delineation is closely correlated with chip formation, each type of chip formation displaying a characteristic force pattern. Figure 35 illustrates representative oscillograph records of tool forces associated with each of the three principal chip types.

Figure 35-A depicts a typical force design obtained during formation of the Type I chip. The cyclical nature of the process is clearly indicated by the generation of force peaks with uniform amplitude and frequency. It will be noted that at the beginning of a chip cycle, there is an increase in force magnitude as the tool face compresses the wood after initial contact. Following this, a very rapid rise in the tool force parallel to the cutting path is accompanied by a simultaneous negative increment in the normal force as the wood is stressed by the tool. The forces reach a peak when the wood fails by splitting, and quickly drop to low levels as the chip is deflected as a cantilever beam until ultimate rupture in bending. Forces are then negligible until another cycle is started.

From parallel tool-force delineations by the oscillograph, it is apparent that instantaneous magnitude may be great, but of such short duration that the area under the curve is relatively small. Thus,



A — Type I

B — Type II

C — Type III

Fig. 35.--Tracings of representative force patterns for each of the three basic types of chip formation. Patterns show sharp peaks of Type I, relatively constant values of Type II, and interrupted form of Type III. Note that normal tool force is negative, or away from work piece, for Type I.

the work required for the formation of the Type I chip is comparatively small, indicating that the efficiency of removing material from the work piece is high. Further, wear on the cutting edge should be relatively slight, since it works during only a small part of the total tool travel. The negative value of the tool forces normal to the cutting path indicates that friction between the chip and the tool face is small in comparison with forces normal to the plane of contact. This is seen to contrast with force relations of the Type II and Type III chips.

A representative force pattern for the Type II chip is shown in Figure 35-B. During formation of this chip type, the cutting process is uniform in nature and failure in the wood ahead of the tool is essentially continuous. Affiliated forces therefore are nearly constant during machining, as the oscillograph record of instantaneous forces indicates.

Formation of the Type II chip is accompanied by positive force components parallel and normal to the cutting path, the resultant tool force being directed toward the work piece. This attests the presence of significant frictional forces parallel to the tool face when positive cutting angles are employed. The work required for Type II chip formation is seen to be greater than that required for formation of a Type I chip of similar undeformed dimensions, since the product of force and distance is comparatively large. Wear on the cutting edge may be expected to be more pronounced with the Type II chip formation than with Type I, since the tool point is subject to attrition at all times.

In Figure 35-C, a typical pattern of force generation is depicted for Type III chip formation, in which the cyclical nature of the cutting process is marked by interruptions in otherwise stable force levels. At the beginning of each chip unit, forces increase as the work is brought into full contact with the tool face, after which a sharp increment in force components is noted as the wood is stressed to the point of rupture. Relatively constant force values persist during compaction of the material ahead of the tool, as stresses are transferred to new areas in the work piece. When the mass in front of the tool face becomes unstable and buckles, force values drop quickly, approximating zero until initial contact for the next cycle is made.

The magnitude and direction of normal tool forces associated with the Type III chip indicate substantial frictional components at the interface of the chip and the tool. From the force records delineated during the discussion of the Type III chip formation, it may be concluded that the work in cutting is relatively great.

In above discussions of the force patterns associated with each of the basic chip types, it has been noted that the work required in Type I chip formation is substantially less than that in Type II and Type III. This appears to be consistent with the results of preliminary experiments in rotary cutting. It was shown that two chip phases are present in the rotary cutting process, Figures 4 and 5, and that the proportion of wood volume in the second phase increases as chip thickness becomes greater. Further, power data show that machining efficiency improves with increased feed per knife, Figure 7, indicating that less work per unit volume is required at heavier chip loads. Since the first chip phase is seen to be Type II or Type III chip formation, and the second is Type I, it may be concluded that the data are in agreement with those obtained from tool-force determinations. Thus, the orthogonal cutting experiments conducted in this research may be expected to show close correlation with more practical machining applications.

Interactions of Cutting Geometry and Wood Properties on Tool Forces

Qualitative preliminary experiments established that the woodcutting process is apparently dependent on interrelationships of wood properties and cutting geometry. Investigating this further, an integrated analysis of tool forces was made by simultaneously varying wood species, equilibrium moisture content, tool cutting angle, and undeformed chip thickness. The results of this series of experiments are summarized in Tables 4 through 12. The data, which are tabulated by species and moisture content, represent the average critical values of tool force components parallel and normal to the cutting path.

Trends and relationships in the above data are made more apparent when force values are plotted graphically, as in Figures 36 through 53. Here, for clarity, the normal tool force and the parallel tool force have been presented separately.

The influences of cutting geometry are clearly indicated in the force data. A general reduction in the parallel tool force is noted as the cutting angle increases and the chip thickness decreases. The normal tool force, which appears to be sensitive to interactions of cutting geometry, evidences a more complex relationship. At small cutting angles, an increase in undeformed chip thickness is accompanied by an increase in the normal force component. However, at the larger cutting angles, an increase in the depth of cut is attended by a decrease, or negative increment, in the normal tool force.

Tool-force influences exerted by the work piece are seen to be equally marked. Both tool-force components show a decline in magnitude as wood moisture content is raised to the fiber saturation point, apparently in response to associated reductions in mechanical strength. The reaction to changes in work piece properties through species variation appears to be somewhat more discrete. Tool forces indicate only a limited correlation with density between species, and hence, with the general strength characteristics of each species. It is implied, therefore, that interactions of certain mechanical properties operate to determine machining forces. The properties involved are given consideration in discussion of the results of mechanical properties tests.

TABLE 4

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — SUGAR PINE AT 1.5 PER CENT MOISTURE CONTENT

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	6.6	5.7	5.6	5.2	3.8	3.8
	F_n	2.5	1.8	1.2	0.9	0.4	0.03
0.005	F_p	12.0	11.8	11.1	9.8	7.0	4.8
	F_n	3.4	2.7	1.7	1.0	-0.03	-0.3
0.010	F_p	20.5	19.9	17.1	13.6	9.5	7.5
	F_n	4.4	3.4	1.8	0.9	-0.3	-0.8
0.015	F_p	30.0	27.0	20.5	17.5	11.1	9.2
	F_n	4.6	3.0	1.4	0.6	-0.6	-1.0
0.020	F_p	35.0	30.0	23.5	18.8	13.5	10.5
	F_n	5.2	3.2	1.6	0.4	-0.9	-1.2
0.025	F_p	43.5	38.5	23.2	25.0	16.9	11.4
	F_n	6.4	2.7	1.5	-0.1	-1.5	-1.5
0.030	F_p	52.5	42.5	25.0	24.2	17.0	—
	F_n	6.8	3.4	1.4	-0.3	-1.4	—

TABLE 5

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — SUGAR PINE AT 8.0 PER CENT MOISTURE CONTENT

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	4.1	5.1	4.9	3.8	3.3	3.7
	F_n	2.1	2.3	1.1	0.8	0.3	-0.1
0.005	F_p	10.9	10.1	9.5	9.4	8.3	6.1
	F_n	3.6	2.3	1.5	1.9	-0.1	-0.5
0.010	F_p	17.2	17.5	19.5	15.8	9.5	7.4
	F_n	5.5	2.6	2.1	0.6	-0.7	-0.1
0.015	F_p	26.8	24.5	25.8	18.5	12.1	8.4
	F_n	5.9	3.6	2.6	-0.1	-1.1	-1.4
0.020	F_p	34.0	32.2	33.0	20.5	12.3	9.3
	F_n	7.0	3.9	3.0	-0.6	-1.4	-1.7
0.025	F_p	41.5	36.5	38.0	20.0	13.5	10.6
	F_n	9.2	4.9	2.4	-1.1	-1.7	-2.4
0.030	F_p	48.5	44.5	46.5	21.2	15.8	—
	F_n	11.1	4.4	2.0	-1.6	-2.4	—

TABLE 6

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — SUGAR PINE AT SATURATED MOISTURE CONDITIONS

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	4.2	3.4	2.4	2.3	1.7	1.4
	F_n	4.9	4.4	2.6	2.2	1.4	0.8
0.005	F_p	6.2	6.4	5.4	5.4	4.7	4.2
	F_n	6.0	5.0	2.8	2.2	1.0	0.3
0.010	F_p	11.1	9.9	8.8	7.9	7.4	6.6
	F_n	7.0	5.5	3.4	2.4	1.1	0.2
0.015	F_p	15.1	14.1	11.8	11.4	10.5	9.2
	F_n	11.0	6.6	4.8	3.5	1.1	0.1
0.020	F_p	—	15.8	14.5	13.8	14.1	12.1
	F_n	—	9.8	4.9	3.8	1.2	-0.2
0.025	F_p	—	19.8	19.8	18.5	16.5	14.2
	F_n	—	10.5	6.0	3.4	1.2	-0.7
0.030	F_p	—	22.8	22.8	22.0	21.8	17.5
	F_n	—	11.0	5.6	3.8	1.1	-1.1

TABLE 7

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — YELLOW BIRCH AT 1.5 PER CENT MOISTURE CONTENT

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	12.1	12.0	9.5	7.6	6.0	5.4
	F_n	4.8	3.2	2.1	1.4	0.6	0.2
0.005	F_p	22.0	20.5	18.2	17.2	13.8	10.3
	F_n	7.2	5.2	3.4	2.2	0.6	-0.4
0.010	F_p	37.5	36.8	36.0	32.0	26.2	19.0
	F_n	12.5	8.8	6.0	3.4	0.8	-1.0
0.015	F_p	53.5	52.5	50.0	48.5	39.0	27.2
	F_n	16.8	11.8	8.4	4.6	0.8	-1.6
0.020	F_p	65.5	66.0	65.5	61.0	54.0	33.0
	F_n	18.2	14.4	11.2	6.3	0.8	-1.9
0.025	F_p	82.5	81.3	77.5	77.5	75.5	41.5
	F_n	20.5	15.8	11.4	6.9	1.0	-2.2
0.030	F_p	106.3	87.5	90.0	85.0	75.5	—
	F_n	24.2	17.8	12.8	6.6	1.8	—

TABLE 8

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — YELLOW BIRCH AT 8.0 PER CENT MOISTURE CONTENT

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	11.5	9.9	7.1	7.1	6.2	5.7
	F_n	4.5	3.1	1.6	1.2	0.6	0.1
0.005	F_p	18.5	17.3	16.0	15.6	13.8	10.6
	F_n	6.8	4.8	3.1	1.9	0.6	-0.4
0.010	F_p	33.0	31.5	31.0	27.0	24.5	19.2
	F_n	10.4	7.5	5.1	2.8	0.4	-1.6
0.015	F_p	46.5	46.0	43.5	42.5	36.5	25.5
	F_n	14.8	10.3	6.8	3.3	-0.4	-2.3
0.020	F_p	58.5	58.0	57.0	53.5	49.0	33.0
	F_n	17.1	12.6	7.6	5.2	-0.6	-3.3
0.025	F_p	72.5	67.0	67.5	65.0	58.5	45.0
	F_n	20.0	13.3	10.5	5.4	-0.8	-4.4
0.030	F_p	88.8	78.8	83.8	77.5	66.5	—
	F_n	25.5	18.0	11.8	4.4	-1.6	—

TABLE 9

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — YELLOW BIRCH AT SATURATED MOISTURE CONDITIONS

Chip Force Component	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	4.4	3.4	3.0	3.0	2.0	1.9
	F_n	4.0	2.2	1.4	1.2	0.6	0.4
0.005	F_p	9.6	6.9	5.6	5.4	4.5	4.1
	F_n	5.1	2.9	1.5	1.2	0.4	0.0
0.010	F_p	15.0	12.1	10.4	9.2	7.2	6.4
	F_n	7.4	4.4	2.2	1.3	0.3	-0.2
0.015	F_p	22.8	15.6	14.1	12.4	9.9	7.8
	F_n	9.6	4.4	2.8	1.6	0.3	-0.5
0.020	F_p	28.0	20.5	18.8	17.1	12.6	10.1
	F_n	12.1	5.9	3.0	1.8	0.2	-0.6
0.025	F_p	31.2	25.0	22.0	20.5	16.2	10.8
	F_n	13.8	6.6	3.4	2.1	0.2	-0.7
0.030	F_p	36.5	30.5	27.2	24.2	17.8	15.8
	F_n	14.6	7.2	4.4	2.2	0.1	-1.2

TABLE 10

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — WHITE ASH AT 1.5 PER CENT MOISTURE CONTENT

Chip Thickness Inches	Tool Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	10.2	8.5	7.5	7.0	4.8	4.8
	F_n	4.1	2.8	2.0	1.1	0.6	0.2
0.005	F_p	16.6	15.5	14.1	13.2	11.5	9.5
	F_n	6.3	4.5	3.1	2.0	0.7	-0.2
0.010	F_p	30.8	28.0	28.0	26.0	23.0	18.0
	F_n	11.1	7.8	5.4	3.5	1.0	-0.8
0.015	F_p	44.5	40.2	38.8	37.8	33.5	25.8
	F_n	14.9	10.9	7.4	4.5	1.3	-1.3
0.020	F_p	56.0	50.5	49.0	46.0	42.0	33.3
	F_n	18.8	13.0	9.0	5.5	1.1	-1.8
0.025	F_p	67.0	59.5	56.5	52.5	48.5	43.0
	F_n	22.6	14.8	9.6	5.6	1.3	-2.3
0.030	F_p	79.0	70.0	68.5	60.0	56.0	—
	F_n	27.7	16.6	11.2	5.5	1.3	—

TABLE 11

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — WHITE ASH AT 8.0 PER CENT MOISTURE CONTENT

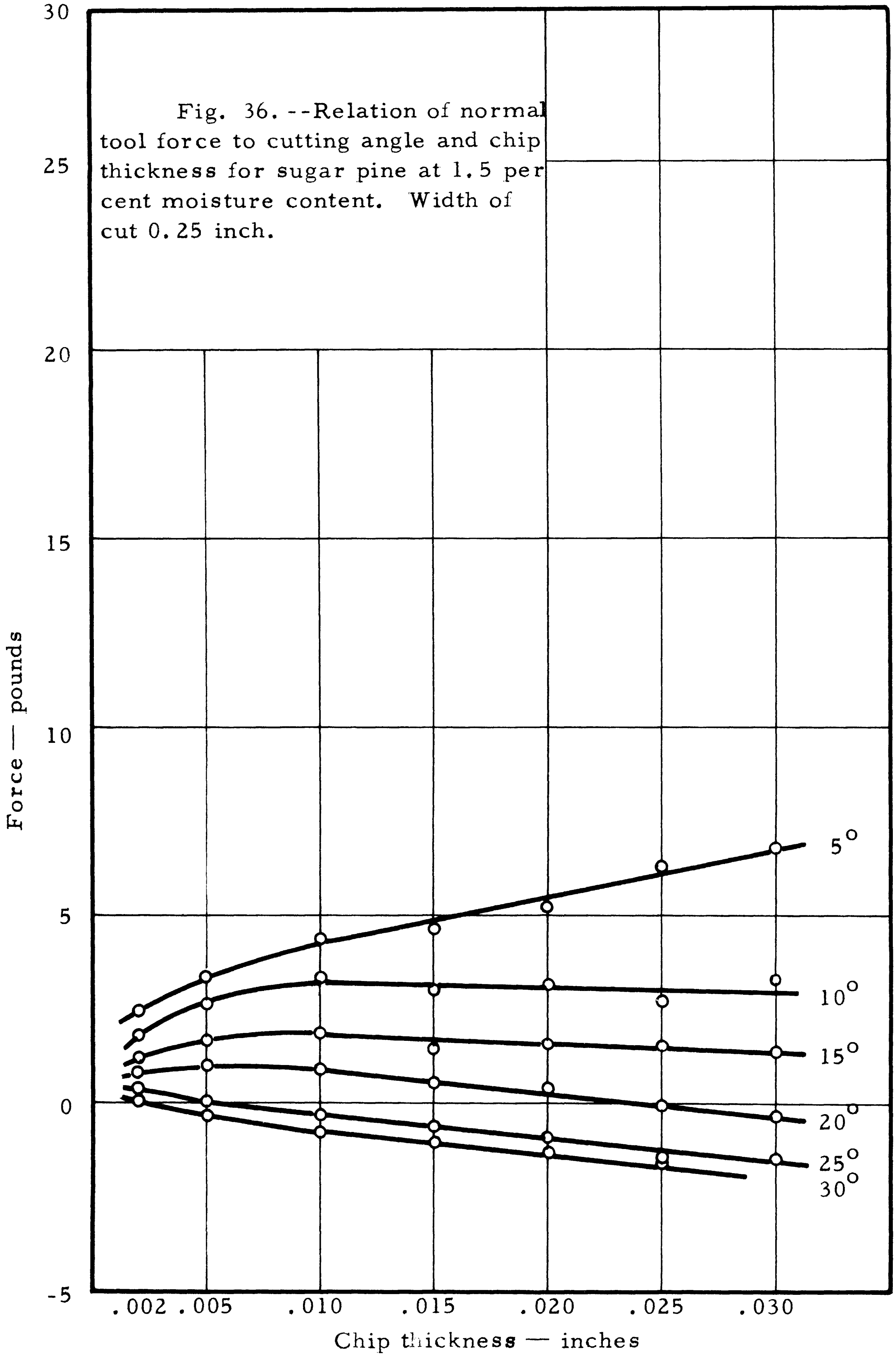
Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	8.5	7.6	6.2	5.8	3.8	4.3
	F_n	3.7	2.6	1.8	1.2	0.6	0.2
0.005	F_p	16.9	13.1	12.5	11.4	11.1	9.4
	F_n	6.7	4.6	2.9	1.7	0.8	-0.1
0.010	F_p	29.0	25.5	23.0	20.8	20.0	16.5
	F_n	10.4	7.4	4.9	2.8	0.9	-0.7
0.015	F_p	40.5	38.5	33.5	29.5	28.8	22.5
	F_n	14.6	11.0	6.9	4.0	1.1	-1.2
0.020	F_p	51.5	47.5	43.0	39.0	37.5	29.3
	F_n	17.3	12.8	8.6	5.2	1.2	-1.8
0.025	F_p	61.3	55.8	54.0	48.5	47.0	37.5
	F_n	19.5	15.3	10.6	6.3	1.4	-2.6
0.030	F_p	73.8	66.0	62.0	56.5	56.0	—
	F_n	21.3	17.0	12.6	7.1	1.5	—

TABLE 12

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING ANGLE AND CHIP THICKNESS — WHITE ASH AT SATURATED MOISTURE CONDITIONS

Chip Thickness Inches	Tool-Force Component	Tool Force in Pounds for 0.25 Inch Chip Width					
		Cutting Angle					
		5°	10°	15°	20°	25°	30°
0.002	F_p	4.2	3.8	3.0	2.8	2.3	1.6
	F_n	2.1	1.4	0.8	0.6	0.3	0.2
0.005	F_p	8.8	6.8	5.6	5.6	4.4	3.8
	F_n	3.2	2.0	1.1	0.7	0.1	-0.3
0.010	F_p	13.8	12.2	11.2	9.8	7.8	6.8
	F_n	4.9	3.2	1.9	0.9	-0.1	-0.6
0.015	F_p	19.2	16.9	16.4	13.9	12.0	8.0
	F_n	6.6	4.2	2.6	1.0	-0.4	-1.0
0.020	F_p	24.7	22.2	22.0	18.2	15.5	10.9
	F_n	8.2	5.4	3.3	1.1	-0.6	-1.4
0.025	F_p	29.8	25.5	26.0	22.8	18.2	12.0
	F_n	10.0	6.3	3.8	1.2	-0.9	1.4
0.030	F_p	36.0	29.5	30.5	26.0	20.2	13.4
	F_n	12.2	7.0	4.2	1.2	-1.1	-1.6

Fig. 36. --Relation of normal tool force to cutting angle and chip thickness for sugar pine at 1.5 per cent moisture content. Width of cut 0.25 inch.



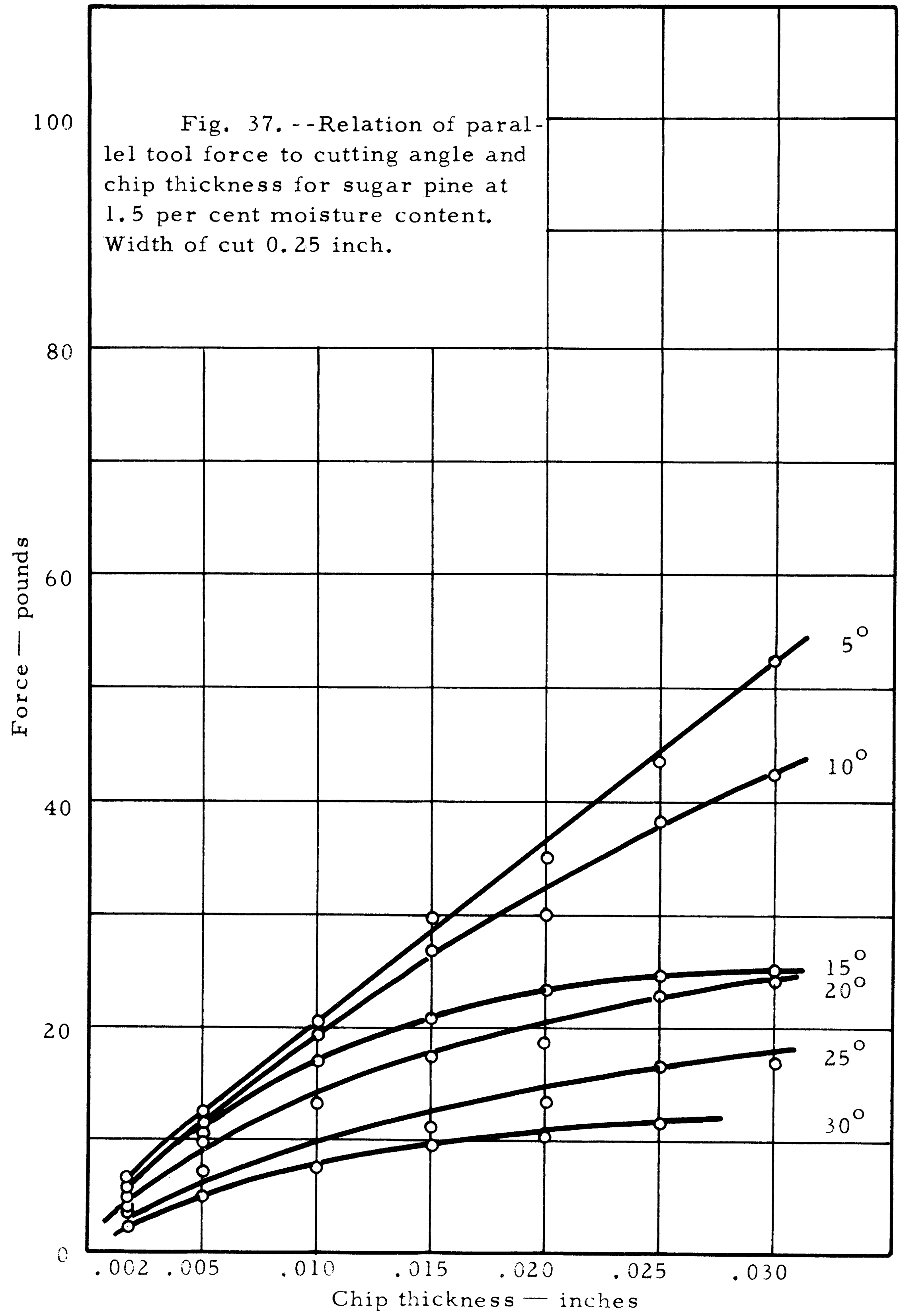


Fig. 37.--Relation of parallel tool force to cutting angle and chip thickness for sugar pine at 1.5 per cent moisture content. Width of cut 0.25 inch.

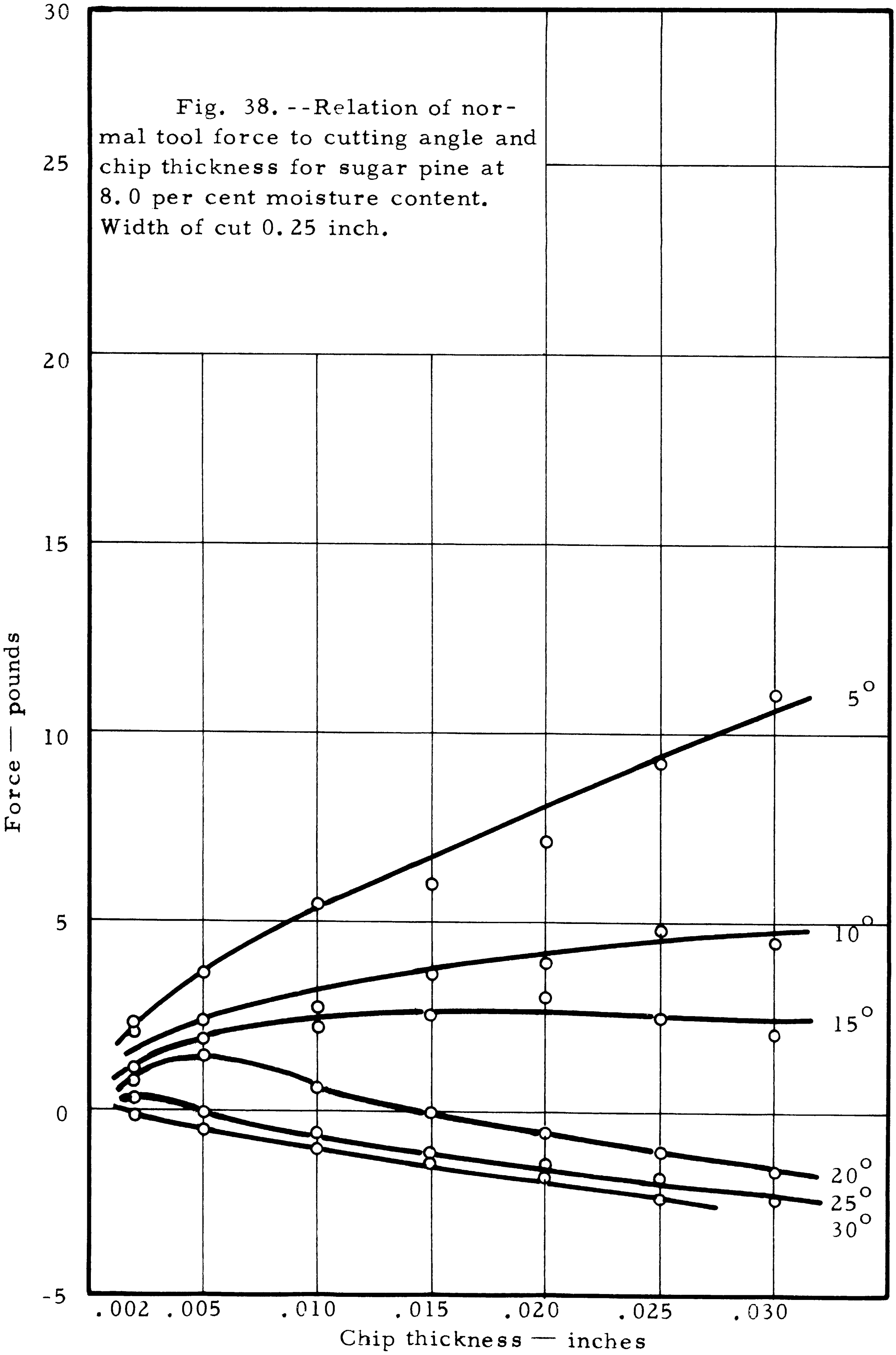


Fig. 38.--Relation of normal tool force to cutting angle and chip thickness for sugar pine at 8.0 per cent moisture content. Width of cut 0.25 inch.

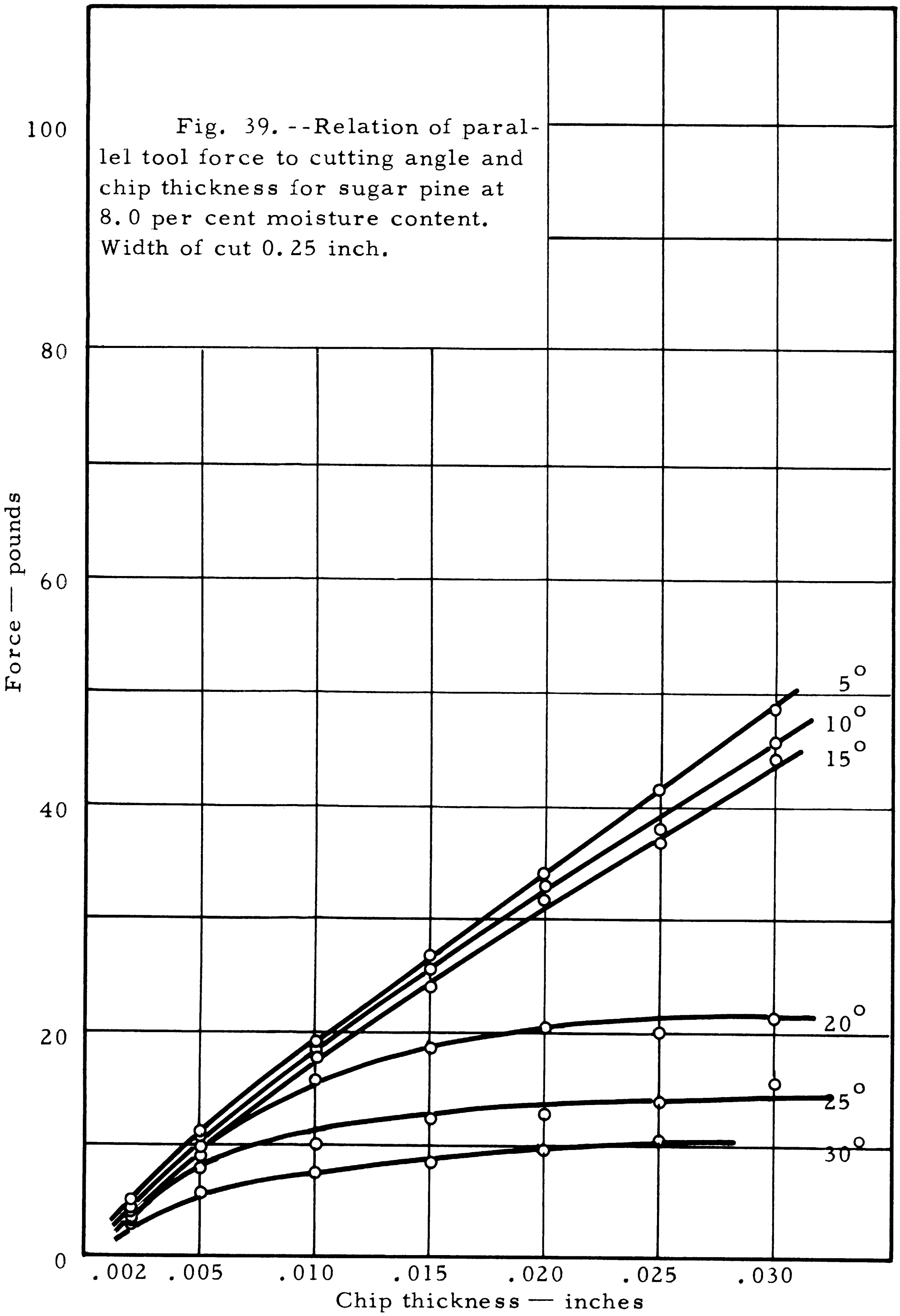


Fig. 39. --Relation of parallel tool force to cutting angle and chip thickness for sugar pine at 8.0 per cent moisture content. Width of cut 0.25 inch.

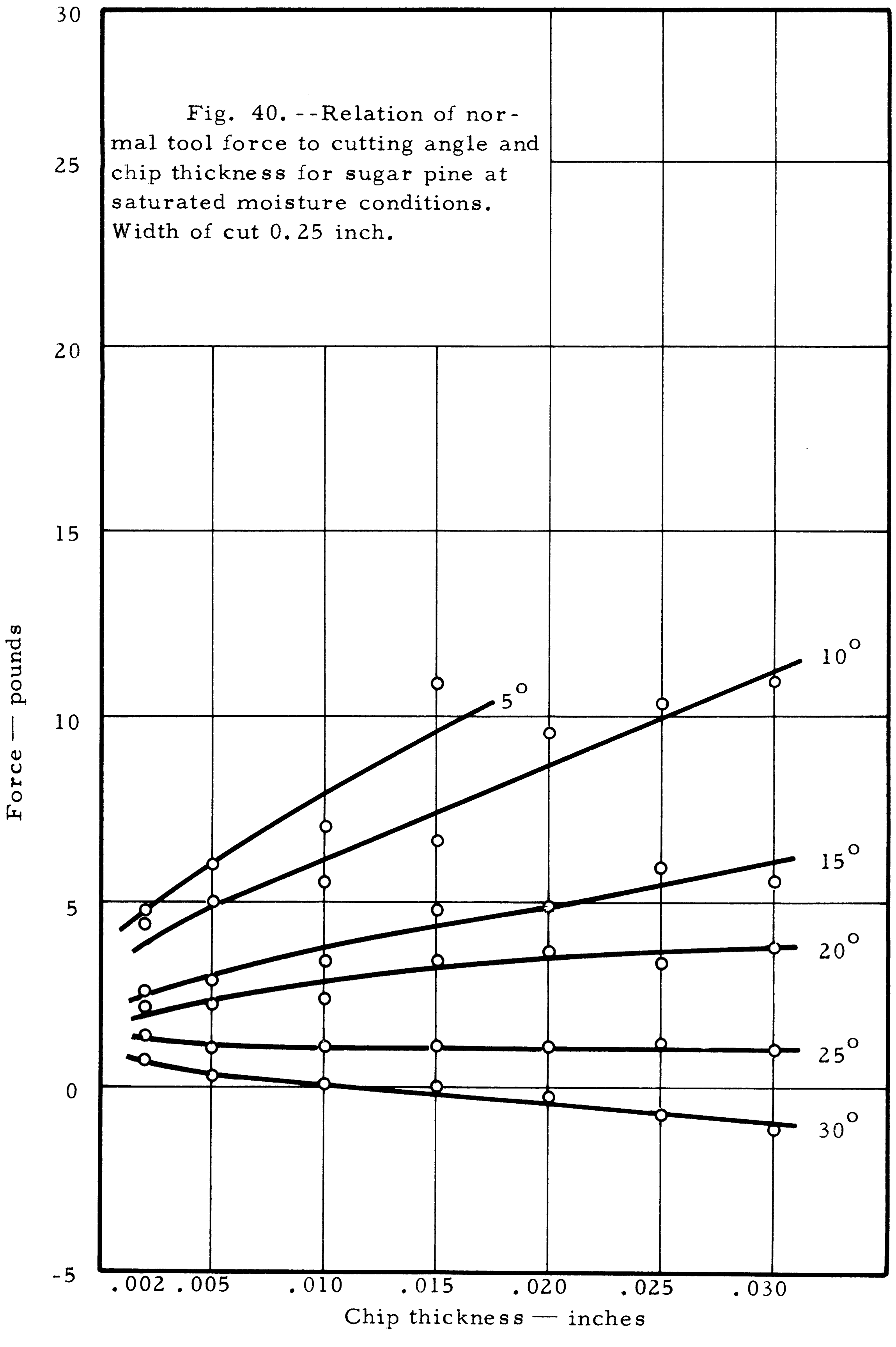


Fig. 40.--Relation of normal tool force to cutting angle and chip thickness for sugar pine at saturated moisture conditions. Width of cut 0.25 inch.

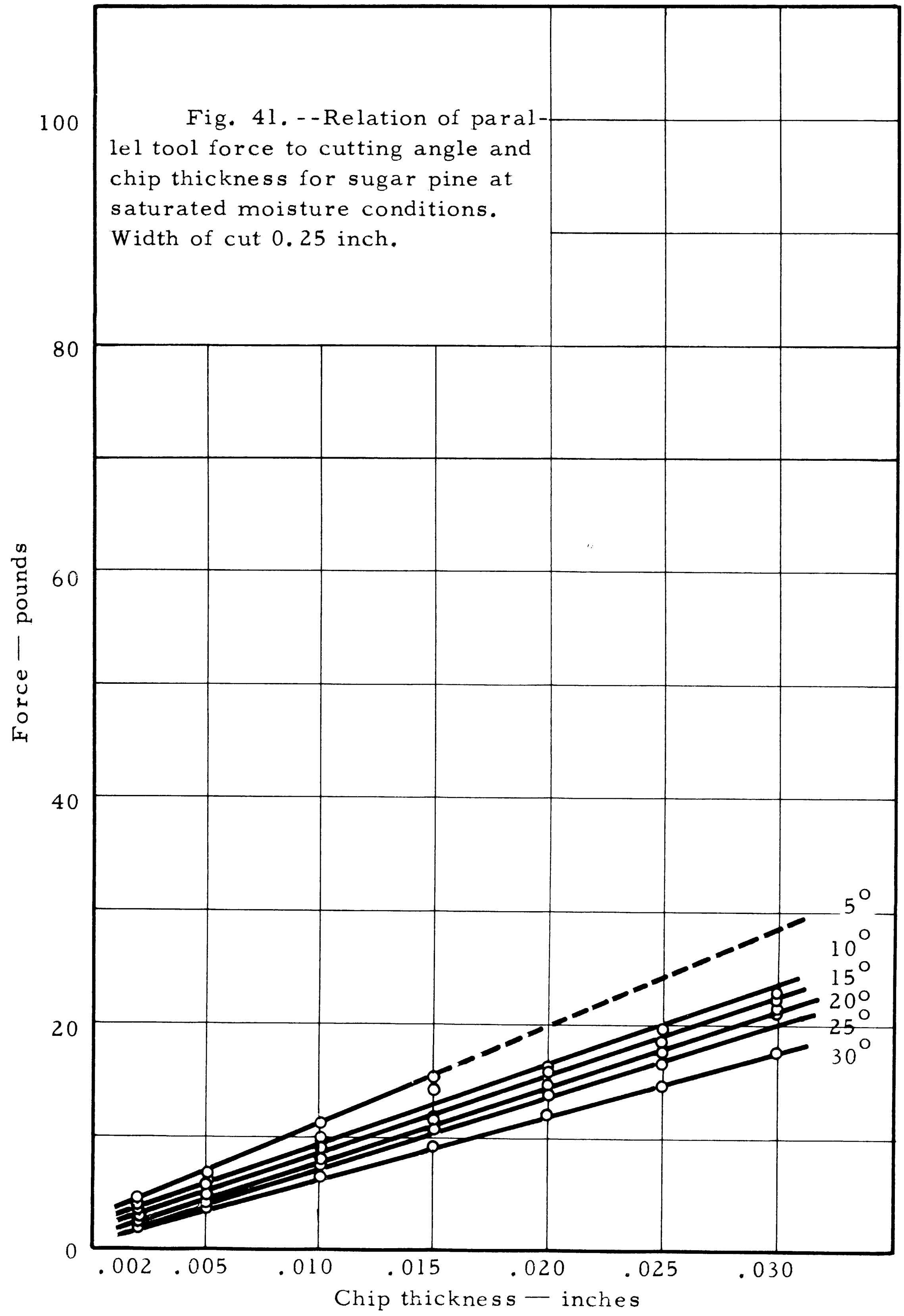


Fig. 41.--Relation of parallel tool force to cutting angle and chip thickness for sugar pine at saturated moisture conditions. Width of cut 0.25 inch.

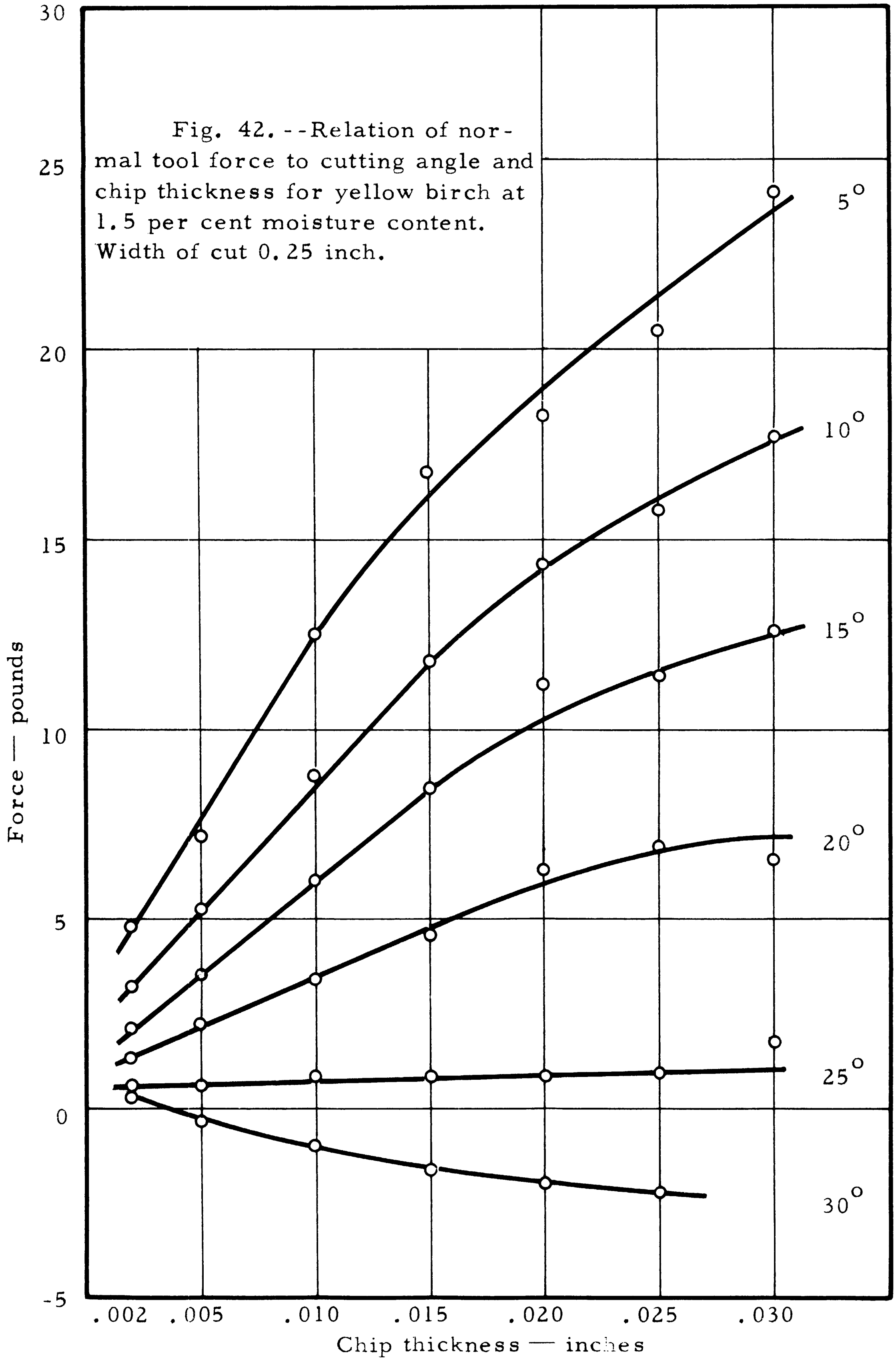


Fig. 42.--Relation of normal tool force to cutting angle and chip thickness for yellow birch at 1.5 per cent moisture content. Width of cut 0.25 inch.

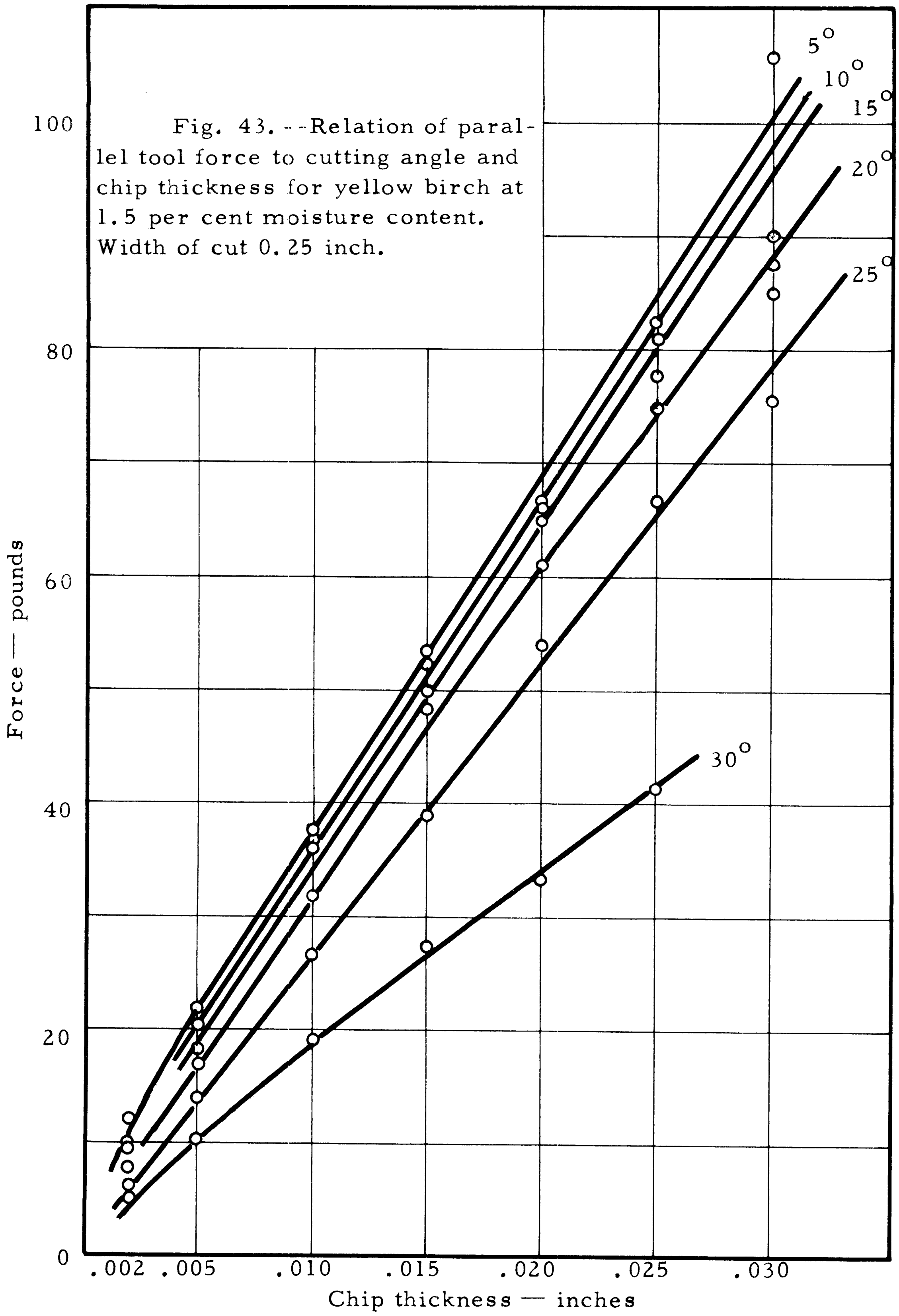


Fig. 43.--Relation of parallel tool force to cutting angle and chip thickness for yellow birch at 1.5 per cent moisture content. Width of cut 0.25 inch.

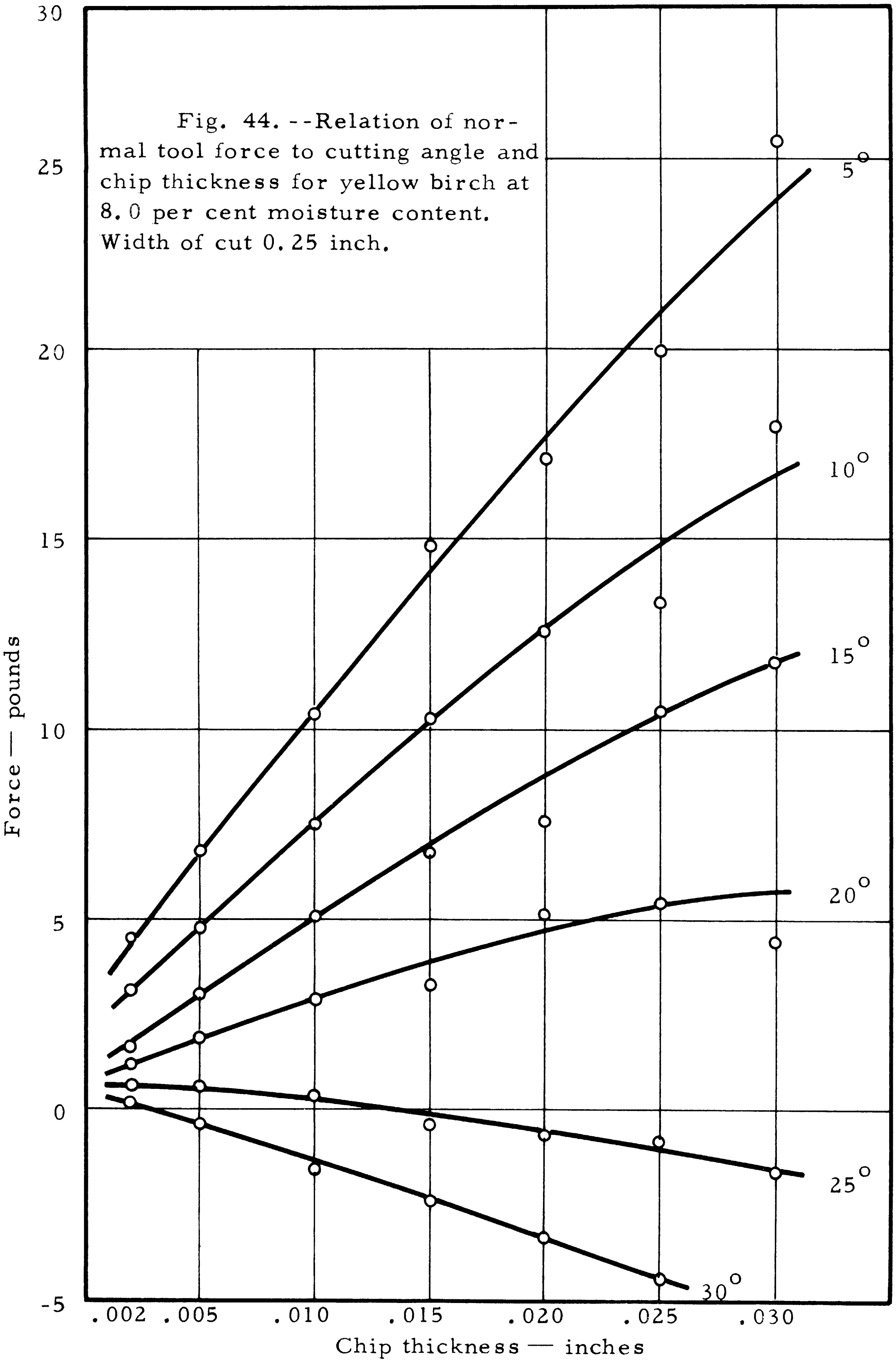


Fig. 44. --Relation of normal tool force to cutting angle and chip thickness for yellow birch at 8.0 per cent moisture content. Width of cut 0.25 inch.

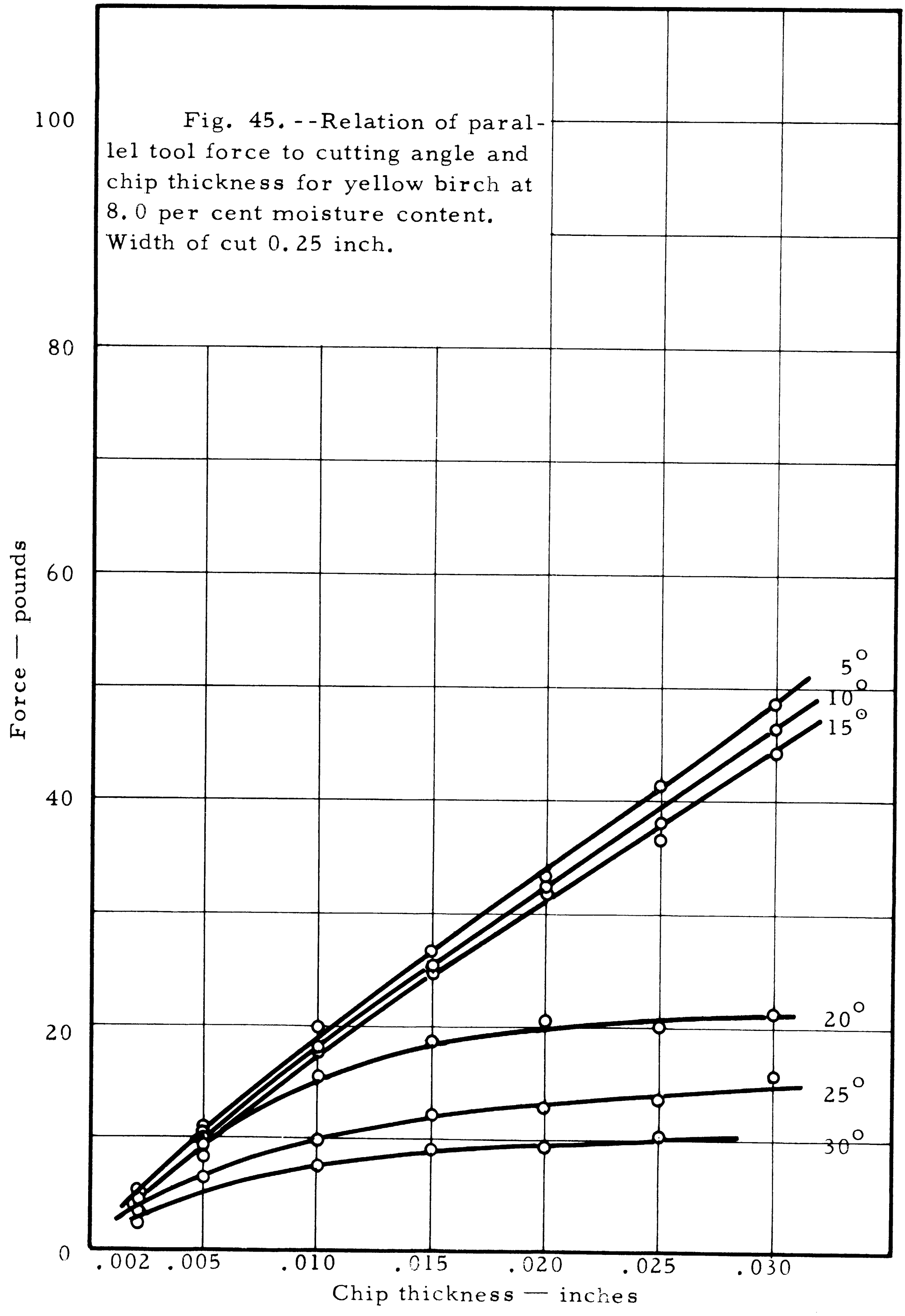


Fig. 45.--Relation of parallel tool force to cutting angle and chip thickness for yellow birch at 8.0 per cent moisture content. Width of cut 0.25 inch.

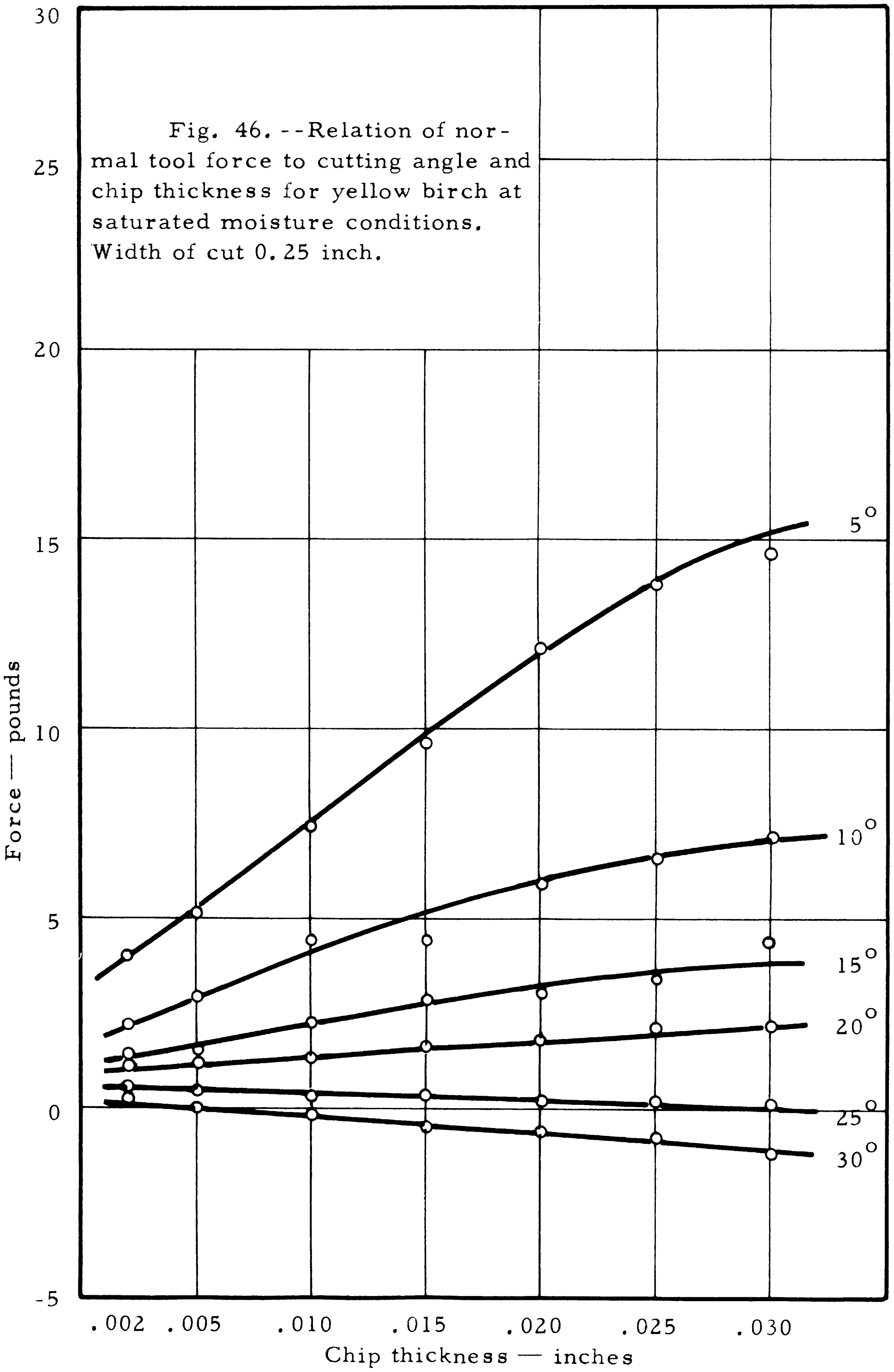


Fig. 46. --Relation of normal tool force to cutting angle and chip thickness for yellow birch at saturated moisture conditions. Width of cut 0.25 inch.

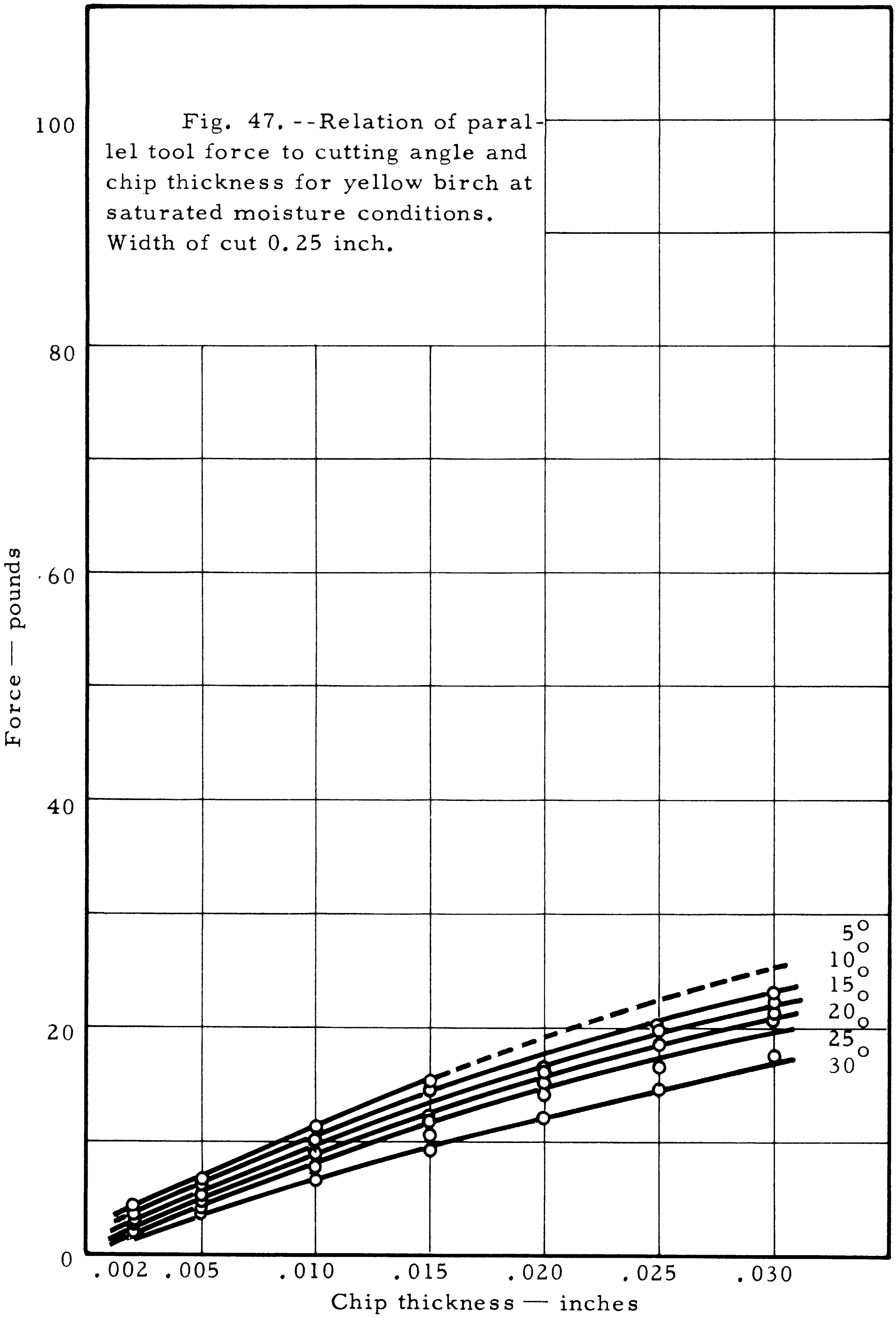


Fig. 47.--Relation of parallel tool force to cutting angle and chip thickness for yellow birch at saturated moisture conditions. Width of cut 0.25 inch.

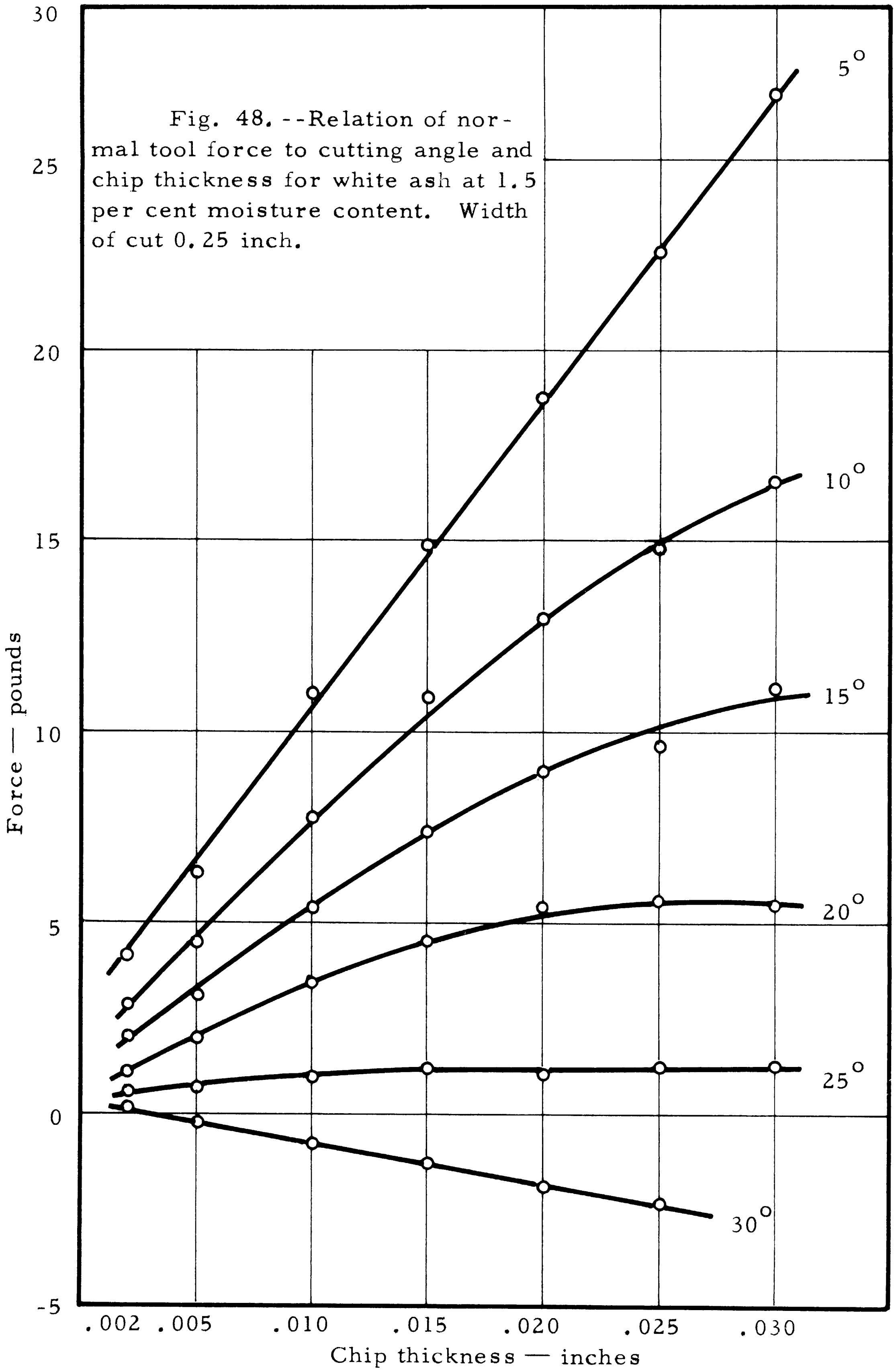


Fig. 48.--Relation of normal tool force to cutting angle and chip thickness for white ash at 1.5 per cent moisture content. Width of cut 0.25 inch.

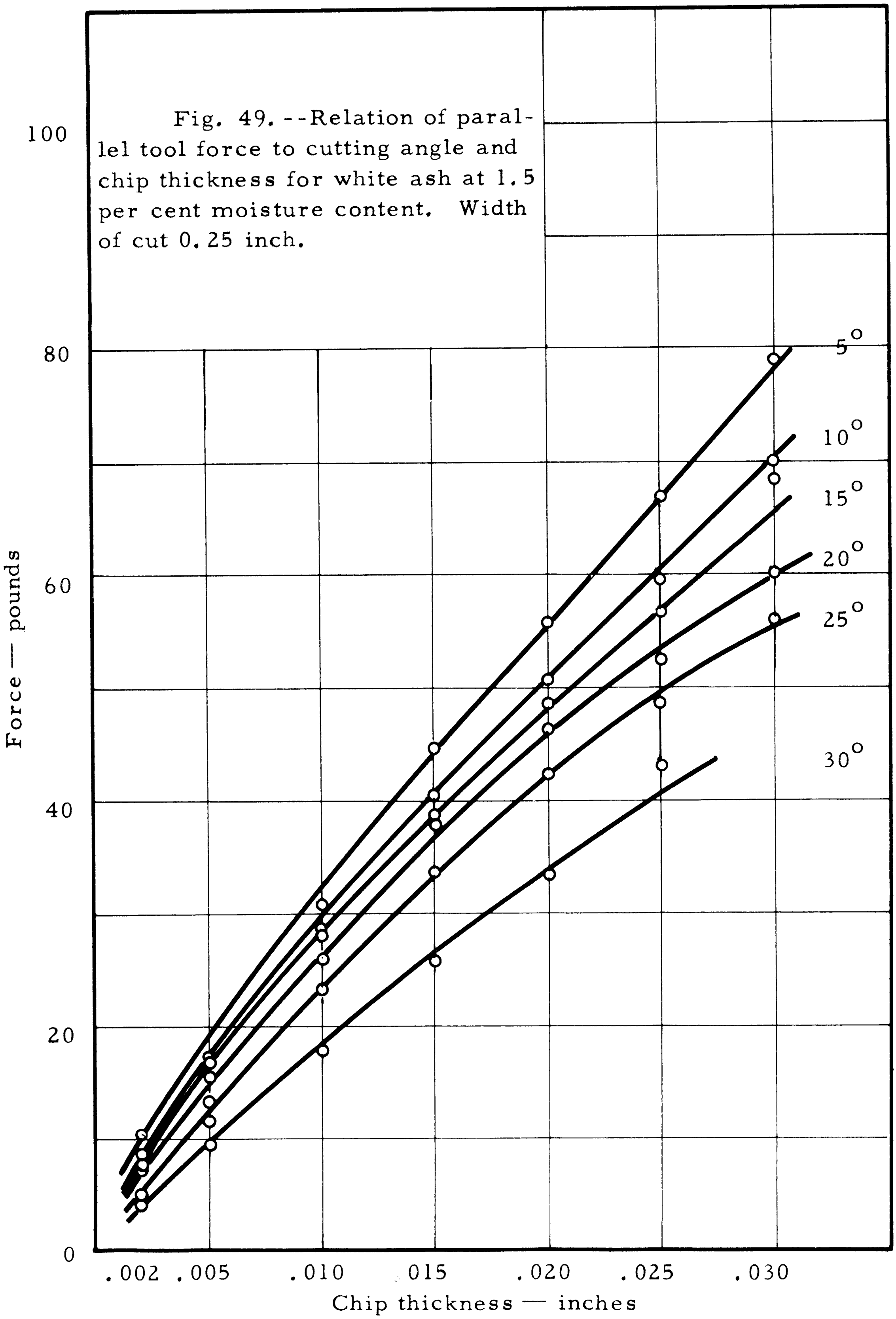


Fig. 49.--Relation of parallel tool force to cutting angle and chip thickness for white ash at 1.5 per cent moisture content. Width of cut 0.25 inch.

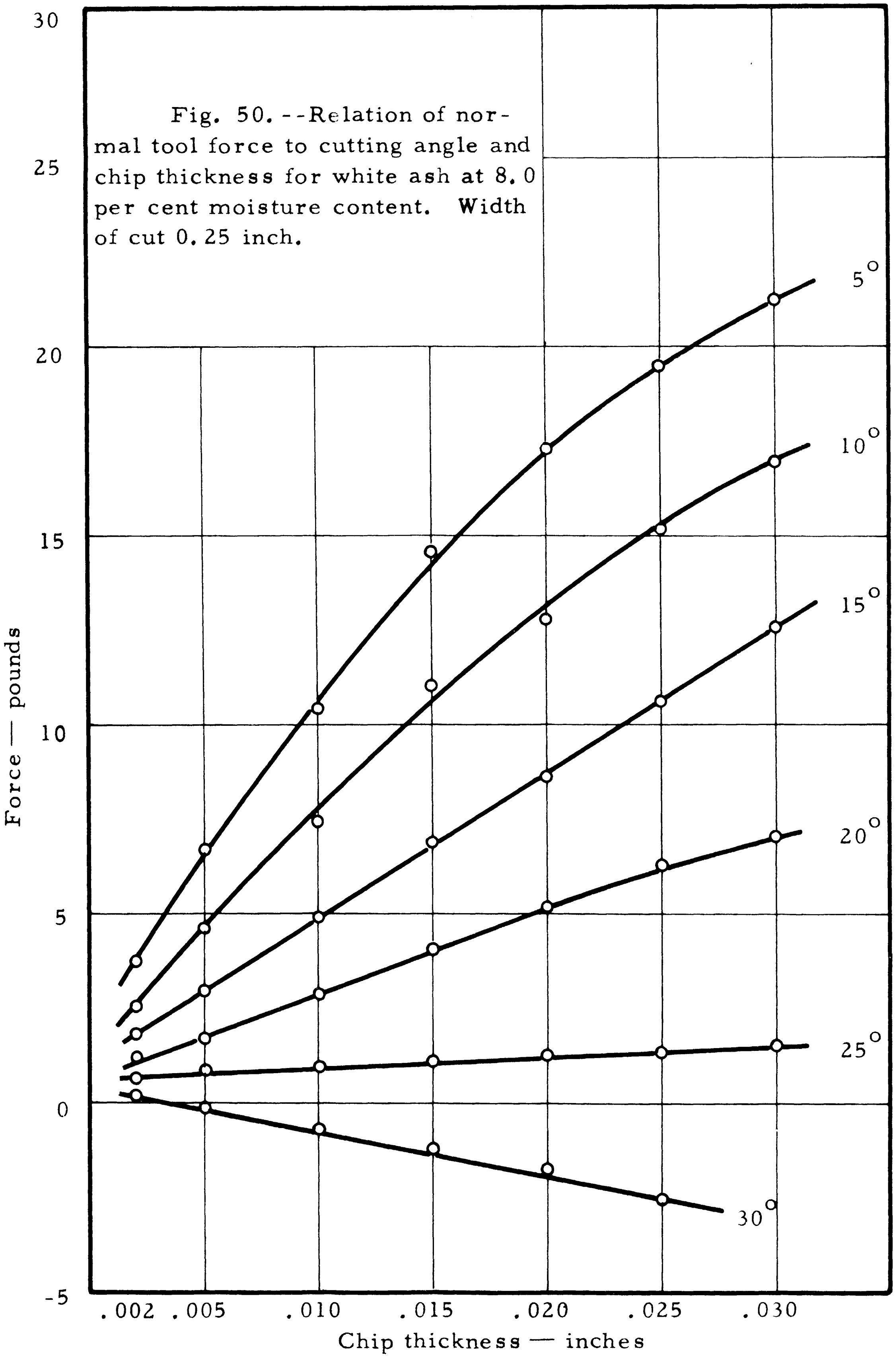


Fig. 50.--Relation of normal tool force to cutting angle and chip thickness for white ash at 8.0 per cent moisture content. Width of cut 0.25 inch.

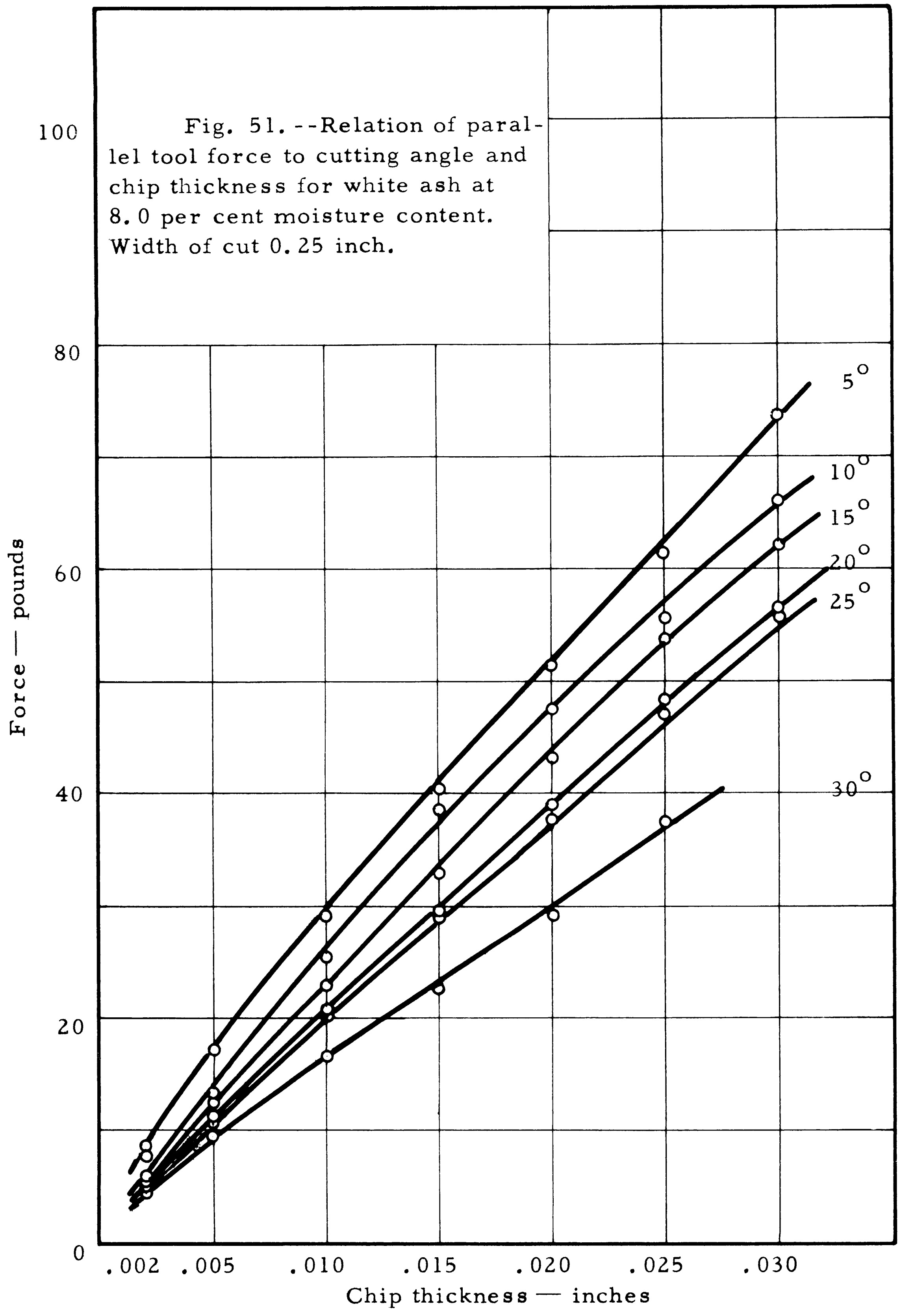


Fig. 51.--Relation of parallel tool force to cutting angle and chip thickness for white ash at 8.0 per cent moisture content. Width of cut 0.25 inch.

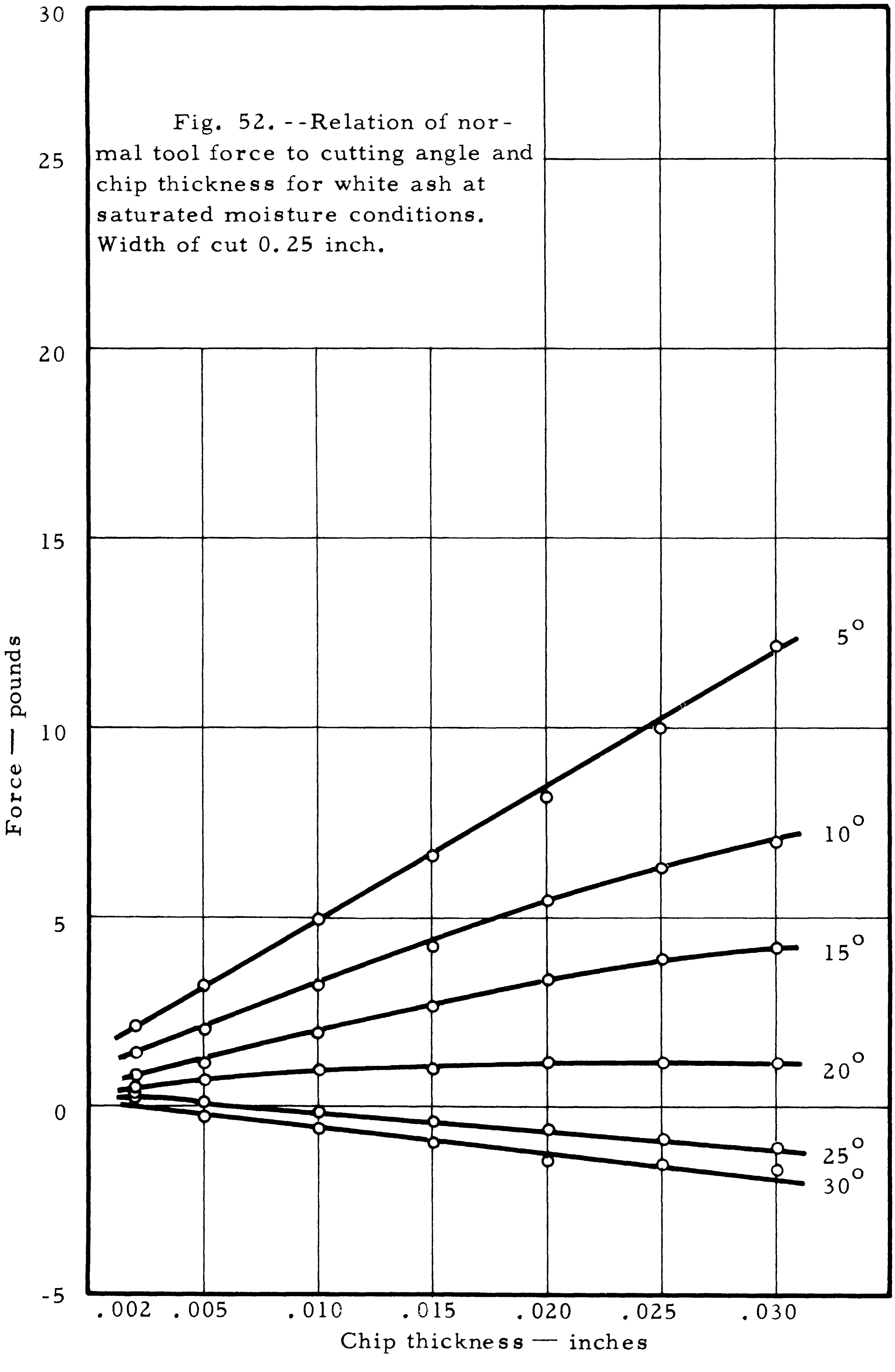


Fig. 52. --Relation of normal tool force to cutting angle and chip thickness for white ash at saturated moisture conditions. Width of cut 0.25 inch.

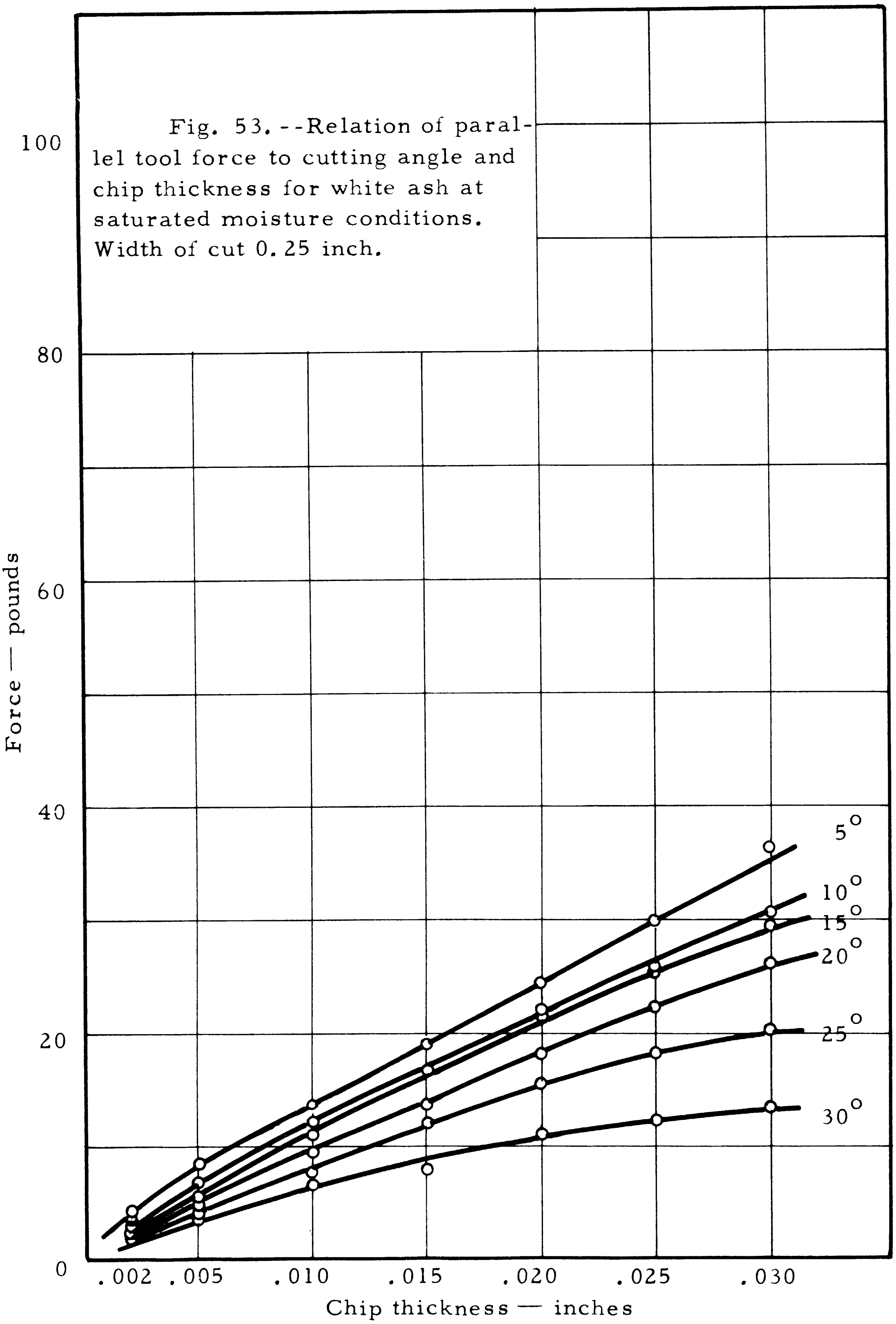


Fig. 53.--Relation of parallel tool force to cutting angle and chip thickness for white ash at saturated moisture conditions. Width of cut 0.25 inch.

Friction between Chip and Tool Face

Tool-force data obtained from experiments in which the roughness of the face of the tool was varied are presented in Table 13. It is apparent from the tabulated values that the magnitudes of the normal and parallel tool-force components are indistinctly influenced by changes in the character of the tool face.

As indicated in Figure 3, the tool-force components may be resolved into a force F acting along the face of the tool, and a force N acting normal to the interface of the chip and tool. Then, from the geometry of Figure 3, it can be shown that the apparent coefficient of friction between the chip and the face of the tool is determined by the equation

$$\mu = \frac{F}{N} = \tan\left(\arctan \frac{F_n}{F_p} + \alpha\right),$$

the terms of which have been defined previously in a discussion of cutting nomenclature.

Applying the above equation, tool-force data in Table 13 develop the respective coefficients of friction included in the tabulation. It will be noted that the frictional differences attributable to variation of the roughness of the tool face are relatively obscure. The apparent insignificance of roughness may be ascribed to the method of grinding the tool bits, which was dictated by design requirements. As indicated in Figure 15, the scratches left by the abrasive wheel on the tool face were developed in the direction parallel to movement of the chip. This would be expected to yield surfaces of relatively uniform roughness in the direction of chip flow, despite substantial differences in roughness perpendicular to the grinding marks. Thus, the topographic features of the face of a cutting tool appear to be significant only when considered with respect to the movement of the chip.

More effective data on friction are obtained from experiments considering the interactions of cutting geometry and wood properties. Calculations made from the force values listed in Tables 4 through 12 give data for the coefficient of friction that develop as exemplified in Table 14. The computed values prove to be independent of cutting geometry for a given species and moisture content, except at the smallest depths of cut where higher values may reflect forces exerted by the work piece immediately behind the cutting edge of the tool.

Table 15 summarizes the approximate order of magnitude of the coefficient of friction for each species and moisture content. It will be noted that the values for sugar pine differ appreciably from those of white ash and yellow birch. Further, the response to moisture change appears to vary between the three species. Sugar pine displays a marked increase in the coefficient of friction at saturated conditions, while that of yellow birch remains nearly constant, and that of white ash appears to decrease slightly. The observed variations would be expected to exert an influence on the cutting process by virtue of effects on the normal tool force. It follows from the values listed for sugar pine that the low coefficient of friction at 1.5 per cent moisture content would be attended by small forces directed toward the work piece, thus suggesting that Type I chip formation would be prevalent. Similarly, the large coefficient of friction at saturated moisture conditions would be expected to be accompanied by tendencies toward Type III chip formation. This is corroborated by experimental results, Figures 24 and 26.

The above findings imply that the frictional forces during machining are primarily a function of wood species and moisture content. However, it is plausible that additional influences on the coefficient of friction would have been noted if the scope of this research had permitted study of tool roughness in cases where grinding marks are other than parallel to the flow of the chip. Should this hold, then surface character-

TABLE 13

RELATION OF COEFFICIENT OF FRICTION AT INTERFACE OF TOOL AND CHIP TO ROUGHNESS OF THE TOOL FACE

(Sugar pine at 8.0 per cent moisture content; width of chip 0.25 inch; cutting velocity 3.5 inches per minute)

Chip Thickness Inches	Normal Tool Force Pounds	Parallel Tool Force Pounds	Chip Type	Coefficient of Friction
Tool-Face Roughness 5-6 Microinches*				
0.005	1.1	9.2	II	0.50
0.010	0.7	15.9	I	0.42
0.020	0.4	19.5	I	0.38
0.030	-0.5	23.0	I	0.34
Tool-Face Roughness 14-16 Microinches				
0.005	0.6	8.7	II	0.45
0.010	0.6	14.4	I	0.41
0.020	-0.4	18.0	I	0.34
0.030	-1.1	24.5	I	0.31
Tool-Face Roughness 25-28 Microinches				
0.005	1.1	9.6	II	0.50
0.010	0.7	15.0	I	0.41
0.020	-0.4	16.4	I	0.34
0.030	-0.9	22.0	I	0.32

*Root mean-square roughness measured perpendicular to grinding scratches which parallel flow of chip.

TABLE 14

CALCULATED COEFFICIENT OF FRICTION, μ, AT INTERFACE OF TOOL AND CHIP — SUGAR PINE, YELLOW BIRCH, AND WHITE ASH AT 8.0 PER CENT MOISTURE CONTENT

(Roughness of tool face 7-12 microinches RMS)

Chip Thickness	Cutting Angle					
	5°	10°	15°	20°	25°	30°
			Sugar Pine			
0.002	0.61	0.69	0.53	0.62	0.58	0.54
0.005	0.43	0.42	0.44	0.61	0.46	0.47
0.010	0.42	0.33	0.39	0.41	0.38	0.41
0.015	0.31	0.33	0.38	0.36	0.36	0.38
0.020	0.30	0.30	0.37	0.33	0.33	0.36
0.025	0.32	0.32	0.34	0.30	0.32	0.32
0.030	0.32	0.28	0.32	0.28	0.30	—
			Yellow Birch			
0.002	0.50	0.52	0.53	0.54	0.59	0.60
0.005	0.47	0.48	0.48	0.51	0.52	0.53
0.010	0.42	0.43	0.45	0.49	0.48	0.47
0.015	0.42	0.42	0.44	0.45	0.45	0.45
0.020	0.39	0.41	0.52	0.48	0.45	0.45
0.025	0.37	0.38	0.44	0.46	0.45	0.45
0.030	0.38	0.42	0.42	0.42	0.44	—
			White Ash			
0.002	0.54	0.55	0.61	0.62	0.67	0.62
0.005	0.50	0.56	0.53	0.53	0.55	0.56
0.010	0.46	0.49	0.51	0.52	0.52	0.53
0.015	0.46	0.49	0.51	0.52	0.51	0.51
0.020	0.43	0.47	0.49	0.52	0.51	0.50
0.025	0.42	0.47	0.49	0.51	0.50	0.49
0.030	0.39	0.46	0.50	0.51	0.43	—

TABLE 15

RELATION OF COEFFICIENT OF FRICTION BETWEEN CHIP AND TOOL TO WOOD SPECIES AND MOISTURE CONTENT

(Average value for 7-12 microinches RMS tool-face roughness)

Moisture Content	Species		
	Sugar Pine	Yellow Birch	White Ash
1.5 per cent	0.35	0.45	0.51
8.0 per cent	0.35	0.41	0.49
Saturated	0.69	0.48	0.42

istics of the tool face may be expected to bear upon the process of chip formation.

Influence of Cutting Velocity on Tool Forces

Investigation of the effects of cutting velocity on tool force components parallel and normal to the cutting path yielded the data summarized in Table 14. From the tabulated data it is seen that force values at all the velocities considered are in close agreement, indicating that attenuation by the tool dynamometer and strain-analyzing instruments is probably negligible. Incidental to this, the data also confirm preliminary experiments in which cutting velocity was concluded to have little or no effect on the machining process, since any change would be expected to be reflected in force determinations.

Repeatability

The results of experimentation to determine the degree of control present in the machining procedure used in this research are given in Table 17. It is indicated by the listed values of tool-force components, which were derived according to previously described procedure, that the control of variables was very precise. Statistical treatment is obviated by the inconsequential differences in the data.

It is noteworthy that the data are in almost exact agreement with results obtained in independent experiments on cutting velocity, Table 16, and the interaction of cutting geometry and wood properties, Table 5, in which sugar pine at 8% E. M. C. was similarly machined with a 15-degree cutting angle at a chip thickness of .010 inch. Tool-force data therefore appear to be highly consistent for a given combination of machining conditions.

TABLE 16

RELATION OF NORMAL AND PARALLEL TOOL-FORCE COMPONENTS TO CUTTING VELOCITY

(Sugar pine at 8.0 per cent moisture content; cutting angle 15°; chip thickness 0.010 inch; chip width 0.25 inch)

Run Number	Cutting Velocity In. /Min.	Normal Tool Force Pounds	Parallel Tool Force Pounds
1	3.5	2.00	19.00
2	0.8	2.00	19.12
3	7.5	2.05	19.25
4	24.5	2.05	19.00
5	1.7	2.05	18.82
6	14.5	2.00	18.82

TABLE 17

REPEATABILITY OF TOOL FORCE MEASUREMENTS

(Sugar pine at 8.0 per cent moisture content; cutting angle 15°; chip thickness 0.010 inch; chip width 0.25 inch; cutting velocity 3.5 inches per minute)

Run Number	Normal Tool Force Pounds	Parallel Tool Force Pounds
1	1.9	19.2
2	1.9	18.8
3	2.0	19.0
4	1.9	19.0
5	2.0	18.8
6	1.9	18.5
7	2.0	19.0
8	1.9	18.5
9	2.0	19.0
10	2.0	18.8

RESULTS AND ANALYSIS OF MECHANICAL-PROPERTIES TESTS

Test Data

The mechanical properties of sugar pine, yellow birch, and white ash specimens used in this study were determined at each of the three prescribed moisture conditions. Data obtained from the various tests are summarized in Table 18, which includes only those properties considered to be pertinent to an analysis of the cutting process. The identification of properties of most probable consequence was made from observations of the wood failure associated with each of the three basic types of chip formation.

The tabulated values for mechanical properties were determined by the standard procedures previously described, with the exception of those given for tension perpendicular to the grain. Recognizing the stress concentrations present in the standard specimen for tensile tests, it was felt that a value calculated from cleavage tests would reflect stress conditions more nearly comparable to those existing during machining. The tensile stress in cleavage was calculated by the familiar equation for eccentric loading (33),

$$S = \frac{P}{bh} \left(1 + \frac{6e}{h} \right), \qquad \text{in which}$$

P = the applied load, in pounds

b = the width of the section under stress, in inches

h = the length of the section under stress, in inches

e = eccentricity of applied load, in inches.

TABLE 18

SUMMARY OF MECHANICAL PROPERTIES DETERMINED FOR SUGAR PINE, YELLOW BIRCH, AND WHITE ASH AT VARIOUS MOISTURE CONTENTS

Moisture Content	Modulus of Rupture in Bending, psi	Modulus of Elasticity in Bending, psi	Crushing Strength Parallel to Grain, psi	Modulus of Elasticity Parallel to Grain, psi	Cleavage, Pounds per Inch of Width	Tensile Strength Perpendicular to Grain, psi*	Shear Strength Parallel to Grain, psi	Modulus of Elasticity in Compression Perpendicular to Grain, psi
Sugar Pine								
1.5 per cent	12,400	1,390	8,760	1,640	140	235	780	62,000
8.0 per cent	11,000	1,310	6,380	1,450	150	250	920	62,900
Saturated	5,300	940	2,360	1,330	140	240	530	27,400
Yellow Birch								
1.5 per cent	23,300	1,870	12,430	2,250	425	705	1,560	115,800
8.0 per cent	19,700	1,850	8,520	1,850	440	735	1,640	115,400
Saturated	6,900	1,080	2,310	1,420	290	485	710	32,000
White Ash								
1.5 per cent	16,400	1,290	9,910	1,580	460	760	1,980	134,400
8.0 per cent	14,100	1,270	6,500	1,300	600	1,000	1,900	127,200
Saturated	8,000	990	2,940	1,250	435	725	1,015	69,000

* Tensile strength computed from cleavage strength by equation for eccentric loading $S = \frac{P}{A} \pm \frac{Mc}{I}$ (33).

Significance of Mechanical Properties

As previously implied, it is logical to assume that the machining characteristics of a wood are directly influenced by the relationships of certain strength properties. Analytical observations of chip formation at the various combinations of species and moisture content, when considered with respect to the strength data presented in Table 18, indicate the validity of this premise. A few examples are cited below as evidence.

Machining experiments showed that formation of the Type I chip was most likely to occur at low moisture conditions, while the Type III formation was inclined to be prevalent at high moisture levels, Figures 24, 25, and 26. Examination of the data from mechanical tests on each of the wood species indicates that the ultimate strengths in all properties except cleavage and tension increase appreciably as moisture content is reduced. Further, it is evident that the values in compression parallel to the grain display the most marked gain as moisture content decreases. Recalling the nature of wood failures attending each chip type, it appears that the relative changes in the above properties offer a plausible explanation of the observed influences of moisture content on chip type.

Cutting experiments also show that white ash was exceptionally tolerant to cutting geometry in the production of a Type II chip, particularly at 8.0 per cent moisture content. A probable reason for the noted characteristic is found in the mechanical properties of the species, which display very large relative values in cleavage, tension, and shear.

Sugar pine is found to be the species most prone to formation of the Type I chip. This is notably evident at 1.5 per cent moisture content. From a comparison of the mechanical properties of the three species considered, the tendency toward Type I chip formation is attributable to the disproportionately low strength of sugar pine in cleavage and tension perpendicular to the grain.

The above examples, which may be corroborated by further comparison of machining data with mechanical properties, indicate that ultimate strength values not only govern the relative ease with which a given wood can be machined, but also determine the type of chip formation, and hence, surface quality, that is obtained with a given set of machining conditions. Thus, it is suggested that the cutting process is theoretically determinable from an appropriate analysis of the controlling interactions of cutting geometry and wood mechanical properties.

DISCUSSION OF THE MECHANICS OF CHIP FORMATION

Application of Merchant's Analysis of Metal-Cutting

The foregoing results and analyses of experimental data indicate that orthogonal cutting parallel to the grain of wood displays certain characteristics similar to those observed in metal-cutting (16, 21, 26). However, the anisotropic nature of wood imparts distinctive qualities to the cutting process. Thus, it would be expected that treatment of the mechanics of chip formation in a manner analogous to that developed for metals would be seriously limited by marked differences in physical and mechanical properties.

The respective cutting processes appear to be most comparable when the continuous chip is formed on metals (16), and the Type II chip is produced on wood. It follows that under these circumstances, equations developed for the mechanics of chip formation in metal-cutting may offer an analysis applicable to wood.

In his analysis of the metal-cutting process, Merchant (18, 23) developed a force system for orthogonal cutting which appears to be physically consistent with results obtained in machining experiments. The relationships of Merchant's analysis are illustrated in Figure 54, in which appropriate substitutions in terminology have been made.

With formation of the continuous metal chip, it may be determined from the figure that the coefficient of friction between the chip and the tool face is represented by the equation

$$\mu = \tan \lambda = \frac{F}{N} .$$

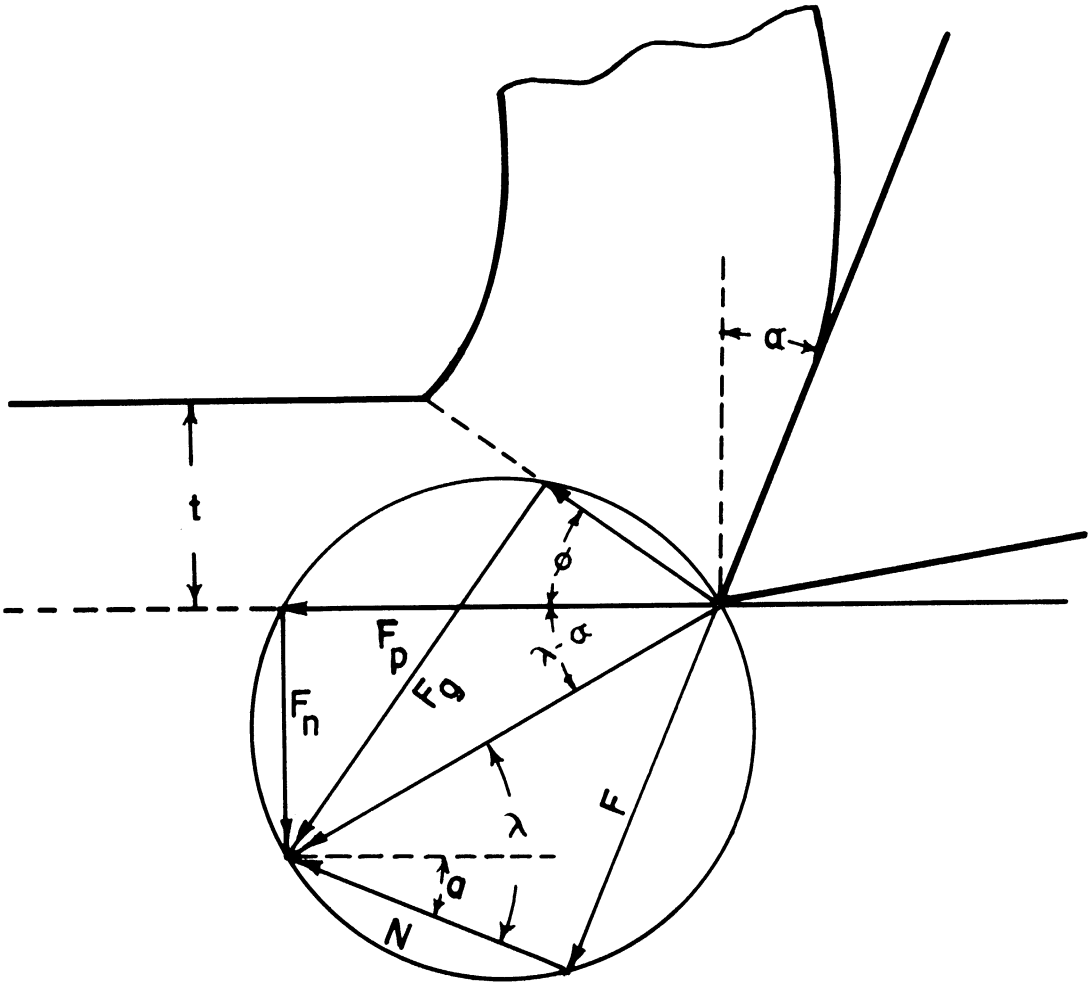


Fig. 54.--Force system developed by Merchant for analysis of chip formation in metal cutting (17). Symbols described in text.

A shear plane extending from the cutting edge to the work surface is identified for the continuous chip in metal-cutting (16, 18). Ernst and Merchant (21) show that the angle φ which this plane makes with the tool path is expressed as

$$\varphi = 45^{\circ} - \frac{\lambda}{2} + \frac{a}{2}\,.$$

Referring to Figure 54, the force F_s' along the shear plane for a chip of unit width is then determined as

$$F_s' = \frac{t}{\sin \varphi} \text{ x shear strength of material.}$$

From the geometry of the figure, Merchant expresses the parallel tool-force component per unit of chip width in terms of the shear strength of the material, and

$$F_p = \frac{F_s' \cos(\lambda - a)}{\cos(\varphi + \lambda - a)}\,.$$

It follows that the normal force per unit of width is then

$$F_n = F_p \tan(\lambda - a).$$

In attempting to apply the above equations to an anisotropic material, it is at once apparent that the analysis is frustrated by the behavior of wood under shear loads at an angle to the grain. Characteristically, failures will develop first in a manner other than shear in the plane of greatest shear stress. On occasion, however, a type of shear failure at an angle of approximately 45 degrees is evident when wood is subjected to compressive loads parallel to the grain. Assuming that the ultimate strength in compression measures failure by induced shear in such cases, it can be shown that

diagonal shear strength = 0.5 x compressive strength (33).

Mechanical properties tests showed that white ash at 8.0 per cent moisture content failed by diagonal shear in a plane intersecting the grain at an angle of approximately 45 degrees when stressed in compression parallel to the grain. Thus, a shear value for the wood may be determined by substitution in the above equation. From Table 15 it is noted that the coefficient of friction between the chip and the tool is approximately 0.49 for white ash at 8.0 per cent moisture content. Considering a cutting angle of 20 degrees, and a depth of cut of 0.020 inch, which were seen to produce a Type II chip, Figure 25, the applicability of Merchant's analysis may be examined. Substituting,

$$\lambda = \text{arc tan } 0.49 = 26^\circ$$

$$\phi = 45^\circ - \frac{26^\circ}{2} + \frac{20^\circ}{2} = 42^\circ.$$

In Table 18, the strength of white ash in compression parallel to the grain at 8.0 per cent moisture content is listed as 6,500 pounds per square inch. Then

$$\text{diagonal shear strength} = 0.5 \times 6{,}500 = 3{,}250 \text{ psi},$$

which may be assumed to hold for shear planes approximating an angle of 45 degrees to the grain. Considering the ultimate strength of wood to be comparable to the yield stress in metals, and substituting,

$$F_s' = \frac{0.020}{\sin 42^\circ} \times 3{,}250 = 97.0 \text{ pounds},$$

from which

$$F_p = \frac{97.0 \times \cos (26^\circ - 20^\circ}{\cos (42^\circ + 26^\circ - 20^\circ)} = 143.8 \text{ pounds},$$

and

$$F_n = 143.8 \times \tan (26^\circ - 20^\circ) = 15.1 \text{ pounds},$$

for a chip one inch in width.

Experimental data recorded for the above machining conditions, Table 11, lists the normal and parallel tool-force components as 5.2 and

39.0 pounds, respectively, for a chip width of 0.25 inch. For unit width, the normal tool force becomes 20.8 pounds, and the parallel tool force 156.0 pounds.

Similar calculations for a cutting angle of 30 degrees and a depth of cut of 0.020 inch, which were observed to produce the Type I chip, yield values of -8.7 and 124.0 pounds for the normal and parallel tool-force components, respectively. These forces compare with experimentally determined values of -7.2 and 117.2 pounds per inch of chip width.

The Type III chip was formed in machining experiments on white ash at 8.0 per cent moisture content when a 5 degree cutting angle was used at 0.020-inch depth of cut. For these conditions, calculations by Merchant's analysis determine the normal tool force to be 71.1 pounds, and the parallel tool force to be 187.0 pounds. Respective experimental values prove to be 69.2 and 206.0 pounds.

The above examples indicate that applications of metal-cutting methods of analysis give results which in order of magnitude are reasonably consistent with experimental data for the cases considered. However, random checks against other experimental data show marked deviations. This is exemplified by calculations for sugar pine at 8.0 per cent moisture content. Computed values for the normal and parallel tool-force components develop as -22.1 and 104.0 pounds, respectively, while experimental data show pertinent forces to be -6.8 and 37.2 pounds. Thus, metal-cutting analytical treatments are clearly limited in application to wood.

A possible explanation of the differing results obtained with white ash and sugar pine is offered by observations of the failures displayed by each in compression tests parallel to the grain. White ash was observed to fail in diagonal shear at loads below those considered average for the species (31). In contrast, sugar pine failed in direct compression. Thus, it appears that failure by induced shear, which is common to many metals, may cause white ash to display some of the characteristics of isotropic materials when machined.

Merchant's analysis of the cutting process does not suggest the reasons for the development of distinct types of chip formation. Further, the analysis of the mechanics of chip formation is clearly limited in application to wood. It follows then, that an analysis is required which is unique to anisotropic materials and which incorporates factors acting to control chip formation.

Development of Analysis for Wood-Cutting

It has been shown that the analytical methods commonly used in studies of metal-cutting are restricted in their application to the machining of wood. This is largely in response to the marked differences between the properties of the two materials, which in wood apparently make critical several factors justifiably considered negligible in metals.

Merchant's treatment of force relationships in orthogonal cutting of metals considers the chip to be an independent body held in mechanical equilibrium by the action of two equal and opposite resultant forces R and R', as indicated in Figure 3. It is assumed that the resultant force exerted on the chip by the tool has a line of action identical with the reaction force in the work piece, and that the effects of a couple arising from non-colinearity are negligible in force analyses.

Since it is recognized that the resultant forces under consideration are not likely to be exactly colinear, it is plausible that the magnitude of the couple may be sufficient to influence the wood-cutting process. This premise, when contemplated with the anisotropic nature of wood, acknowledges the inapplicability of metal-cutting theories. It follows that a theoretical analysis of the mechanics of chip formation in wood-cutting should place force couples under circumspection.

Due to the anisotropic nature of wood, and the extremely complex stress distributions on the chip, an exact theoretical stress analysis is virtually impossible. An accurate solution of the problem appears obtainable only through extensive experimental study of stress distributions by means of photoelastic techniques. However, an approximate solution can be developed which appears to be in reasonable agreement with the results of machining experiments.

Considering the undeformed chip to be a body held in mechanical equilibrium at the instant before wood failure is caused by motion of the tool, the force relationships may be approximated as in Figure 55. The tool face, advancing along the cutting path relative to the work piece, exerts the force R on the chip. This resultant force R may be resolved into a horizontal component F_p parallel to the tool path, and a vertical component F_n normal to the tool path. The force component F_p is resisted by a force F_c which applies compressive stresses on the cross section of the chip, and by a force F_s which acts in shear on the lower surface of the chip. Then it follows that

$$F_p = F_c + F_s, \qquad \text{(Equation 1)}$$

and the direct compressive stress on the chip, S_c, is

$$S_c = \frac{F_c}{wt}, \qquad \text{(Equation 2)}$$

where w and t are the width and thickness of the chip, respectively.

The net effect of the shearing force F_s is to relieve the compressive stresses on the chip body. Applying Saint Venant's principle (34), the shear restraint may be considered as a force distribution

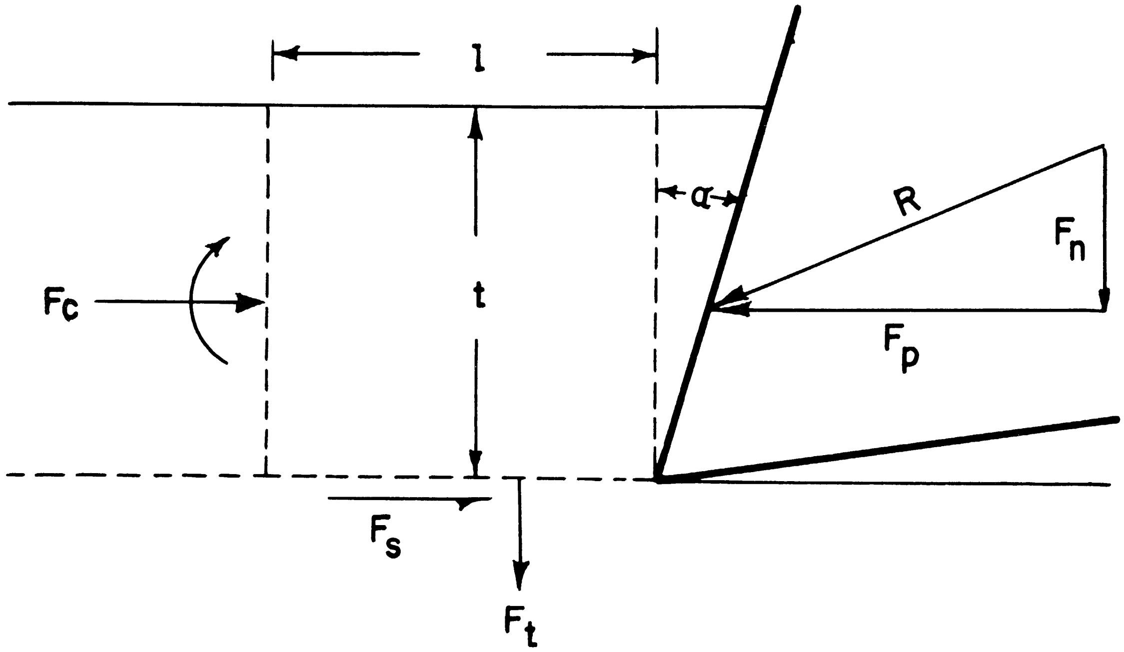


Fig. 55.--Force system developed for analysis of the wood-cutting process. See text for explanation.

which decreases uniformly from a maximum value at the tool edge to zero in a distance equal to the chip thickness. Thus, in Figure 55, the distance l is equal to t. . The eccentricity of the shear plane with respect to the centroid of the chip cross section imparts moments to the associated forces, which may be resolved into a single value with a moment of M_s, or

$$M_s = F_s \times \frac{t}{2}, \qquad \text{(Equation 3)}$$

in which F_s represents the sum of the shearing forces on an area w·t. From the disposition of shearing forces it is noted that the average stress calculated from the equivalent shearing force F_s is only two-thirds of the value for the maximum of the distributed unit stress. It may be reasoned then, that the maximum shear stress which is developed, S_s, is determined by the equation

$$S_s = \frac{3F_s}{2wt}. \qquad \text{(Equation 4)}$$

The normal tool force F_n, acting along the chip surface in contact with the tool face, creates a moment which tends to bend the chip. Since the force F_n is distributed over the area w·t, and ranges from a maximum value at the interface of the chip and the tool to zero at the distance t ahead of the cutting edge (34), the magnitude of the attending moment M_n may be represented as

$$M_n = F_n \times \frac{2t}{3} \left(1 + \frac{\tan \alpha}{2}\right) \qquad \text{(Equation 5)}$$

when the inclination of the tool face is taken into consideration. It should be noted that the direction of rotation of this moment is dependent on the sense of the normal tool force, which is not necessarily positive, or toward the work piece.

In order to maintain equilibrium in the undeformed chip, the net effect of the moments due to shear and the normal tool force must be counteracted by an equivalent moment originating in the work piece. The resisting moment may be considered to develop from bending of the chip as a cantilever beam, and from tension forces distributed along the lower plane of the chip body.

The magnitude of the tensile stresses on the plane projected ahead of the cutting edge may be expected to be a function of deflection of the chip in bending. However, the deflection curve of the body under consideration can be treated as a straight line without serious error, and the moments of the distributed forces resolved into an equivalent moment M_t. Then

$$M_t = F_t \times \frac{2t}{3} , \qquad \text{(Equation 6)}$$

where F_t is the total tensile force on the area w$\cdot$t. Assuming that the stresses are in proportion to the deflection of the chip, a moment diagram shows that the maximum unit stress in tension at the tool edge, S_t, is represented by the equation

$$S_t = \frac{3F_t}{2wt} . \qquad \text{(Equation 7)}$$

It is evident that the sum of the moments in equations 3, 5, and 6 will represent the net moment acting on the chip body. If the sense of rotation of the moment is away from the work piece at the tool edge, bending of the chip causes compressive stresses parallel to the tool path above the neutral axis of the chip and tensile stresses below. These stresses must then be considered with the direct compressive stress arising from the parallel tool-force component. Then the maximum stress in the chip due to axial and bending forces can be determined from the familiar equation (33)

$$S = \frac{P}{A} \pm \frac{Mc}{I} , \qquad \text{(Equation 8)}$$

where the positive sign represents compression, the negative sign tension, and

S = stress at the extreme fiber, psi.
P = direct axial force, lbs.
A = cross-sectional area under stress, in.^{2}
M = bending moment, lb.-in.
c = distance from neutral axis to extreme fiber, in.
I = rectangular moment of inertia of cross-sectional area, in.^{4}

Substituting from equations 2, 3, 5, and 6, and simplifying, equation 8 becomes

$$S_m = \frac{F_c}{wt} \pm \frac{3F_s - 4F_n\left(1 + \frac{\tan \alpha}{2}\right) - 4F_t}{wt}, \text{ (Equation 9)}$$

where S_m is the maximum compressive stress in the chip body and the other symbols are as defined previously.

The significance of stresses at the locations in the chip considered above is indicated by observational studies of chip formation which show that characteristic failures in the wood ahead of the tool were associated with each chip type. In the Type I chip, splitting ahead of the tool indicated that cleavage or tension stresses perpendicular to the grain were critical. When the Type II chip was formed, a diagonal failure extending from the cutting edge indicated that limiting stresses were reached in compression, and perhaps also in shear, at an angle to the wood grain. The Type III chip was characterized by failure in compression parallel to the grain or, when the built-up edge was present by localized compression failures in the lower portion of the chip body.

Application of Mathematical Analysis to Experimental Data

As noted above, a correlation of experimental data and the preceding mathematical analysis indicates that chip type is determined by wood failure in one of several critical properties. Thus, the Type I chip is expected to develop when the tensile stress perpendicular to the grain of the wood at the tool edge exceeds the ultimate strength of the material in this property, while stresses elsewhere in the chip remain below critical values. Referring to equations 2 and 9, S_c must be less than the limiting value for the material under consideration, while the stress S_t in equation 7 must be in excess of the maximum allowable amount.

The Type II chip, which is formed by seemingly continuous failure of the wood on a line extending to the work surface from the tool edge, is apparently the result of compression failures which develop at the upper surface of the chip and migrate toward the cutting edge by shifting of the neutral axis of the chip. Evidence of a cyclical force behavior which may be expected to accompany this phenomenon is seen in force patterns associated with the Type II chip, Figure 35. It will be noted that although force levels during cutting are essentially stable, a small cyclical variation is evident in the figure. Thus, during Type II chip formation the upper surface of the chip apparently is stressed beyond the ultimate strength of the wood in compression parallel to the grain, while stress in the lower portion of the undeformed chip is below the critical stress and the tensile stress perpendicular to the grain at the cutting edge is also less than the critical limit.

Formation of the Type III chip obtains when the tensile stresses perpendicular to the grain of the wood at the tool edge are less than the critical value, and the entire cross section of the chip is stressed beyond the ultimate strength in compression. Further, it is plausible that the bending moment in the chip may be directed toward the work piece when large positive normal tool forces are present, causing the chip to be stressed somewhat more in compression at the lower portions than at the upper surface. This then, would appear to favor the development of the built-up edge.

The above attempt to correlate chip formation with the force and stress system which has been developed appears to be consistent with experimental data from orthogonal cutting. This is evidenced by the illustrative examples which follow.

Example for Type I chip formation. From experimental data, Table 3, it is seen that white ash at 8.0 per cent moisture content produces a Type I chip when a 0.020-inch depth of cut is taken by a tool with a 30-degree cutting angle. It may then be expected that compression and shear stresses in the chip do not exceed critical values, while the tensile stress perpendicular to the grain is in excess of the limit for the wood. Therefore, if the ultimate strength values of the wood in shear and compression are substituted in equation 9, the calculated stress in tension should be in excess of the allowable limit if a Type I chip is to be formed.

From the mechanical-properties tests summarized in Table 18, it is found that at 8.0 per cent moisture content white ash parallel to the grain has a shear strength of 1,900 pounds per square inch, and a compressive strength of 6,500 pounds per square inch. Tool force experiments, Table 11, show that when removing a chip 0.020 inch thick and 0.25 inch wide with a 30-degree cutting angle, the normal tool force is -1.8 pounds and the parallel tool force is 29.3 pounds. Employing equation 4,

$$F_s = \frac{2S_s (w \cdot t)}{3} ,$$

and substituting,

$$F_s = \frac{2 \times 1,897 \times 0.25 \times 0.020}{3}$$

$$F_s = 6.4 \text{ pounds},$$

Then from equation 1, it may be shown that

$$F_c = 29.3 - 6.4$$

$$F_c = 22.9 \text{ pounds}$$

Substitution in equation 9 gives

$$6,500 = \frac{22.9 + 3(6.4) - 4(-1.8 \times 1.3) - 4F_t}{0.020 \times 0.25}$$

from which

$$F_t = 4.7 \text{ pounds.}$$

Then, from equation 7,

$$S_t = \frac{3 \times 4.7}{2 \times 0.005}$$

$$S_t = 1,400 \text{ pounds per square inch.}$$

It will be noted that the value of S_t exceeds the allowable stress of 1,000 pounds per square inch given in Table 18. Thus it is expected that the chip would be of Type I, where tension failure perpendicular to the grain is the critical factor. This agrees with the previously noted experimental finding.

<u>Example for Type II chip formation.</u> Experimental data, Table 11, show that normal and parallel tool-force components are 1.2 and 37.5 pounds, respectively, when a chip 0.020 inch thick and 0.25 inch wide is removed from white ash at 8.0 per cent moisture content, if the cutting angle is 25 degrees. Since Table 3 indicates that a Type II chip is formed under the above conditions, the compression stresses at the upper surface of the chip should exceed the limiting value of 6,500 pounds per square inch before stresses at the lower edge

reach respective critical limits in compression and in tension.

From equations 1 and 4, it can be determined that

$$F_s = 6.4 \text{ pounds},$$

and

$$F_c = 31.1 \text{ pounds}.$$

Substituting in equation 9,

$$6,500 = \frac{31.1 + 3(6.4) - 4(1.2 \times 1.2) - 4F_t}{0.020 \times 0.25}$$

Solving for the unknown,

$$F_t = 3.0 \text{ pounds},$$

and from equation 7,

$$S_t = \frac{3 \times 3.0}{2 \times 0.005}$$

$$S_t = 900 \text{ pounds per square inch}.$$

Since the stress in tension is below the allowable value of 1,000 pounds per square inch, failure in compression at the top of the chip is expected to develop Type II chip formation. This conclusion is substantiated by the experimental data already cited.

Example for Type III chip formation. When white ash is machined at the conditions specified for the preceding examples, and a cutting angle of 10 degrees is introduced, the normal and parallel tool-force components in Table 11 are found to be 12.8 and 47.5 pounds, respectively. Since a Type III chip forms, Table 3, it is expected that forces on the chip cause failure in compression over the entire cross section. and that stresses in tension perpendicular to the grain are small.

Solving equations 1 and 4 as in the previous examples,

$$F_s = 6.4 \text{ pounds},$$

and

$$F_c = 41.1 \text{ pounds.}$$

Then, by substitution in equation 9,

$$6{,}500 = \frac{41.1 + 3(6.4) - 4(12.8 \times 1.1) - 4F_t}{0.020 \times 0.25},$$

from which

$$F_t = -7.0 \text{ pounds,}$$

and, from equation 7,

$$S_t = \frac{3 \times -7.0}{2 \times 0.005}$$

$$S_t = -2{,}100 \text{ pounds per square inch.}$$

It will be noted that the negative value of S_t indicates that it is stress in compression perpendicular to the grain rather than tension. Thus it may be concluded that the Type III chip is formed, and that a built-up edge is probably present during machining. Experimental data in Figure 25 and Table 3 provide corroborating evidence.

Similar analyses of the three basic types of chip formation were made at random for the remaining combinations of wood species and moisture content. In each instance, the mathematical analysis proved to be consistent with the results of cutting experiments.

Determination of Chip Type by Adjustment of Cutting Geometry

In the wood-using industries, the quality of the generated surface is an important consideration in most machining operations. It has been shown in this research that the characteristics of a machined surface are dependent on the type of chip formation attending the cutting process. Further, the chip type was determined to be a function of force relationships governed by interactions of cutting geometry and wood properties. Therefore, since alteration of wood properties usually is not practicable, it follows that appropriate adjustments in cutting geometry offer a plausible means of determining surface quality through control of chip type.

It has been shown in an analysis of the mechanics of chip formation that the stress system during cutting is approximated by equation 9. Substituting from equations 2, 4, and 7, equation 9 may be written as

$$S_m = S_c \pm \left[2S_s - \frac{4F_n(1 + \frac{\tan \alpha}{2})}{w \cdot t} - \frac{8S_t}{3} \right] \qquad \text{(Equation 10)}$$

For a given work piece, the stress values in the equation may be expected to be related to the physical properties of the wood. Hence, it appears that the tool forces, and therefore the cutting geometry, required to produce a given chip type may be calculated from the equation.

Type II chip formation, which is of major importance since it generates a superior surface, has been suggested to be the result of compression failures initiating at the upper surface of the chip. Then, in equation 10, if the value of S_c is less than S_m, and the stress in tension due to a positive bending moment is below the critical limit, conditions will approximate those necessary for Type II chip formation. Assigning a positive value C to the bending moment in equation 10, then for a chip of unit width,

$$2S_s - \frac{4F_n(1 + \frac{\tan \alpha}{2})}{t} - \frac{8S_t}{3} = C, \qquad \text{(Equation 11)}$$

from which

$$F_n = \frac{t\,(2S_s - \frac{8S_t}{3} - C)}{4\,(1 + \frac{\tan \alpha}{2})} . \qquad \text{(Equation 12)}$$

Equation 12 includes an expression containing α, which must be eliminated. Examination shows that for the range of cutting angles considered, an approximate value for α introduces a negligible error. On the basis of experimental observations, α may be assumed to be in the order of 15 degrees.

It has been shown that the coefficient of friction, μ, between the tool face and the chip can be expressed as

$$\mu = \tan\left(\arctan\frac{F_n}{F_p} + \alpha\right) . \qquad \text{(Equation 13)}$$

Then it follows that

$$\alpha = \arctan\mu - \arctan\frac{F_n}{F_p} , \qquad \text{(Equation 14)}$$

From equations 1, 2, and 4, F_p for a chip of unit width is

$$F_p = t\left(S_c + \frac{2S_s}{3}\right) . \qquad \text{(Equation 15)}$$

Making appropriate substitutions in equation 14, and simplifying,

$$\alpha = \arctan\mu - \arctan\frac{2S_s - \frac{8S_t}{3} - C}{4\left(1 + \frac{\tan\alpha}{2}\right)\left(S_c + \frac{2S_s}{3}\right)} . \qquad \text{(Eq. 16)}$$

Equation 16 appears to be an expression in which the cutting angle required for Type II chip formation is determined without use of chip dimensions. Thus, it is implied that there is a cutting angle with which the Type II chip can be formed at any depth of cut. However, this may prove erroneous, since chip thickness is expected to exert some influence in the calculation of stress values in the equation. Since several unknowns appear in equation 16, only an approximate solution is available.

Using white ash at 8.0 per cent moisture content as an illustrative example, the order of magnitude for the cutting angle may be estimated by making several assumptions. For Type II chip formation, the values of S_m and S_c may be taken to be similar, and equal to the ultimate compressive strength of 6,500 pounds per square inch, Table 18. Then, the stress due to bending is a small value approximating zero, giving C and S_t an insignificant value. From examination of the cutting process, it appears that S_s approaches the ultimate shear strength of the wood, or 1,900 pounds per square inch. The coefficient of friction between the chip and the tool is approximately 0.49, Table 15; thus equation 16 becomes

$$\alpha = \text{arc tan } 0.49 - \text{arc tan } \frac{2 \times 1{,}900}{4(1 + \frac{\tan\alpha}{2})(6{,}500 + \frac{2 \times 1{,}900}{3})}$$

and

$$\alpha = 26^{\circ} - 6^{\circ} = 20^{\circ}$$

It will be noted that this value is a good approximation of the optimum cutting angle as indicated by experimental data, Table 3.

The above method for estimating the cutting angle required for Type II chip formation may be applied to sugar pine, yellow birch, and white ash at the three moisture contents considered in this study. The calculated cutting angles, Table 19, show close correlation with the optimum values suggested by the experimental data in Tables 1, 2, and 3.

TABLE 19

CALCULATED CUTTING ANGLES REQUIRED FOR FORMATION OF THE TYPE II CHIP ON SUGAR PINE, YELLOW BIRCH, AND WHITE ASH AT VARIOUS MOISTURE CONTENTS

(Derived by substitution of data from Tables 14 and 18 in equation 16)

Moisture Content	Species		
	Sugar Pine	Yellow Birch	White Ash
1.5 per cent	17°	20°	22°
8.0 per cent	14°	17°	20°
Saturated	28°	20°	16°

SUMMARY AND CONCLUSIONS

Summary

The foregoing study was stimulated by the pressing need for fundamental information regarding wood machining on which applied research and development can be founded. Because of the paucity of information in this field, the scope of a comprehensive investigation was deemed far too broad for consideration. The study, therefore, was limited to selected conditions of cutting offering the greatest promise of contribution to knowledge which may be expanded in future research.

The purpose of the research was to determine key phenomena associated with the wood-cutting process, and to investigate the controlling factors and relationships. Orthogonal cutting parallel to the grain was selected as the method of machining which would yield the most useful information. The objective was attained by observational studies of the chip during formation, and by simultaneous determination of attending forces on the cutting tool, together with a determination of the mechanical properties of the material being machined. Principal variables included species, moisture content, cutting angle, and chip thickness. In more limited phases of the research, cutting velocity, friction at the interface of the chip and the tool, and grain deviation were taken into consideration.

Observational studies of the cutting process identified three basic types of chip formation, each attended by characteristic failures in the wood ahead of the cutting tool. The Type I chip, Figure 21, was formed when the wood appeared to fail intermittently in cleavage. Type II developed by essentially continuous failure in a plane extending from the tool edge to the work surface, Figure 22. In the Type III chip, wood failure appeared to be in compression and shear, which is some instances caused development of a built-up edge on the cutting tool, Figures 23 and 34.

Each of the types of chip formation generated a characteristic surface which reflected the nature of associated wood failures. Further, the instantaneous tool forces attending each chip type displayed specific patterns of development which correlated with failures in the wood.

Chip formation proved to be dependent on interactions of wood properties and cutting geometry, but independent of cutting velocity. Wood mechanical properties exerted control of the cutting process by defining the type of wood failure resulting from a given force system applied by the cutting tool. Both wood species and moisture content were observed to influence the cutting process through attending differences in the relationships of mechanical properties.

Cutting geometry exhibited control of chip formation through the forces exerted on a given work piece. Cutting angle of the tool and undeformed chip thickness were found to have marked effects on tool-force values which, with attending wood properties, determined the nature of failures in advance of the tool.

The coefficient of friction between the chip and the face of the tool was indicated to be an important machining factor, the value of which proved to be a function of wood species and moisture content. Roughness of the tool face appeared to have an inconsequential effect on friction when grinding marks paralleled the motion of the chip.

Analysis of the mechanics of chip formation by methods established for metals appears to be limited. However, a suitable analysis for wood was derived which appeared to be consistent with the results of cutting experiments. An equation was suggested which determines chip formation, hence surface quality and machining efficiency, as a function of friction, cutting geometry, and wood mechanical properties.

Although limited in scope, it is felt that the information developed in this study is basic to the knowledge of machining wood with conventional tools and thus provides a base for research leading to a better understanding of this important phase of wood processing. Needed now are subsequent studies substantiating this information for broader conditions of tool geometry and wood properties. Ultimately, the theories which develop must be applied to rotary cutting under production conditions.

Conclusions

The findings of the research summarized above suggest a number of conclusions regarding the machining of wood parallel to the grain. These are as follows:

(1) The wood-cutting process is characterized by three basic types of chip formation.

(2) Chip type is determined by the nature of failures in the wood ahead of the cutting tool.

(3) The surface generated during machining is a function of the wood failure ahead of the tool. Hence, chip formation determines surface quality.

(4) Instantaneous tool forces develop in accordance with chip type. Thus, the work required for removal of a given amount of material is a function of the type of chip formation.

(5) Chip formation is independent of cutting velocity, except at near-static conditions. This conclusion is diametrically opposed to current opinion in woodworking practice.

(6) The process of chip formation is a function of wood properties and cutting geometry.

(7) Wood properties control chip formation by defining the failure in the chip under a given force system. Both wood species and moisture content influence the cutting process by virtue of effects on the relationships of critical mechanical properties.

(8) Cutting angle and depth of cut influence chip formation on a given work piece by establishing the force system exerted on the chip by the tool.

(9) The coefficient of friction at the interface of the chip and the tool is important to chip formation, since it affects force distributions. The friction forces are a function of species and moisture content, but show little response to roughness of the tool face when grinding marks parallel the flow of the chip. The value of the coefficient of friction appears to be relatively independent of cutting angle and chip thickness.

(10) The anisotropic nature of wood limits the applicability of analytical treatments developed for the mechanics of chip formation in metals. However, an approximate analysis developed for wood appears to be reasonably consistent with the results of cutting experiments.

(11) Wood properties determined from standard static tests appear applicable in an analysis of the cutting process. Apparently, the properties involved show approximately similar response to changes in rates of strain.

(12) The wood mechanical properties which appear to have the most significant effect on chip formation parallel to the grain are: compression parallel to the grain, shear parallel to the grain, and tension or cleavage perpendicular to the grain.

(13) The cutting geometry necessary to produce a specific type of chip formation may be estimated from wood properties and the coefficient of friction between the chip and the tool.

(14) For a given combination of wood properties, there appears to be a cutting angle which is optimum for the generation of superior surface characteristics. This angle can be estimated from statistically determined mechanical properties of the wood and the coefficient of friction between the chip and the tool.

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