"DYNAMIC CHIP BREAKING" - AN EVALUATION OF THE EFFECTS UPON SURFACE MICROGEOMETRY AND FREE CHIP DIMENSION

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PREFACE

Dynamic chip breaking is a process of conveniently breaking long continuous chips into shorter fragments when they are machined from ductile metals. The major emphasis in metal cutting research and development has been greater metal removal per unit time. While these efforts have been tremendously successful the chip has been getting thicker, sharper, longer, and hotter in leaving the work-piece, and has become a serious nuisance to metal cutting technology, a hazard to the health of the operator, and a general deterrent to disposal methods particularly when automated equipment is used. The objective of this research is to analyze the consequences of the process, coined here for the first time as "dynamic chip breaking," upon the surface and chip.

Fortunately my interest in this area of engineering research found a community of interest at Oklahoma State University. Without the generous financial support of the American Society of Tool and Manufacturing Engineers this labor would have been much more difficult. The General Electric Company with its representative, Mr. E. M. Lesch, kindly supplied cutting tools that were extremely useful. The National Science Foundation provided the

means for surface examination via the use of a special light section microscope.

It is difficult to measure my gratitude to the members of my advisory committee who through their counsel and encouragement provided impetus to my graduate work and dissertation. The leadership of Wilson J. Bentley, Head of the School of Industrial Engineering and Management has been an inspiration. His guidance at the time he was a busy President of the American Institute of Industrial Engineers is sincerely appreciated. Gratitude is also acknowledged to Dr. James E. Shamblin, Director of this research for his pleasant advice; Dr. Paul E. Torgersen who provided leadership in my graduate program; Dr. David L. Weeks for his wise counsel on the statistical portions of the research and to Dr. Joseph R. Norton who was helpful in so many ways.

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NOMENCLATURE

English Symbols

A = Amplitude of vibration, inch

A^* = Intersection-amplitude of vibration, inch

C = Constant

C_e = End cutting clearance angle, degrees

C_s = Side cutting clearance angle, degrees

d = Depth of cut, inch

D = Workpiece diameter, inch

f = Tool frequency, cycles per second

F = Feed displacement, inch

F = Feed velocity, inches per revolution

h = Height of measured roughness, inch

H = Height of theoretical roughness, inch

i = Tool pass location

K = Natural number

L = Length of chip, inch

N = Workpiece rotation velocity, revolutions per second

r = Cutter radius, inch

R_W = Roughness width, inch

t = Time, seconds

V_c = Cutting speed, feet per minute

NOMENCLATURE (Continued)

V_t = Tool speed, inch per second

x = Direction coordinate

y = Direction coordinate

z = Direction coordinate

<u>Greek Symbols</u>

α = Tool rake angle

β = Tool geometry value

γ = Included angle of tool

δ = Vectorial sum of V_c, V_t

λ = Scaler

σ = Oscillation angle

χ = Lagrange constraint

φ = Phase shift, radians

ω = Angular velocity

θ = Included angle

CHAPTER I

THE CHOICE AND STATEMENT OF THE RESEARCH PROBLEM

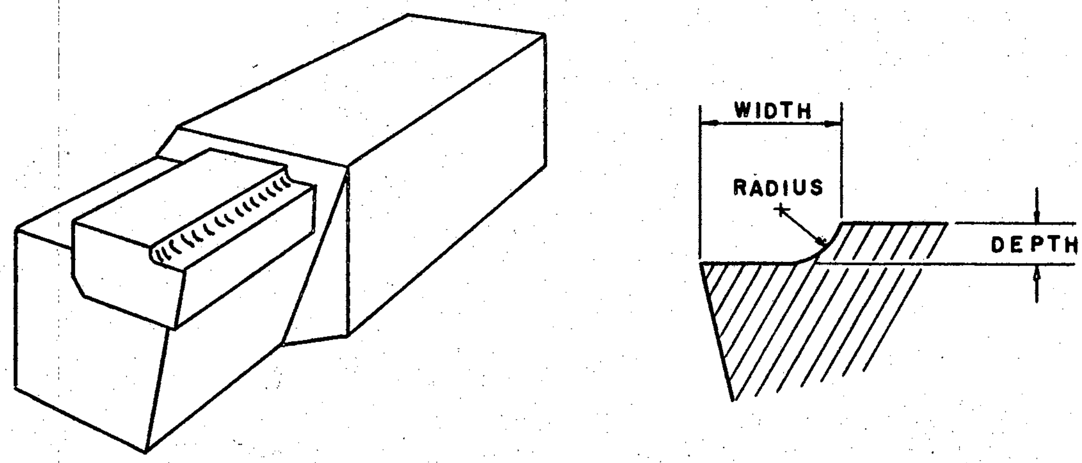
Within the United States metal working is one of the largest sectors of commerce important to national progress and the well-being of its citizenry. For the some two million machine tools in operation it is estimated that an annual cost of 34 billion dollars is required for wages and overhead. The introduction of automation within the last two decades has increased the effectiveness of metal working to a higher level, but this progress is not without its liability.

With greater metal removal rates possible, more metal trailings are produced now than ever before. Despite this broad progress in the metal cutting business one of the important elements in the productivity of the basic machine tool has been overlooked. The component which is fixed to the cutting tool to break the chip has not seen any serious development in the last thirty years. This failure to recognize a need provides the objective for this research.

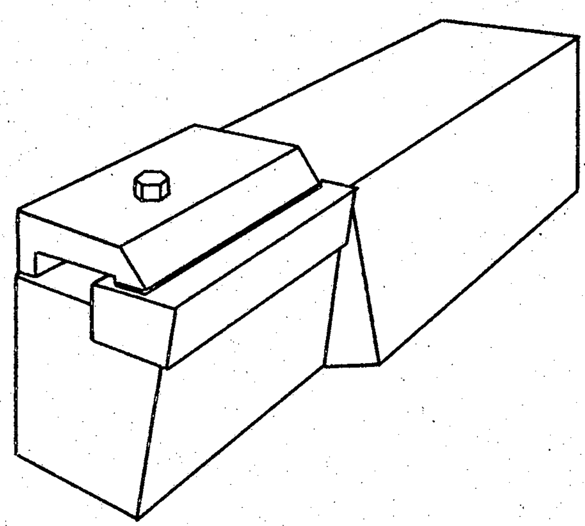
The need to control chips resulting from the machining of steel and other long-chip materials was not necessary until carbide tools came into prominent use. When machining steel with tools made of a high speed steel a continuous chip is produced which is often troublesome but seldom dangerous (1). But if steel is machined at a cutting speed of 400 sfpm (surface feet per minute) with a tungsten carbide tool material, the chip produced every minute will be about 200 feet long. The problem becomes more acute when it is realized that this fast moving ribbon of steel is hot, sharp, and strong and is a hazard to the operator and a nuisance to effective operation.

Two general types of chip breakers are available, one in the form of an obstruction clamped on the face of the tool close to the cutting edge and the other in the form of a groove ground in the surface of the tool face across which the chip flows (2). Representative chip breakers are shown in Figure 1. These chip breakers are generally satisfactory, however, in automated production lines in which loading and unloading are mechanized, flawless chip control is essential (1). Machining conditions never remain as they were originally established due to tool wear, variation in materials, and a host of other conditions which interfere with the processes (3). For these reasons static chip breaking methods are not always suitable.

In recent years vibrations have been deliberately introduced in various manufacturing, commercial, and medical processes to achieve certain advantages which would normally be unobtainable. One potential application for vibrations may be as a remedy to this long standing



STEP - TYPE



MECHANICAL TYPE

Figure 1. Types of Chip Breaker

problem. A title, "dynamic chip breaking," has been coined to describe this process. It is to this concept of dynamic chip breaking that the research is oriented.

There are several formative notions about the proposition dynamic chip breaking. If the goal is shorter chip length, will there be disadvantages that are incurred as a result of this objective? A possible answer to this may lie in the tremendous history of experimentation and research that is a part of metal cutting. Research in metal cutting goes back many years and one gathers the impression that the supply of practical, empirical, and theoretical information is almost limitless. But from this wealth of knowledge the importance and interplay of surface topography as a critical by-product of vibration becomes apparent.

Vibration has been recognized as a formidable deterrent to effective metal removal operations whether the interest lies specifically in surface finish, tool forces, dimensions, or production. The government, machine tool builders, and universities have responded to the problem of vibration in many diverse ways. The machine tool builders have reacted by strengthening the machine members and tools. The government has encouraged optimum operation in industry by the establishment of a data center to dispense "best advised" tool and machine settings. Research has been aimed at finding the maximum conditions of machine operation to provide trouble-free performance.

These well intended replies to the vibration problem lead one to ask: "Is vibration really that bad?" The preponderance of experience answers that vibration or "chatter," its well known nickname, serves no useful purpose. The fact that chatter is destructive to both tool and machine and harmful to surface topography is well established. The precautionary measures to combat chatter definitely aid in the generation of a desirable surface finish. Insofar as the materials used to cut metals possess elasticity and will deform under load, any total escape from the chatter problem is only illusory.

Although useful applications for vibrations are being evaluated in the production equipment field, the overwhelming majority of equipment is intended to be vibration resistant and does not credit the possible benefit that vibrations might provide. Occasional research is now pondering the consequences of the introduction of controlled vibrations in production equipment. It would seem that an investigation of the useful effects of impressed and controlled vibrations upon surface finish would clarify the development of automatic chip breaking devices. The adoption of vibrational techniques in the metal cutting segment of industry is hampered by insufficient knowledge of beneficial effects that vibration might provide. However the thought of the harmful effects from chatter completely shroud the metal cutting field making an impartial industrial evaluation impossible at this time.

One of the many effects of vibration that is incompletely understood is the change in the microscopic configuration of the surface texture caused by impressed and controlled vibrations. To impress a vibration upon the machine and tool system suggests that the total system of vibration cannot be caused by chance. Unintentional vibration may result from periodic fluctuations of cutting forces that arise from discontinuous cutting, or from imperfections of gears or bearings of the machine. This condition known as a forced vibration will continue provided the exciting force persists. The frequency of occurrence of these vibrations will change in proportion to the machine speed (4). Still another type self-excited vibration is independent of the machine speed but its vibration frequency is related to one of the natural frequencies of the machine system.

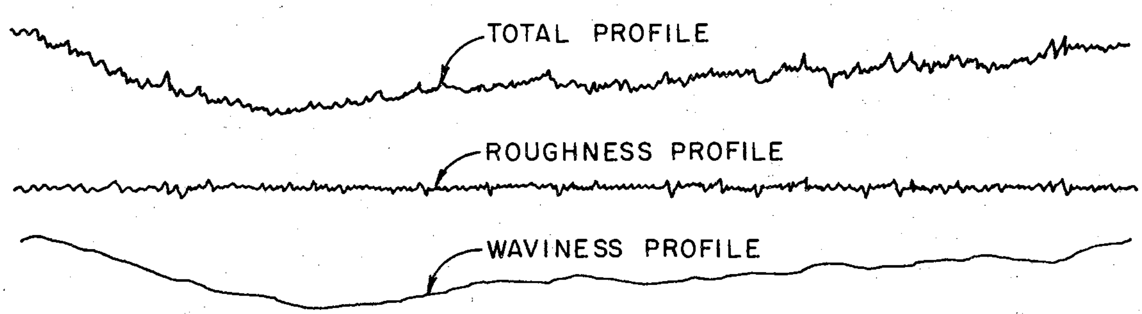
Neither self-excited nor forced vibrations can be closely managed to effectively pursue a research endeavor as they are susceptible to the whim and caprice of unknown factors. In view of the lack of dependability of the natural system, an external system that deliberately impresses a vibration upon the system is preferred for dynamic chip breaking.

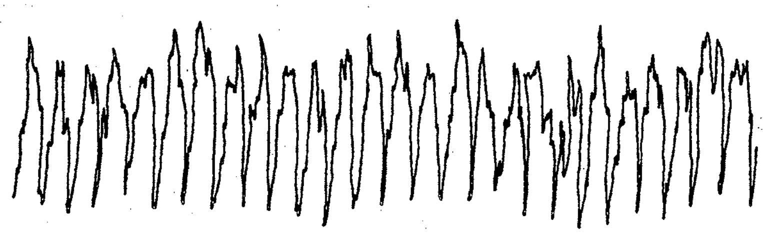
A controlled vibration induces the amplitude, frequency, and direction of the displacement of the member in such a manner that repeatability between tests is assured. Although chatter can be induced simply in the machine tool system, repeatability of the chatter frequency, amplitude, and direction is technically difficult (4).

The outermost boundary of a body adjacent to the air will be called a surface. When this surface is deformed by a sharp cutting edge the term surface finish describes the boundary. In one particular case when a rotating cylindrical body in contact with a tool has an existing surface removed, the substrate surface provides the new boundary. If the tool travels longitudinally and removes material along the axis of the rotating body uniformly, the resulting surface has been altered. The industrial operation performing this alteration is called turning and is normally handled by a lathe machine.

If the turned surface were magnified many times it would have the appearance of successive jagged mountain ranges. Despite the seemingly random natural appearance of a mountainous profile there is mathematical form and geometry to the topography. This analogy extends to the microscopic texture of grooves turned by a tool on a lathe.

The importance of surface finish in the present-day technology is recognized by the consumer and engineer. The brilliance of the surface finish contributes to the commercial and intangible appeal. Excessive cost can be attributed to over-finish. On the other hand, engineers know that the fineness of a surface relates to precision of dimension. Heat transfer, fluid dynamics, lubrication,





ENLARGEMENT OF ROUGHNESS PROFILE

Figure 2. Surface Roughness

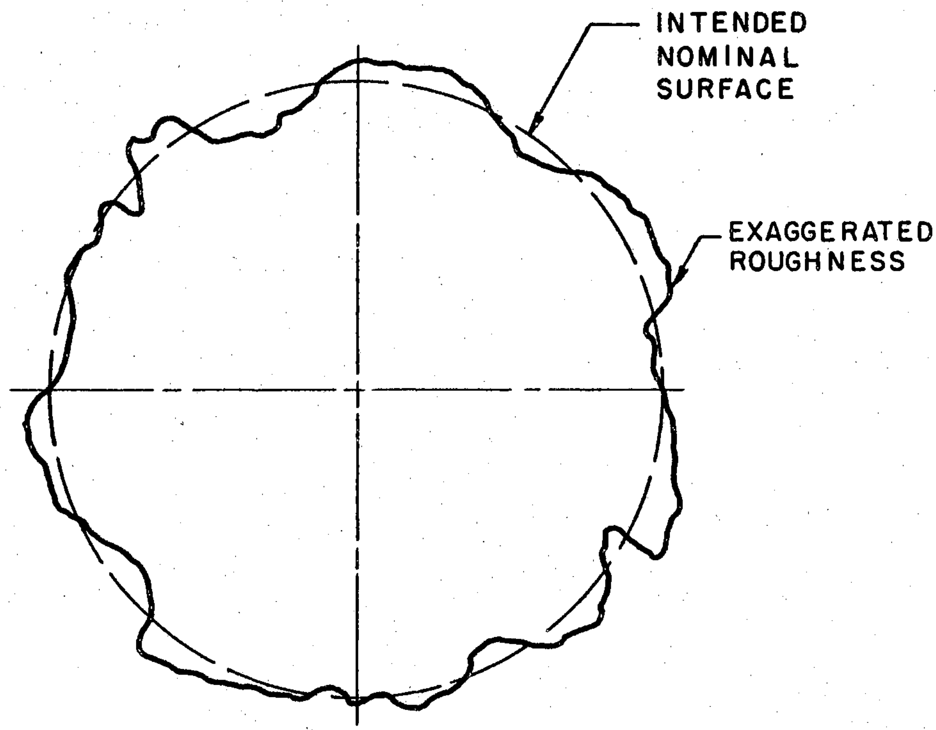
fatigue, and hardness are affected by properties of the surface topology. Regulation of surface finish to meet variated demands remains a continuing goal.

Consider the properties of a surface finish. If an imaginary line were to divide the peaks and valleys of the surface finish so that the area above and below the line were equal, a resulting absolute mean height would constitute the arithmetic average of the surface when measured from the datum line of the peak values. Mathematically it is expressed as $H_{aa} = \frac{1}{L}\int_{L_o}^{L_1} f(y)\, dx$.

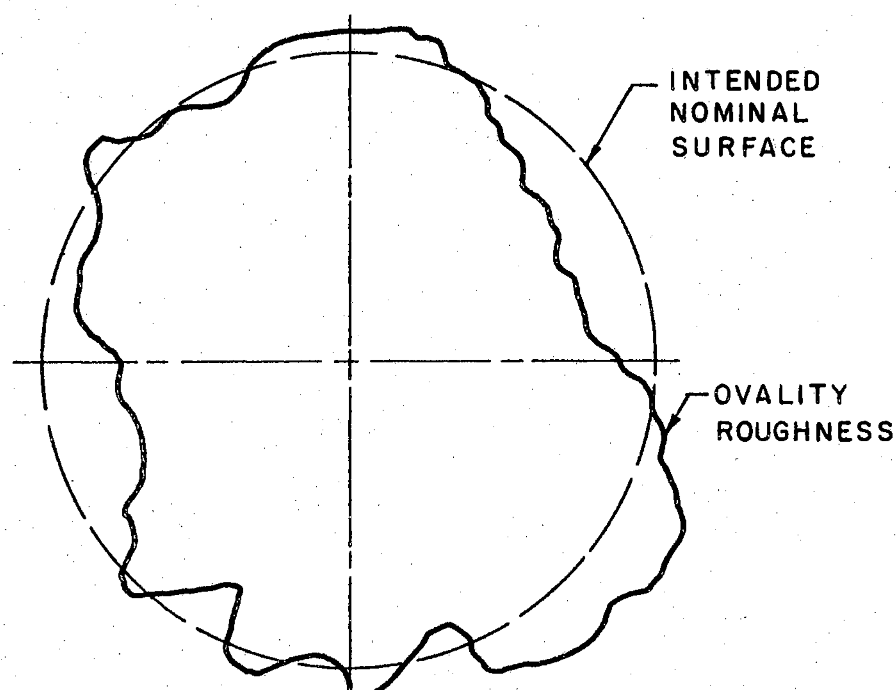
Another surface finish expression well known for its usage, the root mean square value, has the following definition: $H_{rms} = \left[\frac{1}{L}\int_{L_o}^{L_1} f(y)^2 dx\right]^{\frac{1}{2}}$. Of the two H_{aa} is preferred having been officially accepted as the USA standard of measurement.

Surface finish can further be described by the waviness crests that occur uniformly within a certain traversing length. Waviness does not affect either of the two preceding definitions. In addition, there are the checks and flaws that occur in a random behavior and cannot be defined rigorously. Neither waviness nor the surface aberrations that may arise from the material or from its manufacture are considered in this research. A true profile, magnified equally in the horizontal and vertical directions, is shown in the top half of Figure 2. The roughness of the surface can be examined in more detail by exaggerating the roughness effect. The lower half shows the same profile with an intentional exaggeration given to the height with no change in the horizontal direction. The surface finish in Figure 2 is in the profile plane longitudinal to the body, although there are additional transverse variations that exist circumferentially around the body. These transverse variations in the surface finish have an important role upon the dimension of the round body. When measured from the mean diameter dimension of the body, the transverse surface finish is considered, but roughness is disregarded when conditions of ovality exist as this arises from causes outside the intended goals of the research. Figure 3 illustrates the conditions of transverse variation and shows the true profile section and one of ovality.

Surface roughness is subject to measurement electronically and visually. Traditional methods of measurement include the use of the tracer and a tactual standard. In the tracer method a needle with a sharp geometrical point is dragged across the surface. The rising and falling of the point provides an electronic signal which is amplified and usually is indicated. Tactual standards which provide a crude estimate of the surface are available but are not suitable for research although convenient for production. Another device which provides a non-destructive



TRANSVERSE VARIATION IN ROUGHNESS



OVALITY VARIATIONS IN ROUGHNESS

Figure 3. Transverse Conditions of Roughness

means for surface examination is the microscope. Using the Schmaltz principle of microsopy a knifelike edge is played upon the profile which may be observed through an appropriate lens system. A more thorough discussion of these measuring devices is deferred until later.

This research attempts to determine the surface texture and free-chip length effects by an artificial excitation impressed in the direction of the tool travel. Mathematical considerations supported by physical experimentation provide an initial basis for the understanding of the phenomena. Selected technical details suggest optimum operation for dynamic chip breaking whenever the emphasis is the generation of a desirable surface finish and a convenient-to-handle chip.

Metal cutting theory is often misinterpreted by experimental results since the broad spectrum of materials, tools, equipment, and the complex nature of this process is such that uniform results between the possibilities make a practical theory hinge upon the fortunate choice of many factors. The ramifications of the metal cutting technology make it virtually impossible to evaluate all materials, tools, and equipment. It is conceded by other investigators that research and progress in the metal cutting field cannot, unfortunately, be established by sample analysis and consequently an aggregate mathematical model conveying a complete theory is unobtainable. The interest of this dissertation lies in the association of metal cutting theory allied with dynamic chip breaking tests. Because of the importance of the choice of the material for the experimental verification, a search led to selection of polyethylene plastic as the primary experimental material. This material has many interesting properties, and to the extent that the adiabatic gas laws, rigid bodies, and infinity are conceptual, polyethylene plastic was adopted as the test vehicle to simulate the same role as these idealizations.

This chapter concentrated on defining the research and discussing related problems. Chapter II is a gathering of the important documents that pertain to chip breaking by oscillation, surface finish models, and equipment. As the art of metal cutting becomes more rational there are emerging mathematical concepts that attempt to convey the metal cutting phenomena and Chapter III presents some theoretical considerations that pertain to dynamic chip breaking. Chapter IV deals with the experiments while Chapter V relates the results of the experiments. Finally, Chapter VI sums up the conclusions and makes recommendations for extension of the concept of dynamic chip breaking.

CHAPTER II

REVIEW OF THE LITERATURE

Provided the tool can be oscillated in a controlled manner some or all of the following advantages have been claimed (3) (5-16).

1. Break up of the continuous chip
2. Reduction of the cutting temperature
3. Reduction of forces
4. Improvement of tool life
5. Reduction in the work hardening of the material being cut
6. Improvement in the application of cutting fluids
7. Improved machinability when measured in terms of total material removal
8. Maintenance of the accuracy of the part being machined
9. Improvements in surface finish

In each of these alleged improvements, the magnitude of any such effects depends upon the vibration amplitude, frequency, and direction; also its phase relation with the previous cut, together with the normal cutting parameter of feed, speed, depth of cut, tool and workpiece, etc. A concise comparison of all the factors is technically difficult owing to the number of variables present, techniques of research used, reporting means provided, and apparatus used to induce tool oscillations.

Chip Breaking Experience

Waste metal removed in the chip may be in the form of a continuous ribbon typical of cutting ductile metals, or it may be in fragments as with brittle materials. In the condition of ductility there are several physical methods used to break or reduce the chip to more manageable length. The use of a chip breaker groove formed in the tool and immediately adjacent to the cutting point or a reversing step which drastically alters the direction of the chip flow to prematurely induce bending stresses and weaken the cross section are two prominent means of chip breaking (1). Contrary to the intent of chip breaker units on cutting tools, the problem of long, unruly chips has not been eliminated. Russians Poduraev and Zakarov (3) state:

> More intensive machining processes, due to the use of carbide and ceramic tools and the application of multi-tool methods, necessitate serious consideration of the problem of removing swarf from the cutting zone. In most cases of turning the chip is continuous, such a chip interferes with the machine operation due to tangling on the rotating and traversing units and jamming in the gaps, it is often the cause of premature wear and damage to equipment. Furthermore, the high temperature of the chips may lead to the machine operator being burnt, also great quantities of swarf clutter the space around the machine, while transport and processing the continuous chip is difficult. The problem of chip breaking and removal is particularly important when related to the introduction of automatic lines and machines into produc-

tion. The devices used at present (chip breakers and chip breaking grooves) do not provide an effective and reliable solution to this problem. Cutting with oscillating tools appears to have a greater future. This application of this method ensures the reliable and constant chip breaking of various metals machined under different cutting conditions.

Temperature Effects

One of the serious problems confronting heavy cuts is the effect of temperature upon carbide tool material, cutting zone, and the continuous chip. Satel (5) demonstrated that the temperature is 30% lower during tool oscillation as compared with conventional cutting. Whether this reduction was dynamic or represented average values was not stated. Isaev (6) reported a slight increase in the tool temperature. Satel (5) used low frequency for his testing while Isaev (6) was concerned with the ultrasonic range.

Forces in Cutting With Oscillating Tools

The study of forces in the oscillating tool condition has been studied briefly. Isaev (6) confirmed that forces were reduced with ultrasonic tool vibrations in the low cutting speeds, but when higher cutting speeds were introduced there was no apparent difference. The amplitude was small and the direction of the perturbation coincided with the cutting. Voronin (7) explained that the reduction in force for ultrasonic vibration results from the development of fatigue within the metal. In England, Skelton and

Tobias (8) who performed selected testing at a tool frequency of 50 cps stated that a large reduction of the feed force is possible when compared with the static case. The tangential force component is reduced but by a lesser amount. France's Weill (9)(11) confirmed the reduction in the two forces and suggested that the reason may be due to the diminished friction effects of cutting. Kristoffy and co-workers (13) of the Cincinnati Milling and Grinding Machine Co., Inc., studied orthogonal cutting of conventional and high strength materials at 20, 1,000, and 24,000 cps controlled vibrations. The true or apparent cutting force was lower in all cases, but the force reduction did not mean an energy saving by the machine itself since the energy saved had to be supplied by the vibrator.

Tool Life Studies With Vibrating Tools

Insufficient experience with tool life makes accurate conclusions impossible at this time, however, it is generally assumed that vibrations are as detrimental for tool wear as is harmful chatter. Nonetheless there is evidence that tool wear improved during conditions of a particular test (5)(7). But mixed results are typical of the experience that is summarized in Table I.

One author has calculated the decrease of tool life with vibrations assuming that tool life relations remain unchanged when the tool is vibrating. With the tool life

TABLE 1

SUMMARY OF TOOL-WEAR VIBRATORY TURNING RESEARCH

Research Reporter	Criterion of Tool Wear	Axis of Vibration	Type of Cutting	Wear of Oscillating Tool Compared to Standard
Poduraev (3)	Flank	x	Oblique	Mixed
Isaev (6)	Flank	z	Oblique	Improved
Voronin (7)	Flank	y	Oblique	Mixed
Voronin (7)	Flank	y,x	Oblique	Less
Weill (11)	Loss of weight	x	Oblique	Mixed
Weill (11)	Loss of weight	x	Oblique	Mixed
Weill (11)	Loss of weight	x	Oblique	No change
Kristoffy (13)	Flank	x,z	Orthogonal	Less (1,000 cps)
Kristoffy (13)	Flank	y	Orthogonal	Insufficient data

equation $TL = \frac{L}{V_c^n F^p d^q}$ with V_c = speed, F = feed, d = depth of cut, L = minutes, and n, p, and q exponents, the tool life ratio for dynamic conditions becomes

$$\frac{TL\ (static)}{TL\ (dynamic)} = 1 + \frac{p(p-1)}{2} \frac{C^2}{F^2}.$$

It appears from this relation that tool life is sensitive to the feed and is decreased for $p < 1$ and increased when $p > 1$. However, if the relations that affect tool life differ from those given by the formula, factors of vibration amplitude, direction of the vibration, frequency, etc., should be considered in the evaluation of tool life (12). Using substantially the same formula, Isaev (6) found that for 20 minute tool life there was an increase of 13% while for 60 minute tool life results indicate a 9% improvement over standard turning.

Lubrication and Depth of Work Hardening

There are beneficial effects in the reduction of work hardening due to the vibration in the ductile ferrous materials. The depth of work hardening is definitely related to the depth of cut and the feed distance. As Satel (5) relates:

> In conventional cutting, in view of the fact that the depth of penetration of the plastic deformation is 1.5 - 2 times greater than the depth of cut, the tool will be removing a layer which is already work-hardened from the previous pass. Taking a shallow cut with vibratory cutting and in the presence of a phase displacement between the preceding pass, the tool would be removing layers which had been work

hardened to a lesser degree.

It would be logical to assume that the ability of the lubricant to reach the cutting point is aided by an oscillating tool. One of the major difficulties in lubrication of the cutting point is the ability of the molecules of the lubricant to reach the cutting point in the presence of the moving chip, high temperatures, and the labyrinth nature of the chip-tool interface. The artificial tool movement, depending upon the direction of the excitations, may cause a momentary separation between the chip and the tool thus providing an accessible corridor more or less unhindered by the chips.

The Tool Oscillation Experience Upon Surface Roughness

In Poduraev's (3) studies it was found that good quality surface finish depended upon the frequency and amplitude of the oscillations in relation to the cutting conditions and tool geometry. The surface obtained from the machining-tool oscillation process was a result of the interaction of the geometrical track of the tool, plastic deformation in the cutting zone, and the elastic spring back of the metal after tool passage.

A satisfactory surface finish can be obtained by using a frequency which is near the rotational velocity of the workpiece although not an exact multiple of the rotational speed. In Isaev's (6) experiments the workpiece was stopped suddenly during the cutting process.

A microscopic study of the chip base of a segment of the material revealed that the built-up edge present during normal machining was absent during vibrations. Elimination of the built-up edge permits the beneficial effect of surface finish improvement. These studies which varied the direction of the vibrations in the three planes found the greatest effect of the ultrasonic vibrations in the plane of cutting. In one test the average roughness was reduced from 1960 microinches to 76 microinches; a very noticeable improvement in the surface (6).

Czechoslovakian Dlouhy (10) asserts that the methods of low tool oscillations can be used successfully only for roughing or semiroughing operations. Although in the opinion of some authors a uniform surface is obtained, he claims that the appearance does not comply with the highest requirements for a fine machine tool surface.

In another series of tests which spanned low to ultra-high frequency tool vibrations, it was found that using low frequencies reduced the quality of surface finish in all cases. However, as the cutting velocity of the work-piece increased, the difference between the static and the dynamic cases became less. In the moderate tool oscillation range (1,000 cps) the surface roughness was improved during low cutting speeds but at moderate cutting speeds the tool oscillations did not affect the surface roughness. In this particular research ultrahigh tangential vibrations caused only a moderate improvement in surface finish (13).

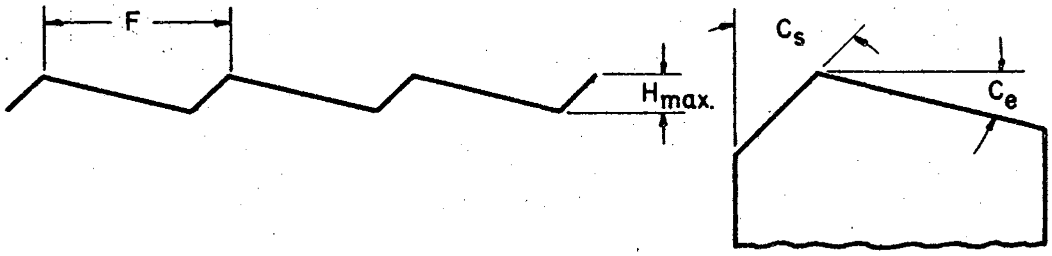
It is well known that when cutting ferrous ductile materials, an intensive formation of a built-up edge leads to a reduction in the quality of the surface finish. In turning with low frequency oscillating tools the volume of interaction zone and built-up edge are greatly reduced and in some cases completely absent (3).

Ideal Surface Roughness Models

For conventional cutting Chisholm (17) proposed a model for an ideal surface provided the surface is machined exactly as the geometrical factors suggest. Three types of tools were selected for their popularity in finishing operations. Figure 4 illustrates the tools with their corresponding model.

These models predict the theoretical surface finish for lathe turning operations. The surface finish, or H_{max} is the crest to root height. The only variables that are considered are the side cutting edge angle, end cutting edge angle, and feed. The model assumes that the tool was static and not susceptible to chatter or other involuntary movements. It was recognized however that the surface would be rougher than the ideal for one important reason, the built-up edge. Gladman (18) confirmed the general characteristics of Chisholm's theory by testing and showed that the theoretical model could be treated as an asymptote.

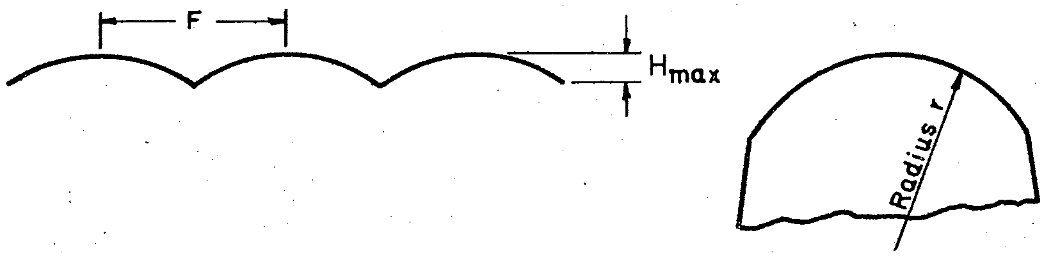
One rule-of-thumb measurement formula for surface height estimation found frequently in the literature is



SURFACE GEOMETRY A

TOOL PLAN A

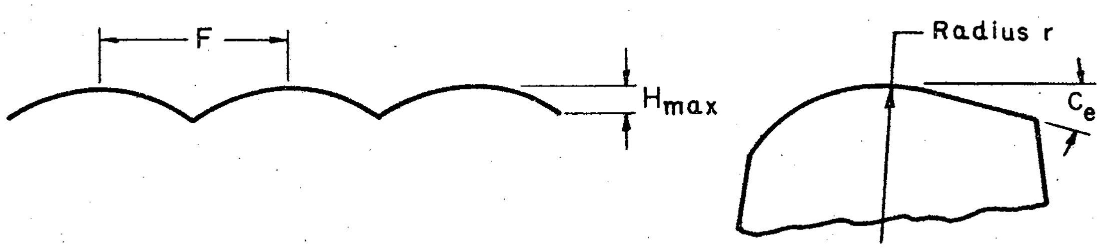
$$H_{max} = \frac{F}{\text{Tan } C_s + \text{Cot } C_e}$$



SURFACE GEOMETRY B

TOOL PLAN B

$$H_{max} = \frac{F^2}{8r}$$



SURFACE GEOMETRY C

TOOL PLAN C

When $F < 2r \tan C_e$, $H_{max} = \frac{F^2}{8r}$

When $F > 2r \tan C_e$, $H_{max} = F \tan C_e + \frac{r}{2} \tan^2 C_e - \sqrt{2Fr \tan^3 C_e}$

Figure 4. Surface Roughness Models

given by the ratio F/60 having the feed distance per revolution denoted by F. In another well publicized method, Gilbert and other associates of General Electric Company (19) suggested that surface finish plays a secondary role in the broad applications of machining calculations. His approach is conceptualized by the use of empirical nomography. This art has reached such a state of development that an analog computer which considers better than 25 variables is commercially available and can be used to find operating conditions that optimize tool life, cutting speed, metal removal rate, horsepower, etc. Irrespective of the sophistication of this analog computer surface finish is not treated as a primary variable, nor is a direct model relating roughness provided as an adjunct to finding the suitable conditions that suboptimize for surface finish. If in using the operating conditions provided by the computer, the surface finish is found unsatisfactory, the setup is readjusted until this difficulty is eliminated.

Brown (20) provided a formula to determine the roughness by a round cutting edge. His method, a computational simplification of the basic Chisholm relationship, considers the geometrical factors of feed and tool-end radius.

Theoretical Considerations for Surfaces With Oscillating Tools

Satel (5) describes the conditions for tool oscillations in the direction of feed:

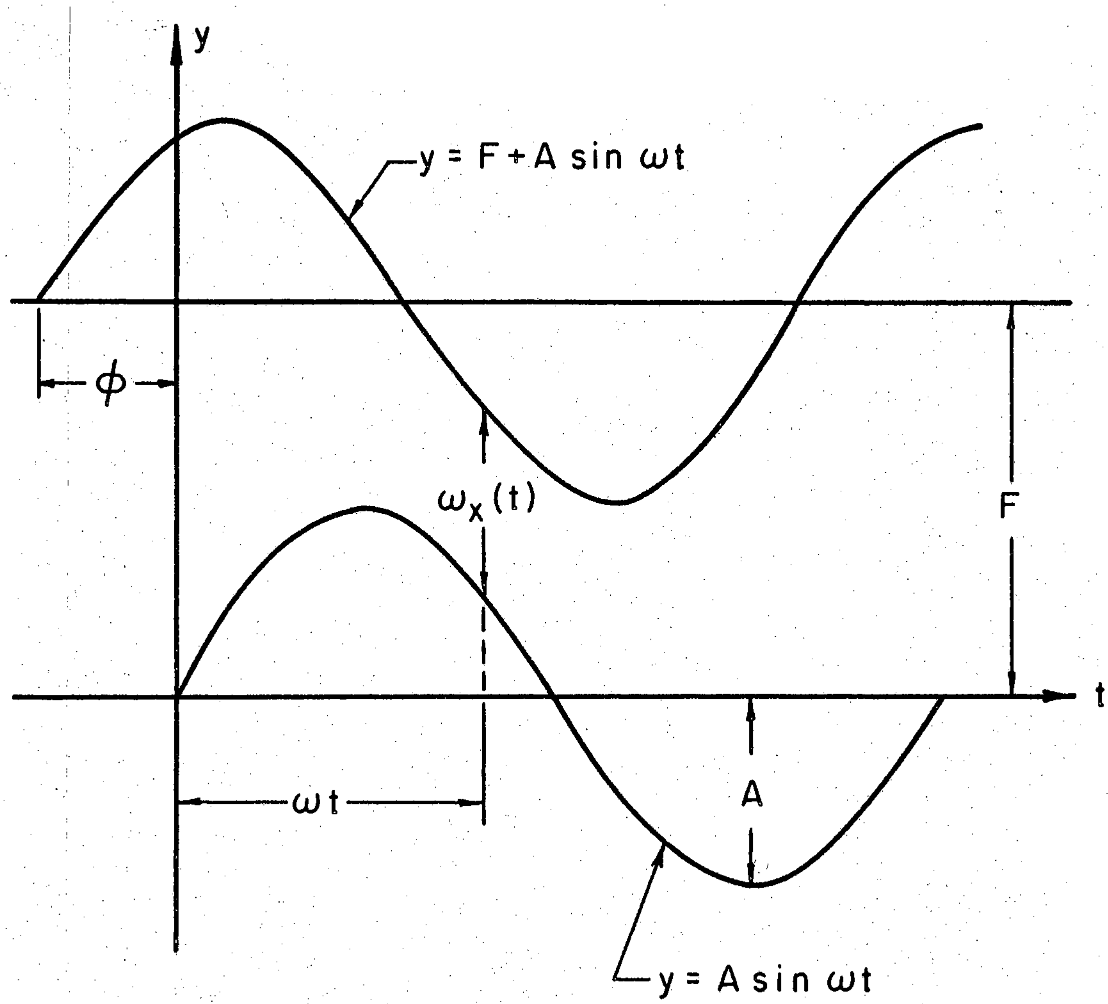
> When cutting with forced tool vibrations in the same directions as the feed, variations occur in the geometrical parameters in the cross section of the layer being removed owing to variations in the rate of feed, and in addition, to variations in the kinematics of the cutting process by changes in the numerical value and direction of the cutting speed and kinematic cutting angles.

The effective feed rate W or the true chip thickness can be expressed by the formula:

$W = F + 2A\sin\frac{\varphi}{2}\cos(\omega t + \frac{\varphi}{2})$ where F is the rate of feed per revolution, A is the amplitude of the oscillations, φ is the phase displacement of the oscillation sine curve for two successive revolutions of the workpiece, and ω is the constant angular velocity of the vibrations.

Several authors have used these sine curve tool paths to graphically construct a series of surface finish representations which show the effective width of the tool traces (3)(5)(6)(8-10). The conditions analyzed by this graphic means are $A = F/2$, $A = F$, and $A = 2F$ with the phase angle assuming values from 0 to π. Figures 6 and 7 are a condensation of these curves. It can be seen that there will be a maximum variation in chip thickness for $\varphi = 180^\circ$ and chip breaking occurs whenever $A = F/2$. Podureaev (3) has shown that in practice the chip breaking will occur for vibration amplitudes smaller than the theoretical value due to the shear across the thinnest section of the chip. His studies conclude that from .4 to .6 F chip breaking would occur.

As the tool vibrates in the feed direction, the clearance angle varies in a sinusoidal fashion and the



$$W_x(t) = F + A\sin(\omega t + \phi) - A\sin\omega t$$
$$= F + 2A\sin\frac{\phi}{2}\cos\left(\omega t + \frac{\phi}{2}\right)$$

Figure 5. Effective Distance Between Tool Paths

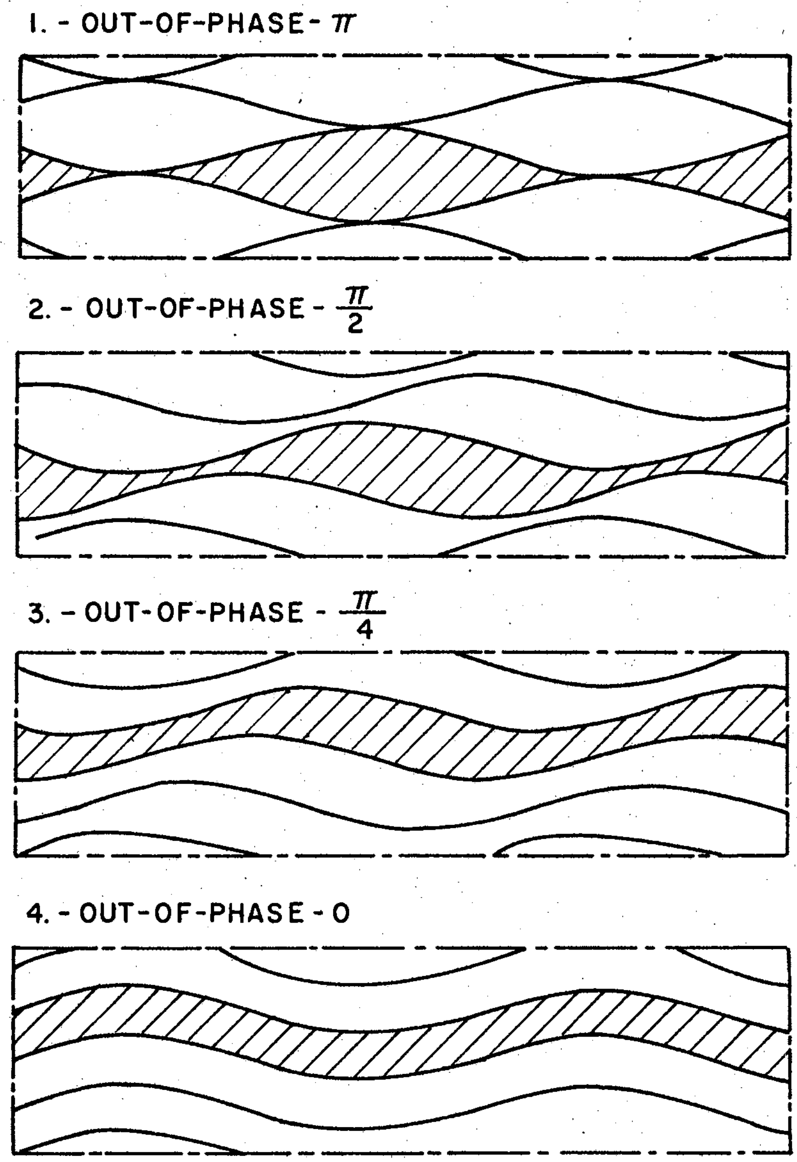


Figure 6. Surface Waviness for $A = F/2$

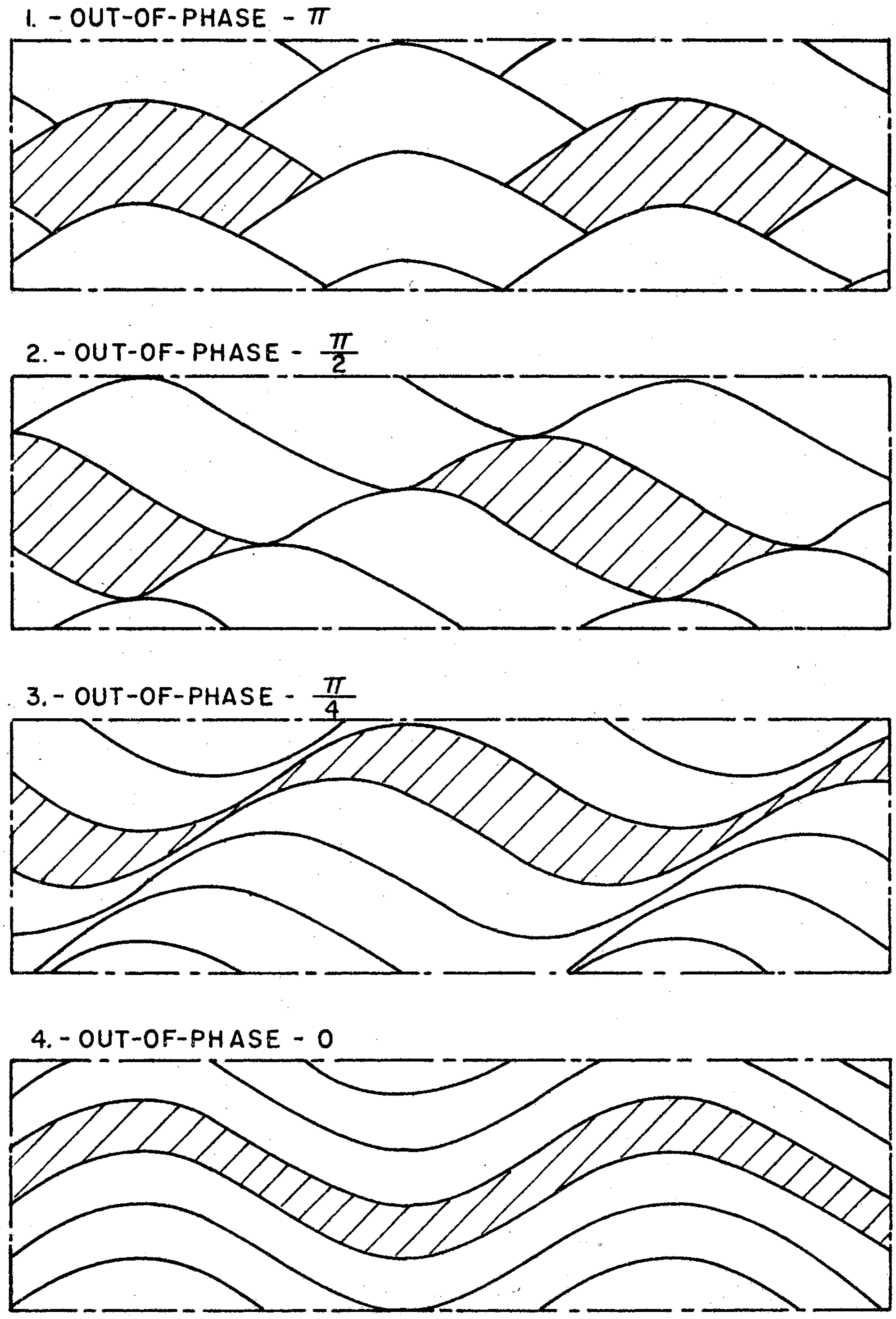


Figure 7. Surface Waviness for A = F

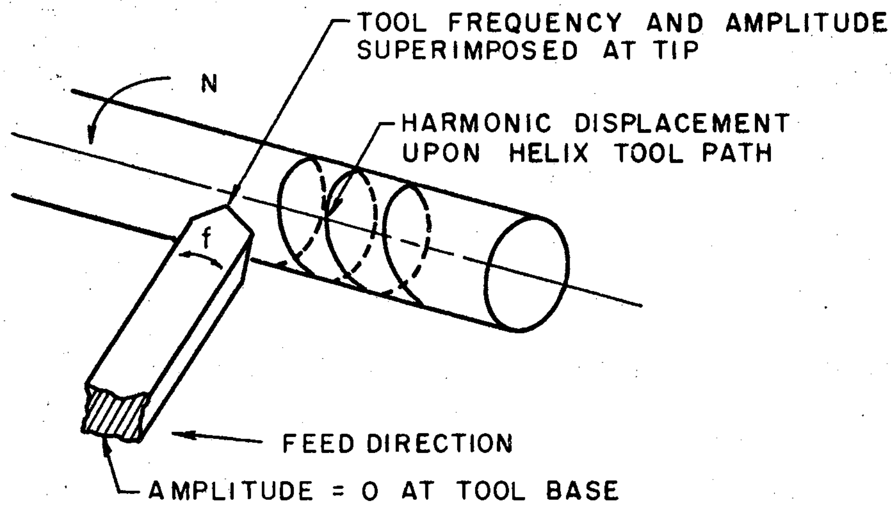
maximum variation from the nominal value being the vector sum of the cutting velocity V_c, and the tool oscillation velocity V_t. This maximum change of clearance angle is given by $\tan\delta = \frac{2\pi fA}{V_c}$. For a fixed tool the amplitude and the frequency must be kept below certain values if rubbing on the clearance face is to be avoided (8). Figure 8 illustrates the influence of the sine curve upon the clearance angle of the tool.

Methods of Excitation for the Tool

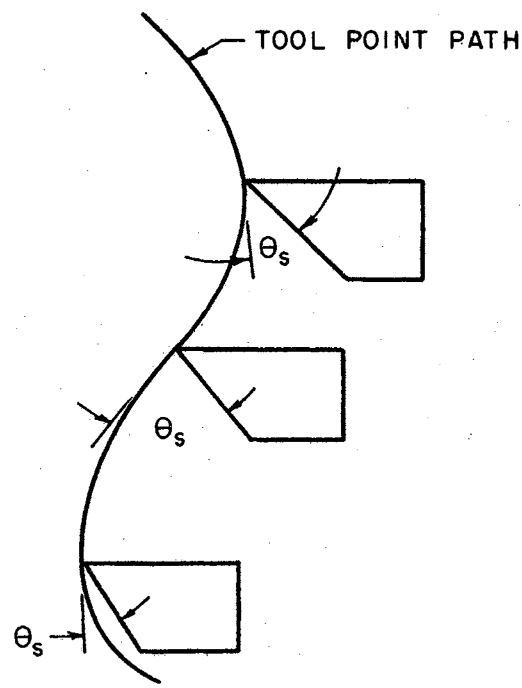
Vibrations superimposed upon rotating equipment already subject to a variety of forced and self-excited vibrations generally tend to cause the system to vibrate at the frequency of the excitation force. In the presence of friction that transient portion of motion not sustained by an excitation gradually dies out. That part of the sustained vibration termed steady state is the desired and useful end product for vibratory turning (4). In spite of these conditions, the adoption of vibratory turning does not reduce the necessity to ensure resistance of the machine tool to harmful chatter (5).

A thorough description of the methods of excitation would prove redundant in many respects. In an effort to alleviate this problem, Table II provides a summary of the design parameters used for vibratory turning.

These several methods can be classified for conven-



TURNING WITH TOOL OSCILLATION PARALLEL TO FEED



THREE TOOL POSITION FROM SIMPLE HARMONIC TOOL MOTION WHERE HELIX EFFECT IS IGNORED

Figure 8. Clearance Angle θ_s Changes During Dynamic Chip Breaking

ience. The term "vibrator" as used in the summary refers to the member which is being actuated. Although it is a cutting edge perturbation that is desired, intermediate to this goal some other major member is used as the receiver for superimposed vibration. Investigators (3)(5)(8) and (9) tried the cross slide and carriage which are heavy and require larger sources of power for their actuation. Direct vibration upon the tool (10) circumnavigates the problem posed by the introduction of the cross slide and carriage masses (6)(11).

The power source may vary from low power systems, resonant systems such as the electrodynamic or electromagnetic, to those capable of larger forces, i.e., mechanical and hydraulic non-resonant systems. If large masses must be pushed, power systems are either mechanical or hydraulic, and in this case the excitation frequency is by necessity lower. Whenever the ultrasonic vibrations are desired the low-power electrical vibrators can be applied but only in small cutting force operations. The principles of magnetostrictive transducers are employed in the ultrasonic regions.

Vibrators may be further classified according to the number of possible directions of vibration. Linear vibrations in one direction, two-axis systems for planar vibrations, and the three-axis for three degrees of freedom are examples of these designs.

TABLE II

SUMMARY OF METHODS OF EXCITATION

Research Reporter	Vibrator	Vibrator Power Source	Oscillation Direction	Frequency Range cps	Amplitude Range Inch
Poduraev (3)	Cross Slide	Hydraulic	x	5-24	.006-.014
Satel (5)	Cross Slide	Hydraulic	x	5-60	0-.078
	Cross Slide	Mechanical	x	20-100	.0019-.039
Isaev (6)	Tool	Electronic	x or y or z	18,000 (fixed)	.0004 (fixed)
Voronin (7)	Tool	Electronic	y	13-30,000	0-.0004
Skelton (8)	Cross Slide	Hydraulic	x	0-150	-
Weill (9)	Tool	Electromagnetic	x	50-110	0-.008
	Tool	Centrifugal Balance	xz	-	-
	Carriage	Mechanical	x	-	0-.0024
	Tool	Mechanical	x	125 max	-
Kristoffy (13)	Tool	Mechanical	x or y or z	20 (fixed)	-
	Tool	Electromagnetic	x or y or z	600-1,000	-
	Tool	Electronic	x or y or z	25,000	-
Dlougy (10)	Tool	Hydraulic	x	-	-

Methods Used in the Evaluation of Surfaces Subjected to Tool Oscillations

Methods to measure industrial surfaces can be grouped in three areas: qualitative methods, methods giving a parameter related to roughness, and methods giving a profile picture. Only the last two are important here (20).

Of the investigators who studied the effect of tool oscillations upon surfaces, it is doubtless that all employed the stylus method (3)(5-13). Satel (5) mentions the use of the profilograph which is an extension of the basic stylus method but instead of an indicator readout the terminating device is a strip chart. Thus the comments about the stylus type of surface measurement with an indicator readout apply equally to the profilograph regardless of the difference in the termination device. The needle tracing type instrument is very common in industry and no discussion is required to disclose the merits of this particular method. The principle of the tracer method is simple. A displacement stylus transforms the motion of the point by an electronic transducer to an analogous electrical signal. Readout devices may be ordinary calibrated voltage indicators or as in the case of the profilograph, a permanent chart is produced. Although the electro-mechanical instrument is popular for obtaining useful industrial data, it is necessary to comment upon the instrument limitations as they pertain to the measurement of surfaces subjected to tool oscillations. Beckwith and Buck (21) point out that the tracer tip has a finite radius instead of a sharp point. Therefore the stylus will not always follow the true contour. If the surface is rugged it is entirely possible that the point will fail to measure the fine scratches and thus filter out the effect of the transducer. In addition, the stylus will probably round off the peaks. This problem increases as the radius of the tip is decreased. Thus there are conflicting advantages with regard to the stylus-tip radius. A more minor problem is the marring of the surface by the diamond-point tracer and the smoothing of the surfaces as the tracer point is reversed back and forth over the same material. Readings would tend to get smaller and more uniform as the tracer unit reciprocated (21).

Isaev (6) reported that he used the Linnik principle to measure roughness in the transverse and longitudinal directions. The Linnik method is a twin-microscope micro-interfermometer which enables one to obtain a contour map of the fine irregularities of a limited area. It is considered well suited for a small portion of the surface. As Isaev (6) did not publish any microphotographs of the surface with this microscope it is not known whether measurements other than height of the irregularities were possible.

CHAPTER III

THEORETICAL CONSIDERATIONS

This chapter attempts to provide theoretical insight into surface roughness height and free chip length under dynamic chip breaking operations. Before the mathematics deal with the problem an exaggerated picture of the tool, surface, and tool path under the activities of an impressed tool action will aid clarity. Figure 9 suggests the ideal physical model. Later chapters will consider the construction of the equipment, and design and analysis of the tests.

Chip breaking as conceived in this research deals with the motion of the tool within a dynamic system. It will be seen that it is the combination of the tool and workpiece that bring about chip breaking by their relative motion. As workpiece angular motion is generally restricted to speeds based on processing requirements placed on the workpiece, it is wise to select the tool to receive a change in the motion pattern. For this reason the tool rather than the workpiece has impressed upon it an oscillatory motion.

Let the maximum excursion of the tool have magnitude A such that the cutting point obeys the law of simple

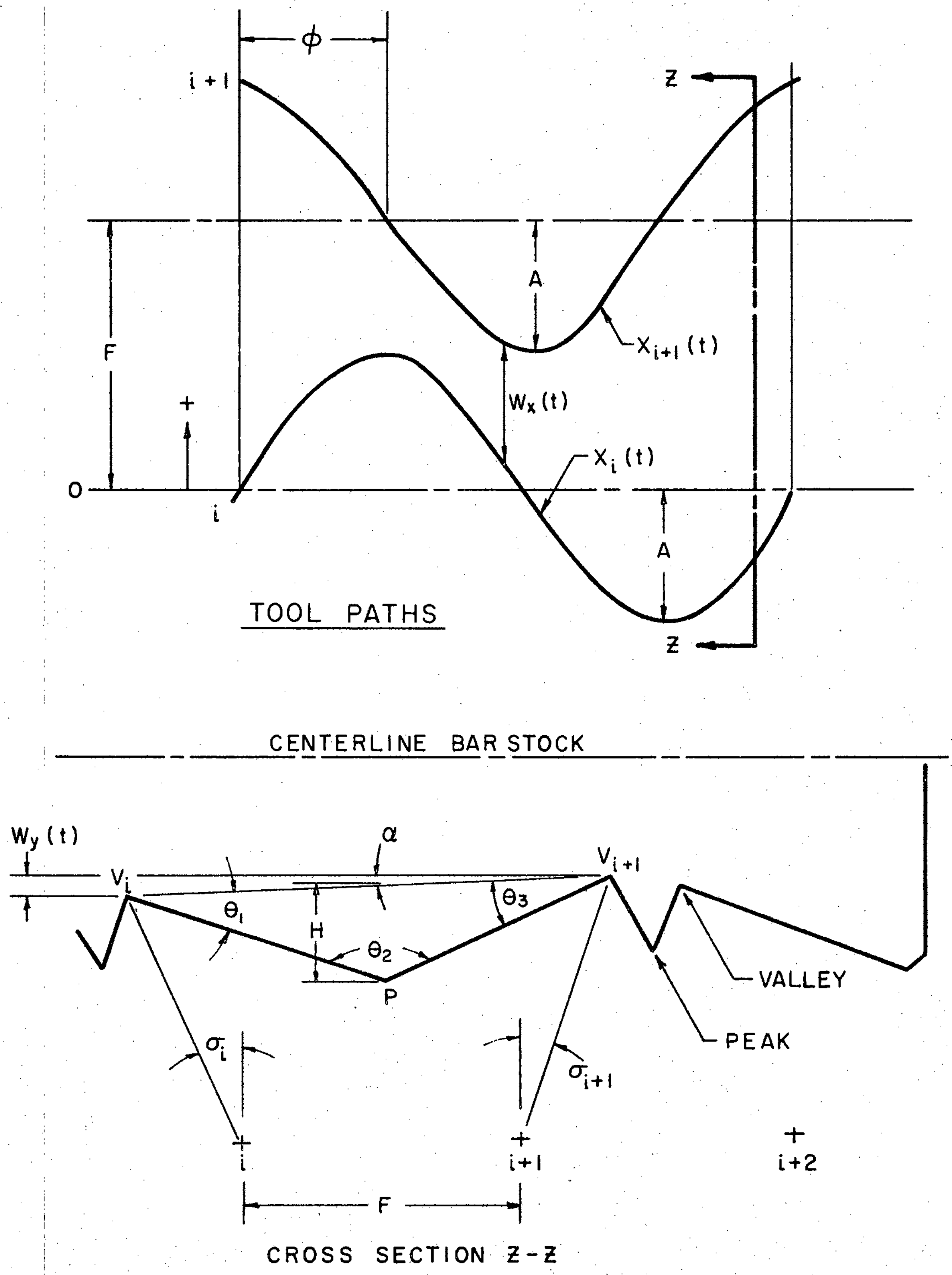


Figure 9. Tool Paths with Cross Section Across Adjacent Peak-to-Valley Surface Roughness

harmonic motion. Consider the case where i is the tool pass of interest where i is the whole number 1, 2, 3, ... With the impression of a frequency f upon the tool and a constant angular velocity ω_1 the motion of the tool can be expressed by a circular function, sine or cosine. Since a circular function repeats itself in 2π radians, the cycle of motion is complete when $\omega_1 = 2\pi f$ radians per second. At instantaneous time t the tool tip displacement $X_i(t)$ becomes

$$X_i(t) = A\sin\omega_1 t \quad \text{or} \tag{3.1}$$

$$X_i(t) = A\sin 2\pi ft$$

The neighboring tool trace indexes a distance F for tool pass $i + 1$ where it is out of phase by the quantity φ radians with the previous pass. For identical amplitude A, the $i + 1$ displacement with respect to the i^{th} tool trace reference becomes

$$X_{i+1}(t) = F + A\sin(\omega_1 t + \varphi) \tag{3.2}$$

$$= F + A\sin(2\pi ft + \varphi)$$

Let $W_x(t) = X_{i+1}(t) - X_i(t)$

$$W_x(t) = F + A\sin(2\pi ft + \varphi) - A\sin 2\pi ft$$

$$W_x(t) = F + 2A\sin\frac{\varphi}{2}\cos(2\pi ft + \frac{\varphi}{2}). \tag{3.3}$$

Since it is presumed that the workpiece angular rotation ω_2 is constant during a chip breaking trial one can write

$$\frac{N}{f} = \left(K + \frac{\varphi}{2\pi}\right) \tag{3.4}$$

where N is the rotational speed of the workpiece in cycles per second and K is a natural number 0, 1, 2, 3, ... such that $\frac{\varphi}{2\pi}$ remains a positive fractional number and is restricted by $0 \leq \frac{\varphi}{2\pi} < 1$. The phase angle φ can be expressed

as $$\varphi = 2\pi\left(\frac{N}{f} - K\right). \tag{3.5}$$

Substituting in (3.3) one obtains

$$W_x(t) = F + 2A\sin\left[\pi\left(\frac{N}{f} - K\right)\right]\cos\left[2\pi ft + \pi\left(\frac{N}{f} - K\right)\right]. \tag{3.6}$$

Assume that the tool is able to move in one plane, as designated by Cartesian coordinates x and y, where x is parallel to the direction of the feed and the y coordinate is along the thrust direction. If the tool has an angle of inclination σ under a one degree of freedom system, the coordinate displacement $X_i(t)$ and $Y_i(t)$ are related by the equation of constraint

$$\left[X_i(t)\right]^2 + r - \left[Y_i(t)\right]^2 = r^2 \tag{3.7}$$

where r is a constant radius.

$$\left[Y_i(t)\right]^2 - 2rY_i(t) + \left[X_i(t)\right]^2 = 0 \tag{3.8}$$

The change in the height of tool trace i becomes

$$\left[Y_i(t)\right] = r - \sqrt{r^2 - \left[X_i(t)\right]^2}. \tag{3.9}$$

The maximum height difference is

$$Y_i(t)_{max} = r - \sqrt{r^2 - A^2} \,. \qquad (3.10)$$

For σ small and when $X_i(t) > Y_i(t)$

then $\left[Y_i(t)\right]^2 = 0.$

$$Y_i(t) = \frac{\left[X_i(t)\right]^2}{2r} \,. \qquad (3.11)$$

The maximum difference in height along the trace becomes

$$Y_i(t)_{max} = \frac{A^2}{2r} \,. \qquad (3.12)$$

For the two tool traces i and i + 1, the difference in absolute distance $W_y(t)$ is

$$W_y(t) = Y_{i+1}(t) - Y_i(t) \qquad (3.13)$$

$$W_y(t) = \sqrt{r^2 - \left[X_i(t)\right]^2} - \sqrt{r^2 - \left[X_{i+1}(t)\right]^2} \qquad (3.14)$$

Then using trigonometry

$$\sigma_i(t) = \arctan \frac{X_i(t)}{r - Y_i(t)} \,. \qquad (3.15)$$

A similar relation for $\sigma_{i+1}(t)$ can be found. Knowing $W_x(t)$, $W_y(t)$, and σ_i and σ_{i+1} the height of the crest to the baseline is now determinable. As Figure 9 illustrates, the symbols P and V_i and V_{i+1} refer to the peak and valley locations respectively while θ_1, θ_2, and θ_3 are the included angles within the triangle. From construction analysis the following trigonometry steps can be followed:

$$\tan\alpha = \frac{W_y(t)}{W_x(t)} \quad \text{and} \tag{3.16}$$

$$\alpha = \arctan \frac{W_y(t)}{W_x(t)}$$

$$V_iV_{i+1} = \frac{W_x(t)}{\cos\alpha} \tag{3.17}$$

The theoretical height at instant t is

$$H(t) = \frac{W_x(t)}{\cos\alpha(\cot\theta_1 + \cot\theta_3)} \ . \tag{3.18}$$

Let γ be the included tool nose angle. By analysis

$$\theta_1 = 90^\circ + \alpha - \sigma_i - \frac{\gamma}{2} \ . \tag{3.19}$$

$$\theta_3 = 90^\circ - \alpha - \sigma_{i+1} - \frac{\gamma}{2} \ . \tag{3.20}$$

Finally the crest-to-root height is found as

$$H(t) = \frac{W_x(t)}{\cos\alpha\left[\cot(90^\circ + \alpha - \sigma_i - \frac{\gamma}{2})\right]} + \frac{W_x(t)}{\cos\alpha\left[\cot(90^\circ - \alpha - \sigma_{i+1} - \frac{\gamma}{2})\right]} \tag{3.21}$$

Equation (3.21) gives the instantaneous height for a tool where the leading and trailing edge angles are equal as in a 60° included angle tool used for thread cutting. This tool selection does not necessarily provide the best surface finish, but it is a useful geometry for research.

Consider the condition of $A \leq \frac{F}{2}$ as one case of (3.21).

Expanding (3.21) (3.22)

$$H(t) = \frac{F + 2A\sin\left[\pi(\frac{N}{f} - K)\right] \cos\left[2\pi ft + \pi(\frac{N}{f} - K)\right]}{\cos\alpha\left[\cot(90^\circ + \alpha - \sigma_i - \frac{\gamma}{2}) + \cot(90^\circ - \alpha - \sigma_{i+1} - \frac{\gamma}{2})\right]}$$

For simplification let $\sigma_i = 0$ and $\sigma_{i+1} = 0$ which is not difficult to reconcile as (3.15) considers division of a small number by a much larger numerical one. For $\sigma_i = \sigma_{i+1} = 0$, then $\cos\alpha = 1$. Hence

$$H(t) = \frac{F + 2A\sin\left[\pi(\frac{N}{f} - K)\right]\cos\left[2\pi ft + \pi(\frac{N}{f} - K)\right]}{2\tan\frac{\gamma}{2}} \quad (3.23)$$

As the included tool nose angle is fixed let $\beta = 2\tan\frac{\gamma}{2}$.

$$H(t) = \frac{1}{\beta}\left(F + 2A\sin\left[\pi(\frac{N}{f} - K)\right]\cos\left[2\pi ft + \pi(\frac{N}{f} - K)\right]\right) \quad (3.24)$$

It is important that (3.24) be examined for minimum and maximum values of the height H(t). Lagrange's method of undetermined multipliers will be used to find the extreme values, however only summary steps will witness the development. In dealing with this extreme value problem there is the constraint $C < A < F/2$ where C is any arbitrary positive constant and not zero, and t is a parameter. The function to be treated has five variables, H(t), A, F, f, and N, while β is fixed for any one tool. The Lagrange equation $U = \mu + \lambda\chi_1$

$$U = \beta H(t) - \left[F + 2A\sin\left[\pi\left(\frac{N}{f} - K\right)\right]\cos\left[2\pi ft + \pi\left(\frac{N}{f} - K\right)\right]\right.$$

$$\left. + \lambda(A + C - F/2)\right] = 0. \qquad (3.25)$$

Here λ assumes the role of the undetermined multiplier. For a solution the following six partial derivatives must hold:

$$\frac{\partial U}{\partial H(t)},\ \frac{\partial U}{\partial F},\ \frac{\partial U}{\partial A},\ \frac{\partial U}{\partial f},\ \frac{\partial U}{\partial N},\ \text{and}\ \frac{\partial U}{\partial \lambda} = 0 \qquad (3.26)$$

A solution to these simultaneous equations leads to the following. $\beta = 0$ which is trivial and is inconsistent with the solution. Therefore, forcing

$\beta \neq 0$, and for the minimum solution H_{min} (3.27)

$$f = \frac{n}{4t}, \qquad n = 1, 3, 5, \ldots . \qquad (3.38)$$

$$N = \frac{n}{4t}\left(K + \tfrac{1}{2}\right), \qquad n = 1, 3, 5, \ldots . \qquad (3.29)$$

In (3.28) and (3.29) n is a periodic value satisfying the circular functions.

$$A = F/2 - C. \qquad (3.30)$$

Substituting (3.27), (3.28), and (3.29) in (3.24)

$$H_{min} = \frac{1}{\beta}\left[F + (F - 2C)\sin\frac{n\pi}{2}\cos n\pi\right] \qquad (3.31)$$

At $n = 1$, $\sin\frac{n\pi}{2}\cos n\pi = -1$ and

$$H_{min} = \frac{2C}{\beta}. \qquad (3.32)$$

If C is permitted to range to 0, then the constraint $0 < A < F/2$ gives $H_{min} = 0$ occurring at a phase angle $\varphi = n\pi$ or 180°, 540°, 900°, ...

For the minimum to exist the two traces i and i + 1 intersect momentarily. This happens whenever $\varphi = 180^\circ$, 540°, 900°, ...

By a similar development H_{max} is obtained whenever

$$\beta \neq 0 \tag{3.33}$$

$$A = F/2 - C \tag{3.34}$$

$$f = \frac{3n}{4t}, \qquad n = 1, 3, 5, \ldots \tag{3.35}$$

$$N = \frac{3n}{4t}(K - 1/2), \qquad n = 1, 3, 5, \ldots, \text{ and} \tag{3.36}$$

$$H_{max} \equiv \frac{2F}{\beta} \tag{3.37}$$

The maximum value exists when (3.35) and (3.36) substituted in (3.4) gives $\varphi = -n\pi$, and for n = 1, the phasing is 180° lagging the minumum value.

As H(t) covers the range from minimum to a maximum within one revolution of the circular function, it is only necessary to examine (3.24) through 0 to 2π radians for an average value. Integrating (3.24) over the length of one cycle $2\pi ft$

$$H_{ave} = \frac{1}{\beta}\left[F + 2A\sin\left[\pi\left(\frac{N}{f} - K\right)\right]\int_0^{2\pi}\left(\cos\left(2\pi ft + \pi\left(\frac{N}{f} - K\right)\right)d(2\pi ft)\right]$$

$$H_{ave} = \frac{F}{\beta} \quad \text{which agrees with Chisholm's} \tag{3.38}$$

determination (Ref. Figure 4) since β is a function of the tool angles. Using the Chisholm classification of tools (Types A and B only) the following expected average height for surface roughness can be found.

Relationship	Tool Geometry	β
$\tan C_s + \cot C_e$	$\gamma = 60^\circ$ sharp point	1.15
$\tan C_s + \cot C_e$	$\gamma = 90^\circ$ sharp point	2.0
$\tan C_s + \cot C_e$	$\gamma = 120^\circ$ sharp point	3.46
$\tan C_s + \cot C_e$	$C_s = C_e = 15^\circ$ sharp point	4.00
$f^2/8r$	$r = 1/32$	varies

Figure 10 gives the expected average height, H_{ave}, from the crest to the valley for five typical tools.

Variation in Chip Width

In the situation $A \leq F/2$ the variation of the chip width follows the sine law. Using the expression

$$F + 2A\sin\pi\left(\frac{N}{f} - K\right)\cos\left[2\pi ft + \pi\left(\frac{N}{f} - K\right)\right] \qquad (3.39)$$

Figure 11 was plotted. In this curve the chip width is the ordinate and is dependent upon the particular F that might be chosen. The abscissa involves the relation $\left(\frac{N}{f} - K\right)$.

It is seen that at $\left(\frac{N}{f} - K\right) = 1$ or 0 there is no change in the chip width although the surface traces have an unusual appearance of waviness or undulating lines. Thus for chip breaking the property of the relative speeds of the tool and the workpiece rule out a setting of $N = Kf$.

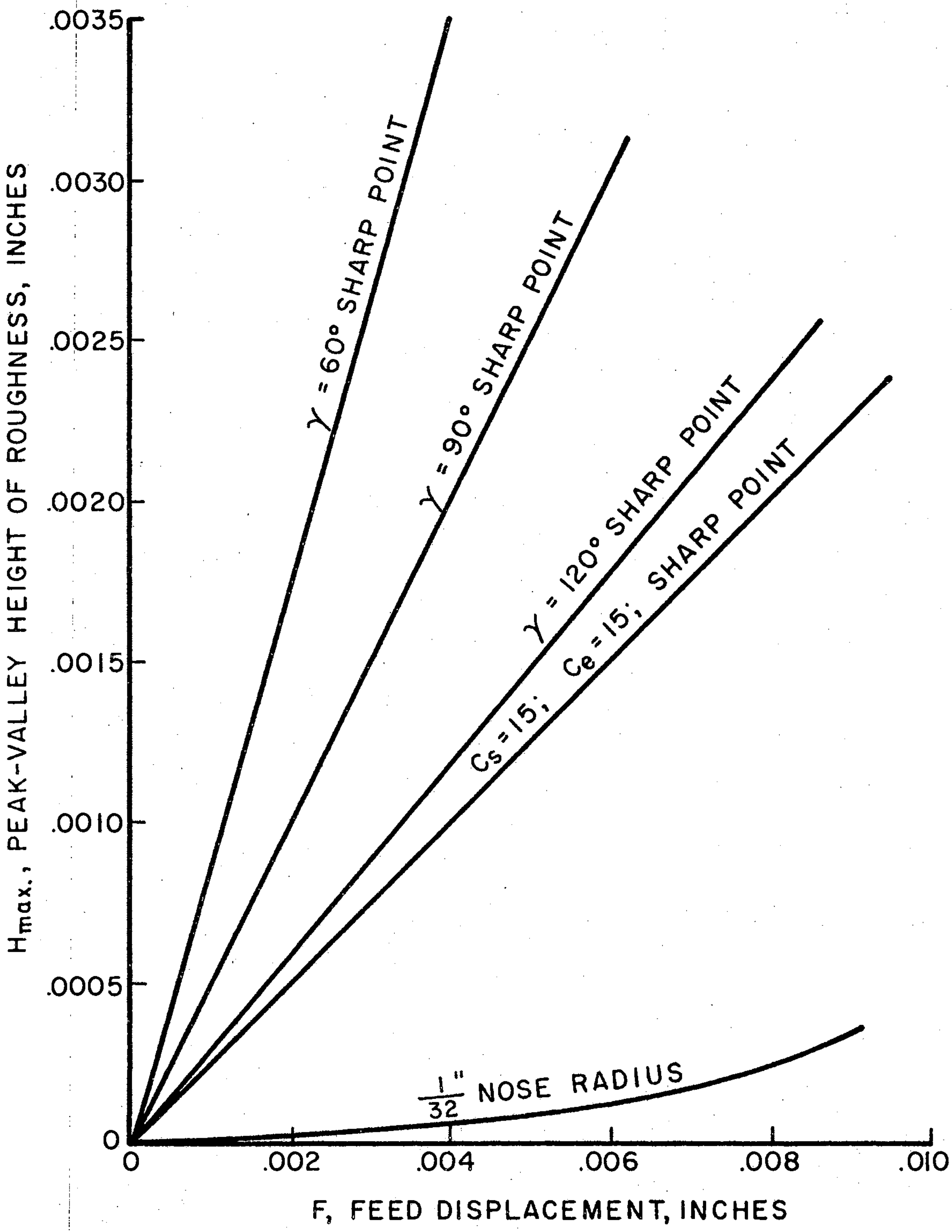


Figure 10. Effect of Feed Upon Surface Roughness for Several Tools

In Figures 5 and 6 this corresponds to schematic #4 where there is given a wavy crosshatched chip area width.
On the other hand at $(\frac{N}{f} - K) = .5$, the maximum variation $F + 2A$ exists. This corresponds to a phase difference of 180° between tool traces i and i + 1.

Increase in Amplitude to Obtain Chip Breaking

Whenever the phase lag is 180° and the tool amplitude = F/2 chip breaking will exist. However it may be difficult to have $(\frac{N}{f} - K) = .5$ exactly, and as a consequence chip breaking may not occur. This can be seen from Figures 6 and 7. To cover the lack of synchronization or mechanical errors in setting $(\frac{N}{f} - K) = .5$, it becomes necessary to increase the amplitude to a critical value A^*. Let $A \leq A^* \leq F$. At a particular t^* on trace i and i + 1 an intersection of the tool traces result such that

$$F + 2A^* \sin\pi(\frac{N}{f} - K)\cos\left[2\pi f t^* + \pi(\frac{N}{f} - K)\right] = 0 \qquad (3.40)$$

$$-\frac{2A^*}{F}\cos\left[2\pi f t^* + \pi(\frac{N}{f} - K)\right] = \csc\pi(\frac{N}{f} - K)$$

For any $\frac{N}{f}$, K is defined. For the equation to hold

$$-\frac{2A^*}{F}\cos\left[2\pi f t^* + \pi(\frac{N}{f} - K)\right] = \frac{-2A^*}{F} \text{ as}$$

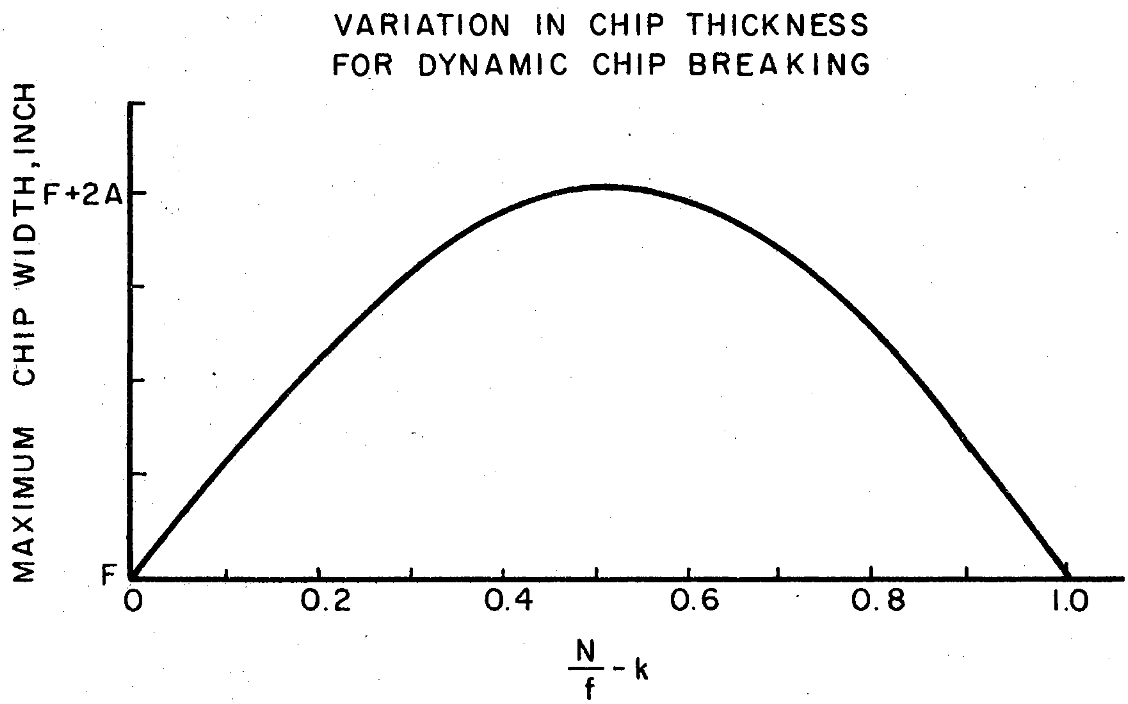


Figure II. Dynamic Chip Breaking Effects Upon Maximum Variation in Chip Thickness

$$\cos\left[2\pi f t^* + \pi\left(\frac{N}{f} - K\right)\right]$$ must be 1. Then

$$\csc\pi\left(\frac{N}{f} - K\right) = \frac{2A^*}{F} . \qquad (3.41)$$

Figure 12 is a plot showing the increase in amplitude for various values of the variable $(\frac{N}{f} - K)$. It is seen that there is relatively little increase in $\frac{A^*}{F}$ for ratios that are near the midpoint .5. At the extreme values of the curve, either 0 or 1, chip breaking becomes theoretically impossible. Thus it can be seen that the variable $(\frac{N}{f} - K)$ should be set as near .5 as possible.

For any value of $(\frac{N}{f} - K)$, $\frac{A^*}{F}$ can be determined from the curve. An example illustrates. For N = 5 cps, f = 4 cps, and F = .00925 ipr, find the critical value of A^* which will insure an intersection of tool trace i and i + 1.

$(\frac{N}{f} - K) = \frac{5}{4} - 1 = .25$. Using the graph, Figure 12, and reading off the vertical scale, $\frac{A^*}{F} = .70$. Therefore $A^* = (.7)(.00925) = .0065$ inch.

Length of Broken Chip

Since the objective of the research is the promotion of short chips, the question of the chip length may naturally be raised. Assume a tool perturbation A^* such

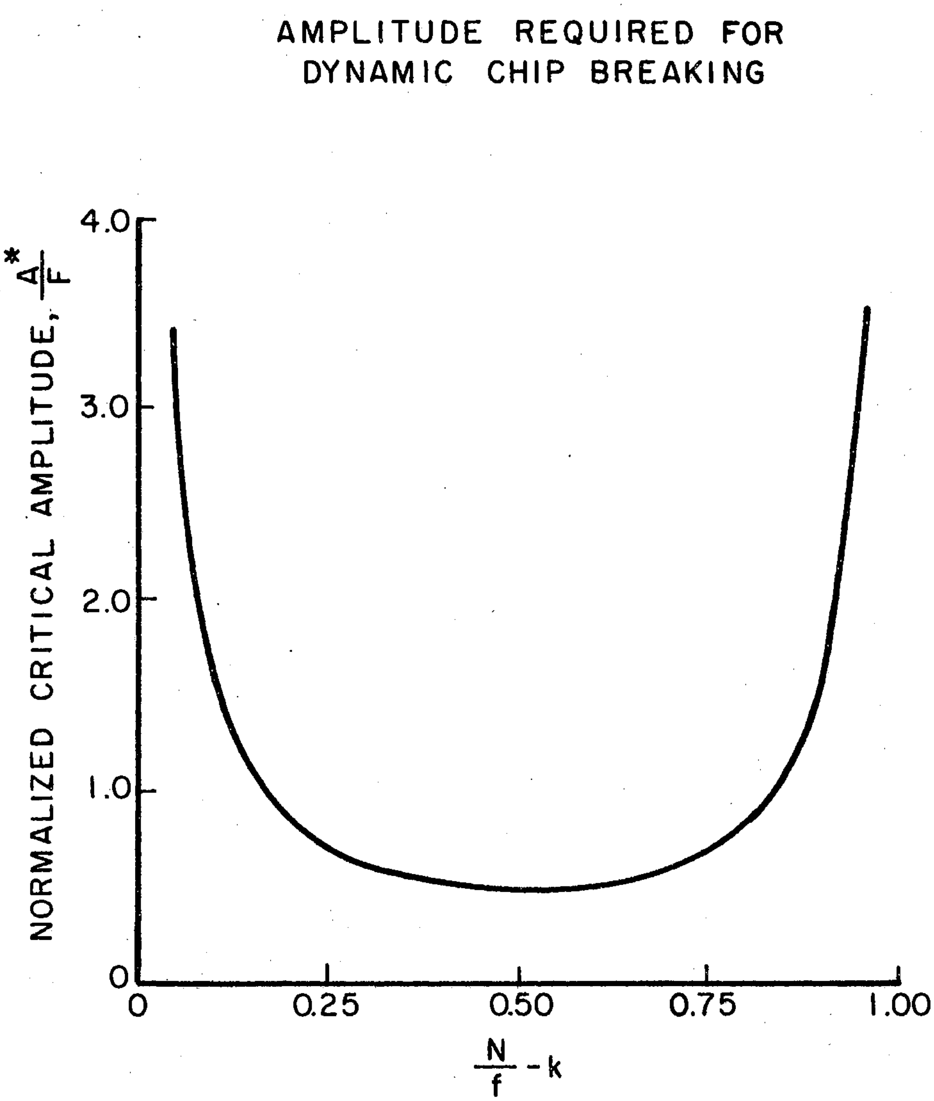


Figure 12. Critical Amplitude Required for Tool-Intersection Amplitude A^* for Chip Breaking

that chip breaking is assured. For a workpiece cutting velocity, V_c, chip length L may be found.

$$L = \frac{V_c}{F} \quad \text{and} \tag{3.42}$$

$$L = \pi D \frac{N}{f} \quad . \tag{3.43}$$

It is evident that the chip length is a function of the workpiece diameter, speed, and tool frequency. Figure 13 presents this relationship for key diameters. At low values of the variable $\frac{N}{f}$, it can be speculated that the chip length is almost dust while at higher values the chip length increases to a size where disposal problems exist again. If the surface speed of the workpiece is fixed due to other processing requirements, the normal procedure would be to find the appropriate frequency to break up the chips into convenient size.

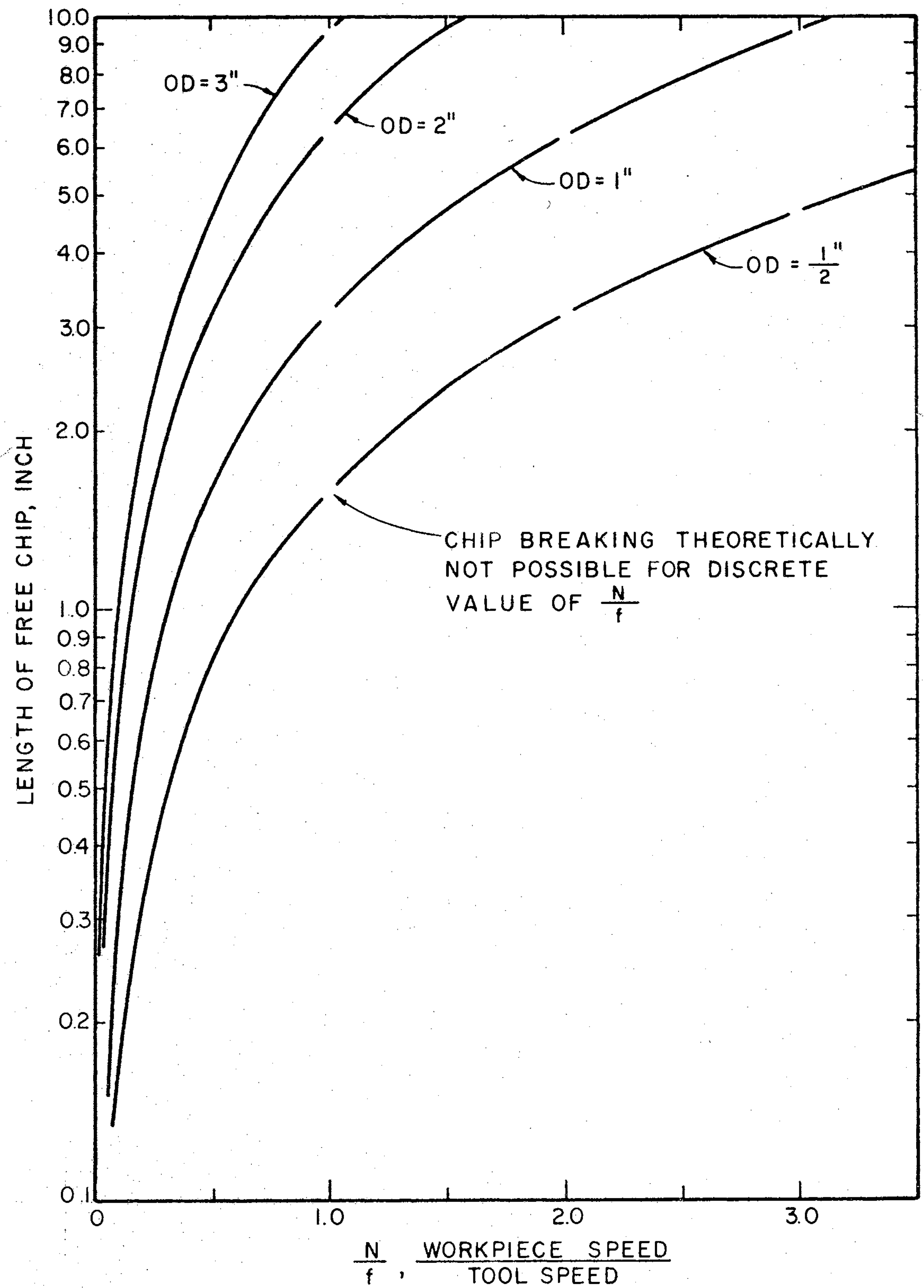


Figure 13. Chip Breaking Length

CHAPTER IV

APPARATUS, MATERIALS, AND EXECUTION OF EXPERIMENT

Emphasis in metal cutting research has traditionally relied upon testing and experimentation. Although the analytical approach is gaining widespread recognition and acceptance, rational design and analytical prediction may not faithfully describe practical results for the general case. Only specific models have found success as the metal cutting field does not lend itself to aggregate analysis and prediction, nor can the empirical approach solve the almost limitless variety of tool and workpiece materials, geometries, and cutting conditions since cost and time diminish the value of the information. If practical results are elusive in the metal cutting field, a compromise between the analytical and the empirical approaches may provide vital useful information. As conceived in this dissertation, research in the metal cutting field will use the critical experiment to prove a model rather than to provide operational data for machinists use. For example, the substitution of wax for metal to simulate the formation of certain classes of chips and a two-dimensional orthogonal model replacing actual oblique cutting conditions are typical non-operational proofs used to substantiate the model with metal cutting data. One of the objectives of the experiment is to provide a non-operational test of a model using conditions which depart from practical machine settings. This chapter discusses the design and development of the apparatus, materials, and testing procedures used for a non-operational test under conditions intended to provide a qualitative and quantitative proof of the model developed in Chapter III.

Purpose of Experiments

The purpose of the experiments is to uncover the effects of premature and tardy tool excursions, periodic in nature, upon workpiece surface height and the dimensions of the free chip. Additionally, the theme of experiment-design-analysis is to test non-operational machine conditions that may depart from optimum and to evaluate the departure in terms of surface and chip geometry from optimum machine settings as found in the test. Finally, the research considers the comparison of test data to generalized analytical predictions as stated in Chapter III.

The Shaker Mechanism

In terms of the equipment required, dynamic chip breaking calls for a shaker which is capable of impressing a harmonic tool oscillation through a wide range of frequencies and amplitudes. As it is necessary for research and for practical application, adjustments which are simple to make encourage better operation. A non-resonant mechanism with an electric motor drive was adopted as the tool actuation vehicle to satisfy these requirements. Figure 14 is a simplified diagramatic sketch of the high-energy low-cost shaker selected for this research. Construction drawings may be found in the Appendix.

In this device, the arm bends the tool alternately in opposite directions at the root point of the tool and tool post. The bending arm encircles the workpiece and joins to an eccentric connecting rod behind the workpiece. A variable speed motor provides the range of speeds to rotate the eccentric which is adjustable. The connecting rod imparts the oscillations to the arm which grips the tool behind the cutting point. Maximum tool-tip double-amplitude is .044" while the D. C. motor has an adjustable speed range from about 2 rpm to 3,000 rpm.

The shaker mounted on the cross slide may move either longitudinally or transversely with the cross slide without affecting normal operation of the lathe. Operation of the shaker is completely independent of the machine feeds and speeds and other controls required in the lathe operation. There was no synchronization between shaker speed control or machine rpm.

Other shaker designs can be used for effective chip breaking. The most prominent is the oscillation of the cross slide parallel to the direction of the feed. Mechanical or hydraulic power can be provided for actuation.

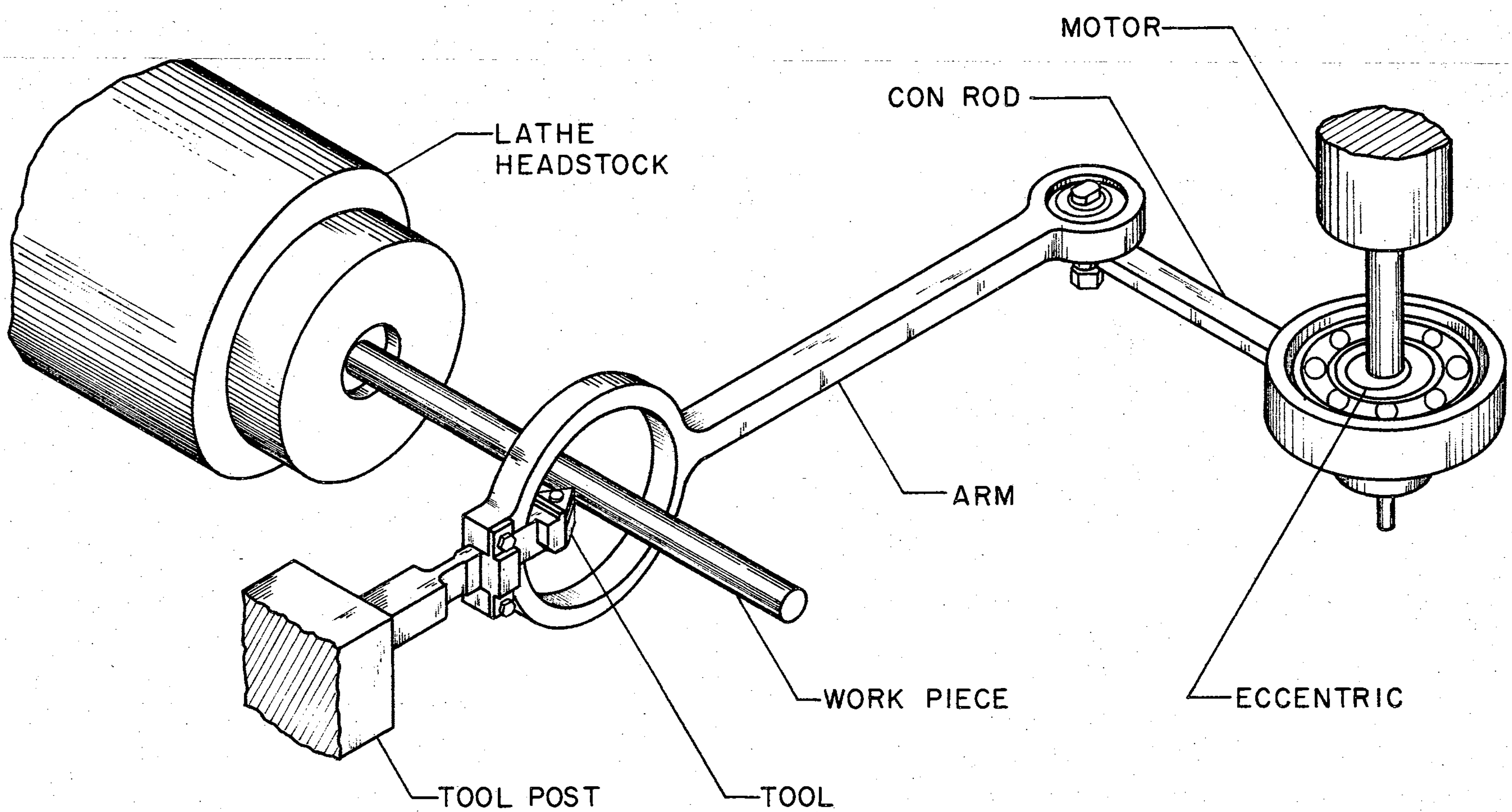


Figure 14. Schematic Illustration of "Dynamic Chip Breaking" Mechanism

However, it may readily be seen that such a system requires more power and introduces complications in the conventional machining system.

Another shaker method unreported upon by other investigators would use a cam to impact hammer blows on a bumper joined to the tool. A bumper arrangement could be designed to specifically direct the impact in the direction of the feed. This method was tried in an earlier investigation, but proved faulty in a number of respects. Although the energy requirements were low for this design, resonance and chatter problems were undesirable aftereffects of the impact. Analysis and measurement proved difficult under the impression of hammer blows upon a tool.

Electronic shaker methods insist upon tremendous power sources for chip breaking. If practical application is to become a reality, the reliability of a system must be high. Although there are extravagant claims concerning reliability for equipment of this sort, it is expected that industrial demands exceed the ability to deliver the energy for chip breaking consistent with reliable service.

Hydraulic driving systems were considered as another means to obtain tool oscillations. Hydraulic methods would be subject to less wear than mechanical systems and would be approximately equal in flexibility. For research purposes hydraulic systems were discarded in favor of simpler and more dependable drives. Nonetheless there can be no doubt that hydraulic systems are useful, but they do entail greater initial cost.

The intention of the shaker design as proposed in this research was to limit the vibration to a single degree of freedom, but spurious vibrations did exist in the other two directions of tool movement. Although the tool had a moment of inertia modulus in the vertical direction six times greater than in the horizontal or feed direction, unwanted sympathetic vibrations were recorded in the direction of the cutting force. Normally vibrations along the thrust component are considered very small. Thus an elipitical path was formed by the coupled motion in the horizontal and vertical directions. Due to the elasticity of the materials employed in the tool and carriage and the forces of metal removal, it can be anticipated that this extraneous movement, though undesirable, must be accepted in the course of tool oscillations at low frequencies and large amplitudes. Serious attempts to limit tool vibrations to one direction would cause an impractical design and introduce other problems. The analyses and measurements assume, however, that deflections and motions of the tool in the cutting and thrust plane are negligible.

The dynamic chip breaking arrangement depended upon alternate reverse bending of the tool at the junction of tool and the tool holder. Naturally, the tool root is subjected to alternating stresses and fatigue failure could be expected to develop over a period of time. Secondly, there is an occasional tendency for the chips to jam between the bottom of the tool and the encircling bending arm. The latter drawback could be eliminated by having the shaker mounted on the front side of the workpiece. Fatigue of the tool can be eliminated by having a knuckle joint mounted within a bearing to provide free rotation.

During certain ranges of operation excessive chatter and violent machine vibration occurred which limited the upper regions of the oscillation. As a result, operation was limited to lower ranges (0-20 cps) of frequency. The limiting upper frequency depended upon the tool amplitude. It is believed, however, that this particular constraint did not restrict the usefulness of the equipment in fulfilling the objectives of the test.

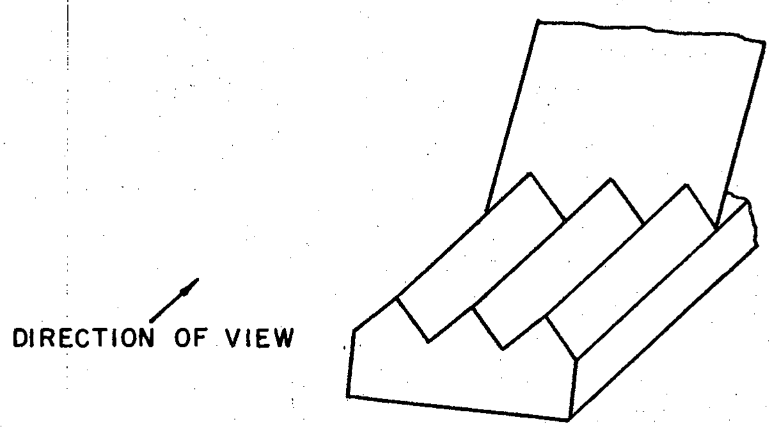
Other investigators provided for synchronization between the tool frequency and the machine rpm (3)(5-9). This assures a fixed value of $(\frac{N}{f} - K)$ throughout the length of chip breaking. Dlough (10) contended that this was an unnecessary complication for practical application and was the first investigator to ignore the possible effects of shifting tool or machine speeds.

The Machine Tool

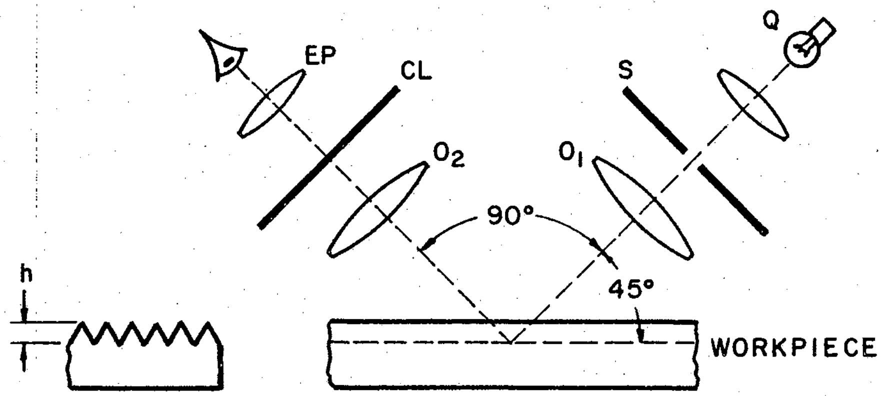
A variable-speed and variable-feed tool-room engine lathe was used as the machine tool for the test. Hardinge Model HLV-H is a small finishing lathe used principally for close tolerance work. The fact that a stepless speed and feed arrangement existed permitted testing advantages over a production lathe with fixed speeds and feeds. A layout of the lathe giving important dimensions is provided in the Appendix.

Surface Measurement Equipment

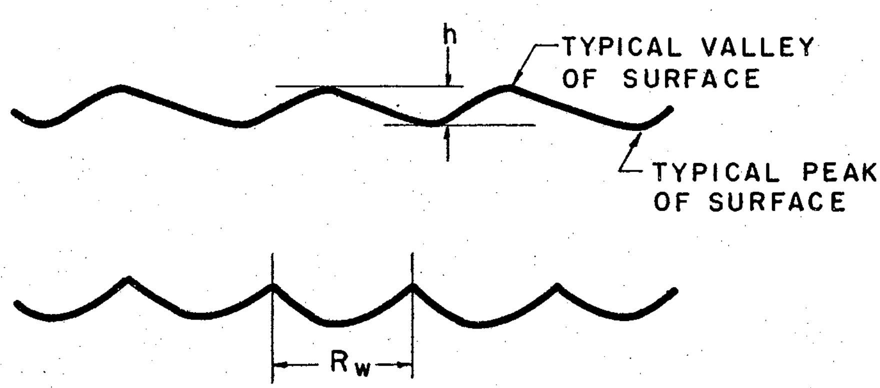
Although two methods of surface measurement were used only one method germane to this research will be discussed as it is assumed that the tracer method is sufficiently well known. A second instrument developed by Schmaltz and marketed by Zeiss operates on the light section principle. A diagramatic sketch is provided by Figure 15. According to this principle, an optical "cut" is made through the surface without touching or scratching. In operation an incandescent lamp Q illuminates slit S. A razor-like beam projects through objective O_1 at a 45^o angle to the surface of the specimen or workpiece. This band of light is observed through a microscope at the opposite 45^o angle. The microscope objective O_2 has the same magnification as objective O_1. This fine band of light traces out the profile of the surface and one is able to observe the peaks and valleys. A cross line reticle CL in the eyepiece EP can be shifted within the field of vision by means of a graduated measuring drum. Two measurements are possible: roughness height, h, which is a measurement of the peak to valley distance, and roughness width, R_w, which corresponds



PERSPECTIVE OF "LIGHT CUT"



SKETCH OF SCHMALTZ OPTICAL PRINCIPLE



TWO SAMPLES OF SURFACES

Figure 15. Optical Light-Cut Section Microscope

to the distance between peaks or valleys. Height measurements are in microns; width is in inches. The instrument can detect a range of .000040 to .016 inch. Height measurements are read directly off the measurement drum with calibration being unnecessary. A 35 mm. camera may be attached to the body of the microscope for contour picture taking. Typical pictures are presented in Figure 26 and 27. Discussion of analysis of the microgeometrical properties will be explained in greater detail in Chapter V.

Other investigators used the tracer method whereby an indicator reading was obtained. In a few instances a strip chart replaced the indicator, however, the strip chart does not faithfully resolve the microgeometrical properties of the oscillated surface.

Other Instrumentation

To obtain close control of the tool frequency, an initial trial run was made to determine the frequency from an oscillograph trace and by successive approximations the speed control was adjusted until the desired frequency was obtained. It was not a difficult technique as the first setting of the direct current motor control was close to the intended frequency.

It was not possible to make measurements of the tool amplitudes by dynamometry as the tool point location constituted an indeterminate structure point and displacement readings could not be considered reliable. To provide these amplitude distances, a differential transformer type transducer was mounted near the tool point. Displacements were recorded by an oscillograph which was able to record frequency and displacement of the tool. Naturally, the transducer could not be mounted at the point of cutting, but it is safely assumed that the deflections of the cutting point were identical to that of the differential transformer despite its 1/2 - 3/4" distance from the actual point of cutting.

The lathe provision for speed indication was not trusted. A calibrated hand tachometer was used to control rpm. A digital decade counter system displaying rpm was considered, however, the accuracy of ½% was considered no better than the simple hand tachometer.

Recording of information was handled by a two-channel carrier-type oscillograph, with recording speeds of 1, 5, 20, or 100 mm. per second possible. Limiting frequency for dynamic recording was specified as 125 cps. The instrument was manufactured by the Sanborn Division of Hewlett Packard and has a model designation of 321.

A three-axis tool-post dynamometer with internally mounted strain gages was used to mount the various 5/8" square tool shanks. Its usefulness was limited to monitoring tool cps.

Tools and Workpiece Materials

Two types of tools employing sintered carbide material for the cutting edge were used for this research. One tool was designed and constructed especially for the research while the second was donated and modified to suit the requirements.

A right-cut sintered-carbide tipped, single-point tool with the signature -5, -5, 5, 5, 13.6, 13.6, .005 was of the patch type style. The brazed tip had the dimensions of 1/4" x 1/4" x 1/8"R x 1/16" thick. The tool shank, 5/8" square, was reduced in cross section to 3/16" thickness to allow gripping by the tool bending arm. The cutting point radius of .005", though not specifically stated, was measured by a toolmakers microscope with an enlarged viewing screen. No static chip breaker was employed. The Appendix provides dimensional details for construction.

The second tool was of the replaceable insert variety. The tool and insert had the signature of -8, 0, 5, 5, 30, 30, 1/32. The Carb-O-Lock Style E triangular insert was blended for high temperature service and was plain with no grooves for chip breaking. The Carboloy Model TE-10 tool holder was modified by reducing the 5/8" section to a 3/16" width to permit grasping by the tool arm. The 5/8" height of the shank was left unaltered.

Only visual tool wear measurements were made during the course of testing. It is safely assumed that wear would be negligible with the workpiece materials. Additionally, all cutting was done without cutting fluid.

Extruded polyethylene plastic constituted one of the two materials used. Physical properties for the plastic supplied by the Spencer Chemical Company were:

Elongation:	260 - 400%
Color:	White
Surface Friction:	.10
Tensile Strength:	2,500 - 3,000 psi
Density:	.918 gms/cc.

The plastic proved excellent in the machining properties. The chip length did not break randomly due to internal stresses of machining as is customary for ferrous or non-ferrous materials. There were no problems associated with a built-up edge at the tip of the tool. Reduction in friction, increased tool wear, and retained ductility are further qualities that proved this material worthwhile as the testing medium. It is suspected that residual stresses from machining were low.

One of the interesting material properties was that of surface friction. While the coefficient of friction for steel on steel ranges between .98 to 3.0, the polyethylene plastic has a surface friction value of .10 which approaches the value for teflon. This lubricity accounts for fine machining properties.

The aluminum material, 2011-T3, possesses high finish properties and frequently is used in automatic lathes because of its ease in machining. The physical properties for the 2011-T3 are: Hardness, 95 Brinnel and Tensile, 43,000 psi.

Discussion of Variables

As in most metal cutting research some of the variables are susceptible to errors of measurement, control, and repeatability. In this research six variables were subjected to various amounts of skills in their measurement. The following is a discussion of these variables and the influence they have upon the pursuit of the experimental progress of the dissertation.

The workpiece rotation, N, was preset prior to each test by a hand tachometer. As the forces of cutting were small, the speed reduction under load was less than one rpm. Repeatability did not present a problem.

Tool frequency was established by adjustment of the D. C. speed control. The initial setting was controlled by a calibrated value on the voltage regulator and adjustments were made to correspond to the cycle trace readings from the oscillograph. Once the established frequency was selected, the test proceeded with the oscillograph recording the tool frequency. At the conclusion of the test, the actual tool frequency was found. If a frequency change occurred, the magnitude measured less than 2.5%. Errors from the nominal were considered negligible.

Due to the dynamic effects one amplitude selected for one frequency would be greater or less if another frequency were chosen, thus making it necessary to set amplitude values for each value of frequency. The adjustment of the amplitude was the most frequent adjustment as it was necessary for each trial. The setting of the amplitude followed this pattern. Once the frequency was set the amplitude value was correspondingly increased or reduced by merely changing the eccentric in the con rod. Scribed marks on the eccentric encouraged repeatability but did not assure absolute presetting of the amplitude values. Adjustments of the eccentric again relied upon the measured oscillograph readings for correct alteration of the amplitude. Setting the critical amplitude A^* by this means could hold the actual test amplitude to the desired value within an average of + .00015" which corresponds to a deviation of 2.7% from the desired.

Of the fundamental variables affecting surface finish, feed was subject to fewer errors of operation or repeatability problems than the variables already discussed. Two methods were used to set the feed. The most direct method used the gear box, while the second relied upon the lathe variable speed motor which was a stepless drive within its operating range. Repeatability was assured for the fixed gear selections provided, of course, that the correct gear ratio was chosen. In using the stepless feed control each selection of the feed depended upon a setting that was subject to errors of operation. However, it is believed that these errors were minimal.

The major dependent variable was surface roughness height, h_i, for tool trace i. The advantages of surface measurement by the method of the light section microscope and tracer have been discussed, but the technique of surface height measurement must now be described.

One must first consider the materials used for the workpiece. When using polyethylene plastic the tracer method is unsatisfactory because the diamond point needle scratches the surface and depresses the peaks to give a smaller surface height. As a result, the surface roughness height of the plastic specimens was measured by the light section microscope. A similar problem of scratching was found for aluminum materials, however, the magnitude was not as exceptional as for plastic. Both methods of surface finish measurement are suitable for aluminum.

The two devices differ with respect to the measured quantity. In indicating an average value the tracer method electronically integrates the absolute average value of peaks and valleys above an imaginary central line above a selected sampling length. Sampling length is normally .030" which is standard for the industry. The tracer indicated value of average surface height does not correspond directly to the value as determined from the light section microscope.

The surface roughness height measurement by the optical light-cut method involves several operator techniques that have a significant bearing upon the success of the final measurement. As the light-cut method is not as automatic as the tracer method, procedures become important.

Within each trial, a minimum of 20 readings were taken and averaged to give a final single reading. Since the height was expected to have a high-low pattern for adjacent peaks, it was important that bias be prevented in the selection of the particular peaks to be measured. For example, if every other peak or every fourth peak were measured, it would be possible that only low or high peaks were measured thus falsely influencing the readings. On the other hand, if every consecutive peak were selected for observation this bias would not be evident. After five consecutive readings were obtained the workpiece was rotated randomly along the circumference and displaced along the longitudinal axis. Figure 16 illustrates cases where it is possible to measure only low peaks or low and high peaks. Randomization of peaks for measurement was considered technically difficult and no formal attempt was made to do so. As Chapter III suggested, the average of the height of any two neighboring peaks constituted the theoretical surface roughness height. Nor did it matter where on the diameter the observations were made. However, in an effort to further confuse any possibility of bias, the barstock was rotated 90° after five readings were obtained.

A second type of height measurement error was possible. By reference to Figure 9 in Chapter III it may be seen that the reference line that serves as the floor for the height can vary depending upon which side of the peak the measure-

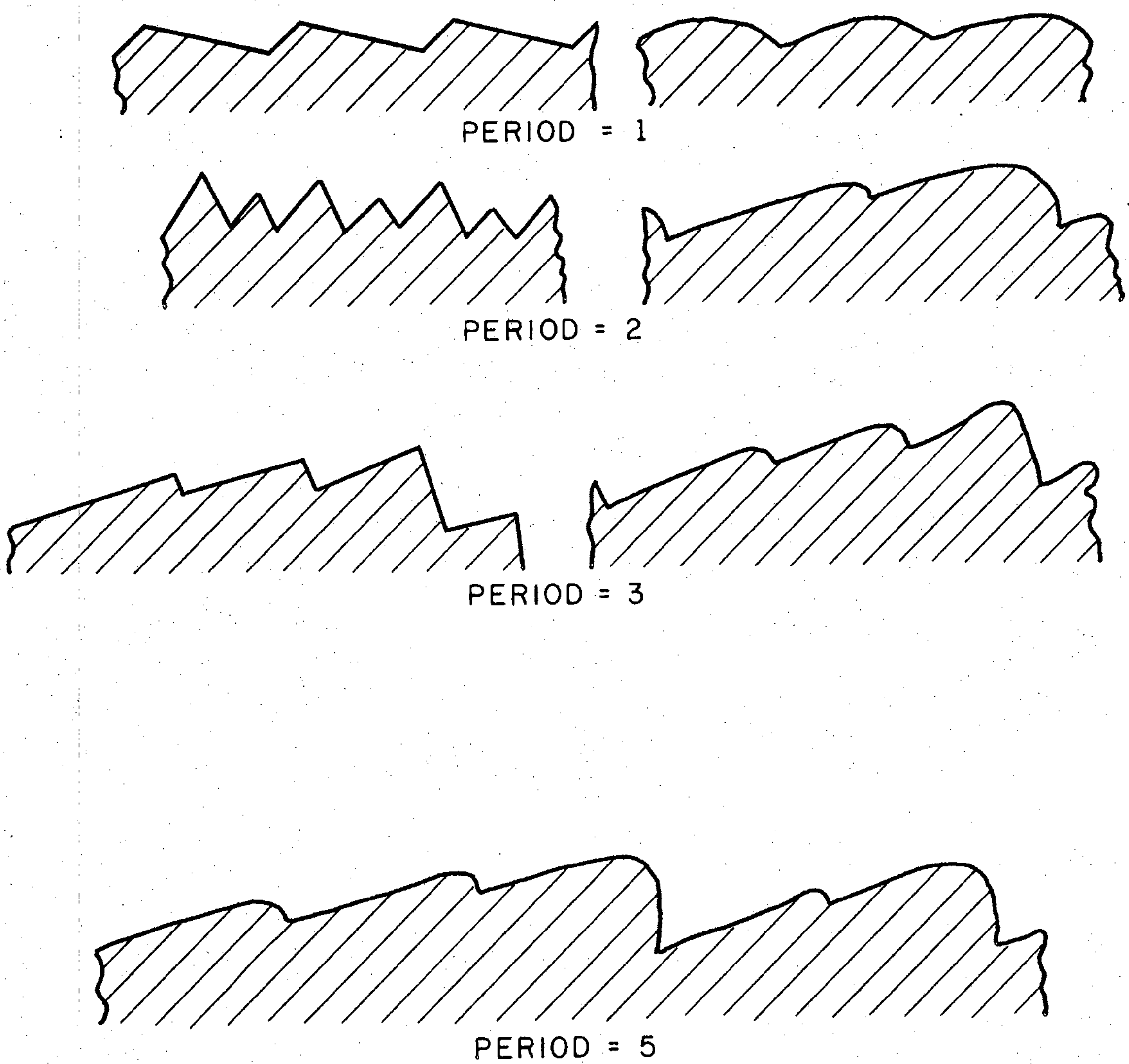


Figure 16. Typical Profiles

ment is taken. Figure 16 illustrates this point. Figure 26 shows pictures of height variance depending on which side of the peak was chosen for measurement.

Another major dependent quantity, chip length, was measured by a scale and presented no problems for plastic. Aluminum chip length was not measured. Chip geometry other than length is another facet for investigation, however thickness values would be difficult to measure because the width varies as a sine function as described by Figure 11 of Chapter III. A chip is expected to vary from a maximum width at the midpoint of the chip to zero at the ends.

Several variables are considered fixed within a test. Such variables as the tool geometry, depth of cut, and length of cut are typical constants. As was seen in Chapter III the effect of depth of cut was ruled out and considered a variable of little importance. There is one caution on depth of cut; it must be sufficiently deep to classify it to one of the three models that Chisholm (17) proposed. Figure 4 of Chapter II illustrates the results when depth of cut is too shallow. In this illustration tool type B and C could easily converge for a shallow cut.

It was necessary that the length of cut be sufficiently long to permit a measure of assurance that the chip breaking process would not change. Once the oscillation started transient vibrations would dampen out leaving the externally forced vibration to continue. The transient vibrations, existing only at the start or end of the forced vibrations, were unimportant from the experimental or theoretical standpoint. The surface roughness height had to be determined at a sufficient distance from either the starting or stopping point to assure that the height would not be affected by this extraneous and temporary influence. The minimum testing length of $\frac{1}{4}$" guaranteed an adequate interior length unaffected by the transients.

Two different types of tool geometry were used. Within a test series, the tool type was constant. No direct test comparisons on the effect of surface roughness height were planned for the two tools.

The factor of diameter was not believed to have any influence upon the outcome of the surface roughness height, although it is significant for chip length. To prevent the bias that diameter might have upon the outcome, one of two experimental designs were used. The first used a random scattering of the different diameters within a test, thus distributing the effect if it existed experimentally among the units. The other method used a constant diameter for all test items. The first method was necessary for a situation having only a limited amount of material with the six experimental units varying in diameter by $\frac{1}{4}$". The diameters of the experimental units were measured before and after testing to verify that a constant depth of cut was removed.

Experimental Procedure

Five tests were conducted during the experimental portion of the research. Although some of the routine may have varied between the test programs, they were substantially alike. Once the test bars were prepared, the testing routine was as follows:

1. Material loaded in lathe
2. Workpiece rotational speed established, resetting unnecessary for tests using one speed
3. Feed selected by gearbox or variable-feed dial
4. Depth of cut set
5. Tool amplitude and frequency set for particular test point
6. Recorder started for duration of test
7. Test performed
8. Repeated for number of separate tests on test bar, removed test piece from lathe.

Once the material was exhausted and no more tests could be run on the test pieces, surface measurements and in some cases chip length measurements were begun.

The essential steps for surface measurement for the light section microscope were as follows:

1. Specimen loaded in blocks
2. Necessary optical adjustments made to permit surface examination
3. Measurements made and recorded by means of height gage dial.

Experiment 1: Influence of Frequency, Feed and Amplitude Upon Crest-Root Height

This test, a 3^3 factorial, was performed on six test bars of plastic material approximately 2" in diameter. The test bars were reused two additional times with a reduced diameter caused by the previous runs. The measure of the effect of the diameter upon the nature of the response, surface roughness, can be assessed on a between-run basis.

The test impressed three levels of amplitude, frequency, and feed upon the tool. Workspeed of the material was held constant at 180 rpm. The technical details of the test are given in the Appendix.

As an adjunct to the purpose of this test, a "control" on the effect of feed was run to determine the response of the variation in feed upon surface height. Operating conditions were N = 300, frequency = 0, depth of cut = .040", and tool geometry was -5, -5, 5, 5, 13.6, 13.6, .005.

Experiment 2: Influence of Frequency Upon Crest-Root Height

One of the significant variables subject to control by the operator was the frequency of the oscillating tool. As the speed of the workpiece was determined by other considerations, the tool speed gained in importance and understanding. This test, a single-factor randomized block design, singled out the influence of frequency upon the surface geometry under chip breaking activity.

The factor, frequency, was varied for several pieces of material. A total of eight frequencies were impressed upon the tool. One of the eight, f = 0, served in the role of a control of quality upon the test. Each of the eight frequencies were randomly assigned to the six specimens and were examined by the Zeiss Light Section Microscope following testing. The speed of the workpiece was held constant at 420 rpm, depth of cut at .040", and the tool signature was -8, 0, 5, 5, 30, 30, 1/32.

As the amplitude of the vibration necessary for dynamic chip breaking may be expected to vary with the frequency steps, the theoretical value was determined by methods described earlier. This special amplitude, A^*, was then used in the test. The Appendix provides the technical details for the test.

Experiment 3: Influences of Frequency and Amplitude Upon Free Chip Length

Dynamic chip breaking has the objective of making long chips into shorter ones. Although other tests were involved in chip breaking, this test was specifically arranged to test the theoretical length as determined by Figure 13, Chapter III.

Two conditions of chip breaking amplitude were established. Condition one used the amplitude value A^* for the chip breaker while condition two employed excessive amplitudes. The purpose was to determine the effectiveness of the chip breaking unit, and to compare the lengths and surface roughness between the two conditions. Other than amplitude, there were no significant differences in the operation of the comparison tests. The Appendix provides the test details.

This comparison used a constant workspeed of 3 cps. To cross check for other difficulties chips were collected during the course of Test 2 which was run at 7 cps workspeed.

Experiment 4: Influence of Amplitude to Break Chips in Aluminum

Unlike the polyethylene plastic material, aluminum curls when machined in the conventional "figure-six" and "spiral-eights." The determination of the chip breaking is not as straightforward as with the plastic material since the aluminum may break prematurely from cutting stresses. For this reason a test was conducted to determine under what conditions of amplitude the chips would be expected to break. As it is desirable to hold the amplitude to a minimum and at the same time achieve chip breaking, the test results were based upon a visual determination.

The conditions for the parameter were $(\frac{N}{f} - K) = .5$, $N = 3$, and $f = 2$.

Test	A	DOC
1	.0038	.040
2	.0038	.020
3	.00225	.040
4	.00225	.020
5	.0016	.040
6	.0016	.020

The test was conducted in the following manner. The speed of the workpiece and the amplitude of the tool were preset. The feed of the workpiece was adjusted by the variable speed control of the lathe until the chips were broken by the action of the perturbation. The feed setting was then noted. The determination of the actual point at which the chips broke due to the dynamic chip breaking action was based upon visual observations of the chips leaving the workpiece. This measure was found a minimum of three times for each of the treatment combinations.

Experiment 5: Influence of Tool Frequency, Material, Work-speed Upon Roughness in Machining Aluminum

Aluminum is one of the more ductile materials known for its troublesome history with continuous chips. Consequently there is a need to demonstrate the principle of dynamic chip breaking with a material of this sort. The purpose of this test was the determination of the success of dynamic chip breaking and surface roughness resulting from the chip breaking action. To achieve the goals of the testing, a factorial with six levels of frequency and three levels of workspeed was selected. Additionally, based upon the knowledge of the workspeed and tool frequency an amplitude sufficient for dynamic chip breaking, A^*, was determined and used as one of the nesting factors inherent in the procedure. Additional details may be found in the Appendix.

CHAPTER V

ANALYSIS OF EXPERIMENTAL DATA

The purpose of Chapter V is to explain the results of the experiments that were discussed in the previous chapter. Its objectives are limited to specific remarks relevant to the experiment and it leaves for later any inferences, conclusions and recommendations on research that may be pertinent to dynamic chip breaking. Only curves or important table values are provided here and statistically significant data are included in the Appendix.

The reporting of this information will simultaneously convey a discussion on the classes of errors that may have influenced the reliability of the errors, both personal and experimental, upon the outcome. Systematic and assignable causes of error will be evaluated whenever possible although it is impossible to consider these classes on the basis of statistical law. Finally, the importance of the size of the scale division on the practicality of the measurement will be assessed.

In certain tests a control or standard was similarly treated, thus enabling a comparison between the response of a treatment and one where there was no treatment. Usually the analysis takes the form of a comparison between the surface height from an experimental unit with tool perturbations and one under normal machining.

Experiment 1 Discussion: Influence of Frequency, Feed, and Amplitude Upon Crest-Root Height

Two of the three main effects tested by this experiment, amplitude and feed, proved statistically significant. Their values are plotted in Figures 17, 18, and 19. The control is shown in Figure 20.

As the feed was increased the surface height was correspondingly increased. In every case the responding crest-root height was acted upon either increasing or decreasing the height as the feed was similarly changed. This characteristic response is well known and the test presented no new revelation.

Three levels of amplitude were employed. For each condition of frequency and feed a particular amplitude was used. The lower level $\frac{A^*}{2}$, did not break the chips into short sections which agreed with theory. The middle level, A^*, adequately broke the chips, although in some cases they were hanging together by the finest of threads. Under these operating conditions, the polyethylene behaved well, for had there been internal stresses, the continuous chip would have fallen apart during subsequent handling. This level of amplitude was selected to give an indication of the accuracy of the equipment to agree with the theoretical

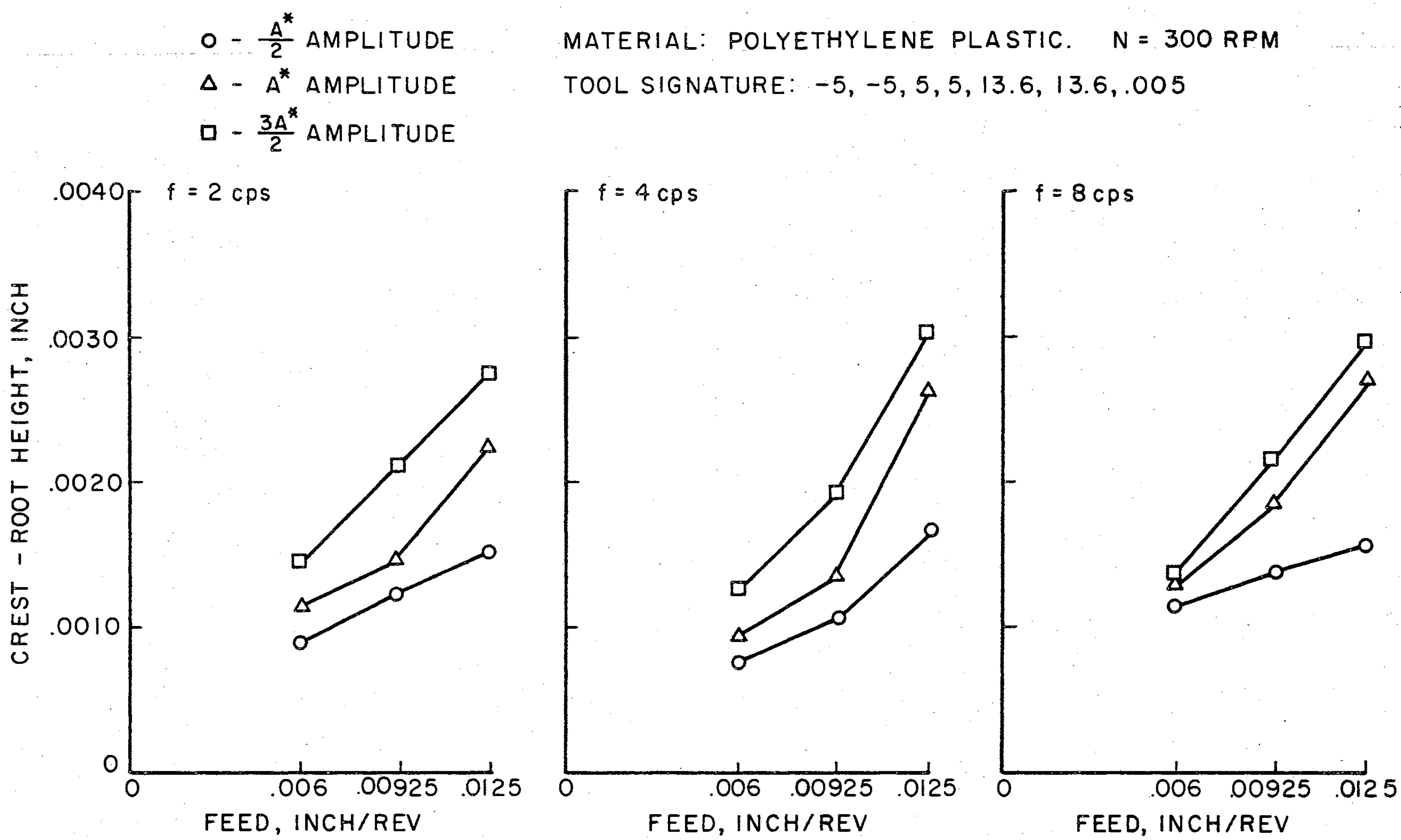


Figure 17. Response of Surface Height to Test Conditions

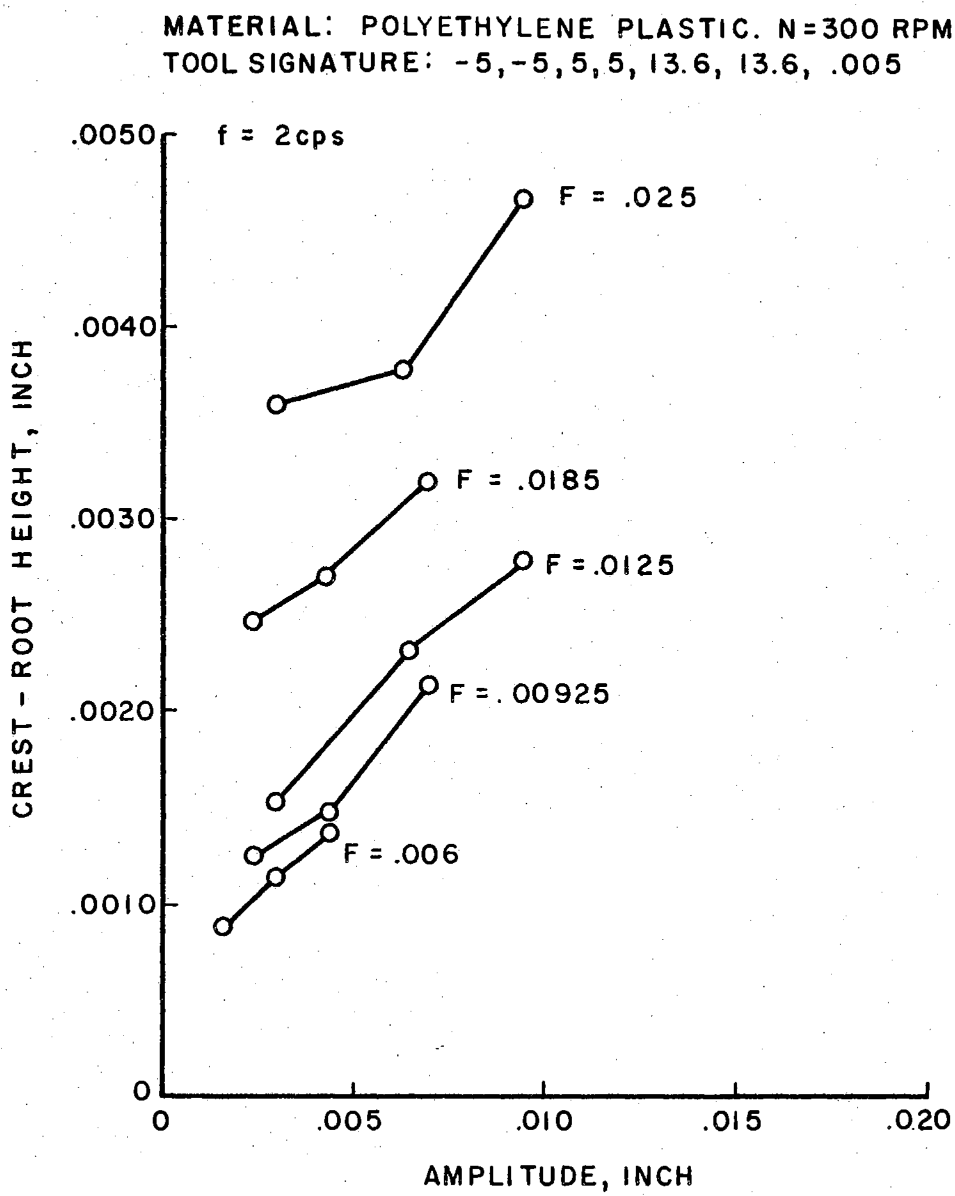


Figure 18. Response of Surface Height to Test Conditions

MATERIAL: POLYETHYLENE PLASTIC. N = 300 RPM
TOOL SIGNATURE: −5, −5, 5, 5, 13.6, 13.6, .005

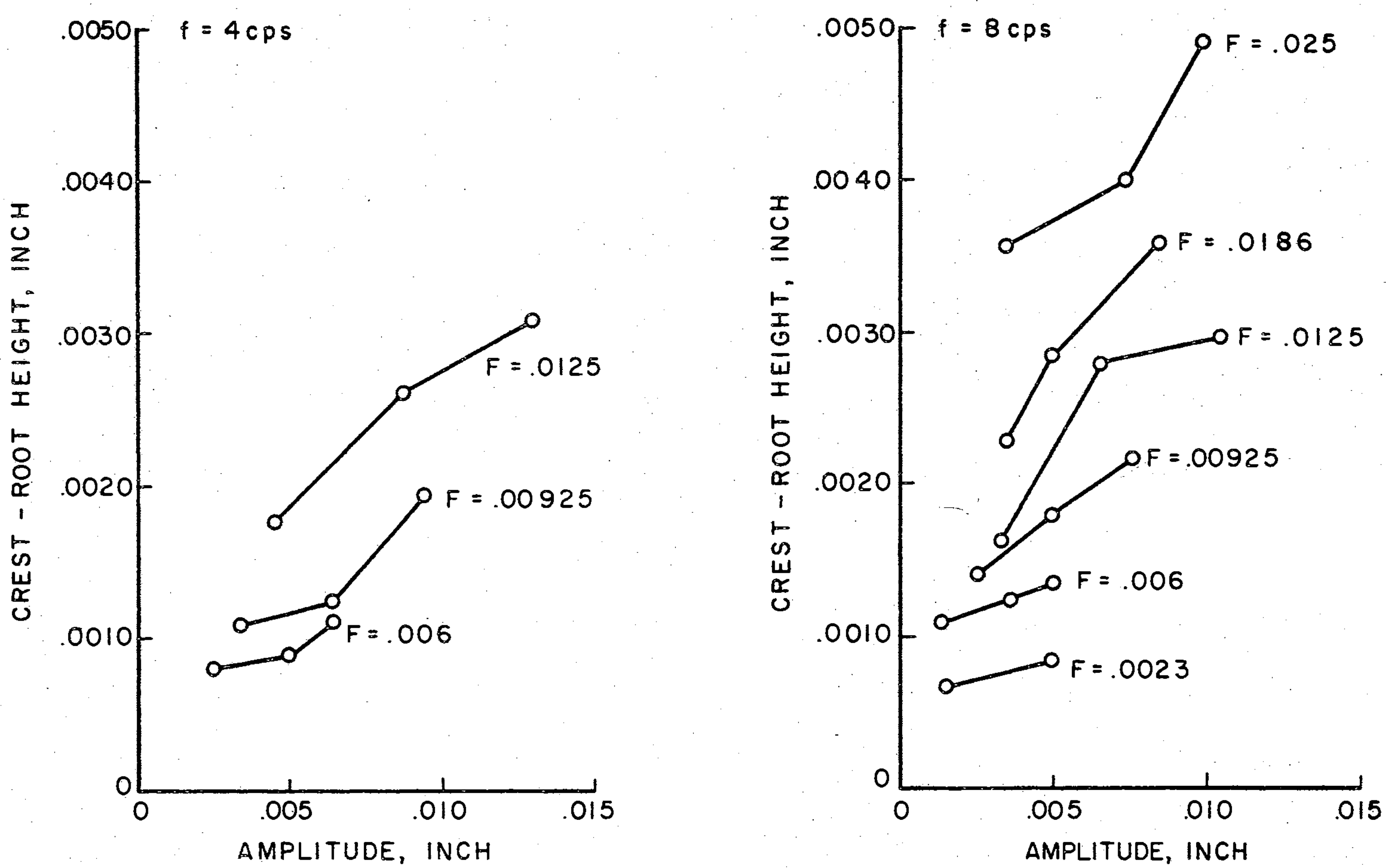


Figure 19. Response of Surface Height to Test Conditions

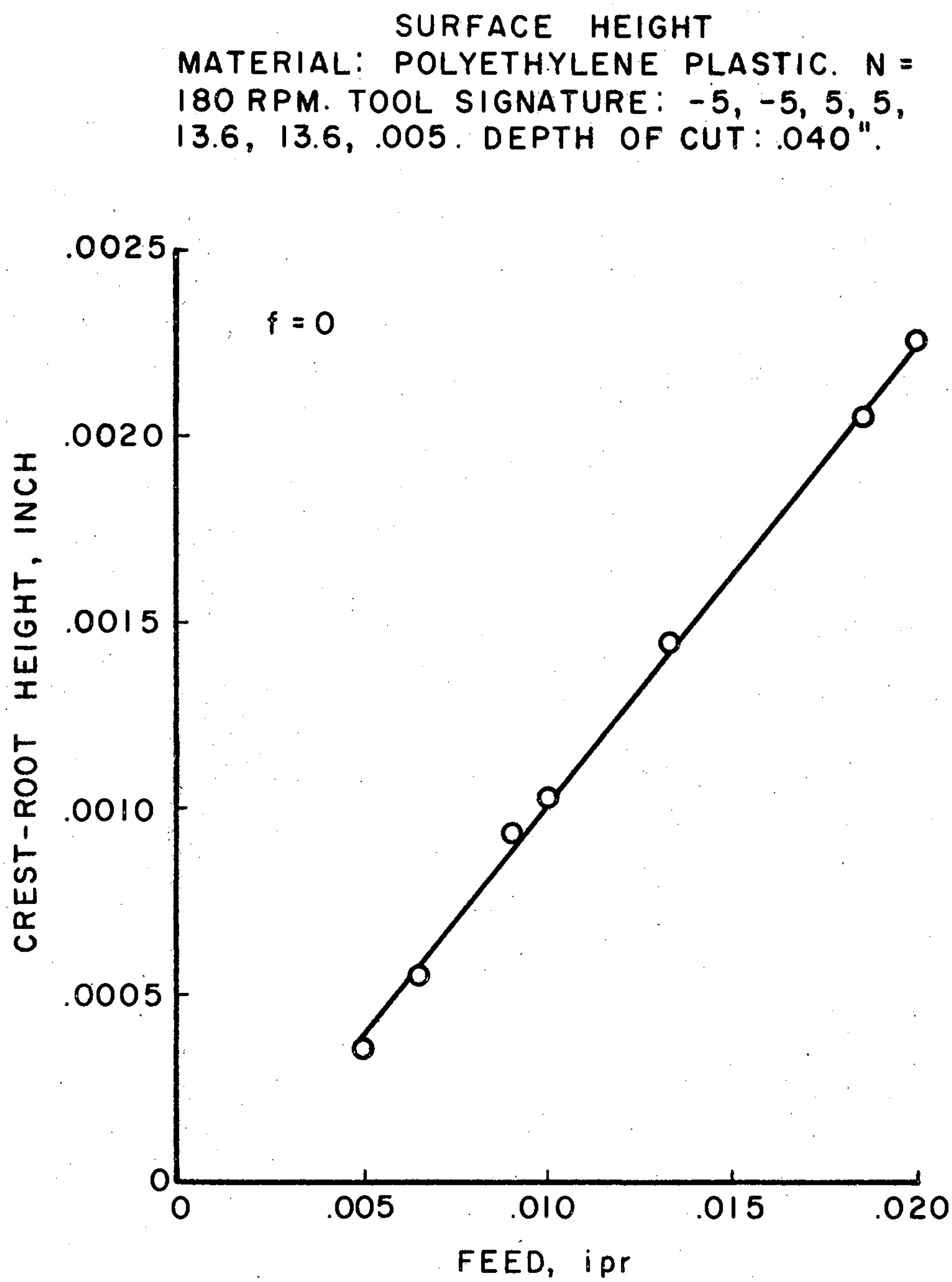


Figure 20. Conventional Surface Height Without Dynamic Chip Breaking

requirement of the amplitude for chip breaking. When the amplitude was properly adjusted to a value of $\pm .0002"$ around the theoretical requirements the equipment performed as required. The third level of amplitude, $\frac{3A^*}{2}$, broke the continuous chips in all cases.

In examination of the recorder traces, the deflection of the tool behaved harmonically, and the impact of the tool upon reentry into the material during excessive amplitudes was unaccompanied by any hard hammer blows of the material upon the tool. During the cutting operations for the three levels of amplitude, the harmonic perturbation of the tool did not appear to change.

As dynamic chip breaking was the objective, operating conditions A^* and $\frac{3A^*}{2}$ met the stipulated requirements. The excessive amplitude condition, which initially might be considered desirable, served to increase the surface height by 22% over the minimum amplitude required to sever the continuous chip.

Response of the material was excellent and continuous chips were easily produced unless the tool deflected to deliberately cut the cord. In coming off the work material, the polyethylene chip reminded one of nylon kite string and felt very slippery. The chips were lukewarm to the touch and could be handled without harm.

In comparing the treatment to the control, the crest-root height grand average increased by 80% over the nonoscillated conditions. This percentage decreased as the feed dimension increased. At lower feeds, .006 for example, the increased roughness amounted to 128% while at .0125 the increase was 76%.

Sample pictures of microphotographs taken with the Zeiss Light Section Microscope are provided in Figures 26 and 27. Originally it was believed that the microphotograph could be used to numerically determine the quality of the surface. Unfortunately a stage micrometer was unavailable which negated the potential use of this measure. The stage micrometer is normally photographed with the sample specimens and follows the same path of picture processing. As the surface was magnified by the microscope camera and enlarged during the film processing it was technically difficult to relate features of the photograph to dimensions. For this reason, only qualitative remarks can be made regarding the pictures. In viewing the plates, the image is inverted with peaks pointing downward and valleys pointing upward.

In analyzing the photographs it becomes apparent that the premise of similarity of peaks and valleys on a period basis where the period equals two is not valid. It was assumed in Chapter III that after two peaks were machined, the following surfaces would ideally be a repeat of these two peaks. Only infrequently was this condition of duplicate peaks on a period basis found. Picture A of Figure 26 suggests this contour. On the other hand, the fact of a periodic contour is valid; however only a few pictures were capable of showing this feature since the period length was wider than the width of a picture. In many cases the period was three, four, or five before the surface geometry repeated itself. Picture B suggests a period of three.

It was noted that the microgeometry varied from picture to picture. In some cases the surface resembled the tool, but in most the surface geometry was different than the expected appearance of the plan view of the tool. The included angle of the tool was 90^{o} but in Picture C, the included angle was about 120^{o}.

In a few pictures, the point at which the chip may have been pinched off by the tool can be discerned. The suspected pinch-off point may be viewed in Picture D for it is not a replica of the surface of the tool. The pinch-off point has a unique geometry and is found infrequently.

One of the more obvious manifestations found in the picture is the shortening of the valleys due to the bending action of the tool. As the tool reached the maximum amplitude of oscillation, the tool height relative to the surface was shortened, collaborating Figure 9 of Chapter III. Pictures E and F indicate this response. The changing datum for the surface caused surface undulations and unusual surface patterns.

The light section microscope was used principally for measurement of the crest-root height. This measurement was vital to the determination of surface roughness of the plastic material. The reference datum was the valley floor of the tool path, since this was more of a datum line than the crest-height point. The valley floor offered a more reliable reference plane. When using the valley floor, the movement of the cross hairs to the height of the crest required a judgment as to the exact point of the height. The line intersection of the high point was often blurred as it was out of focus. A sharp fixation on this height required an approximation. In repeatability tests on the same crest-height ridge, the measurement could be expected to vary within ± .000080" or the equivalent of two microns or two scale divisions on the measurement drum of the microscope. For each test specimen it was necessary to take a minimum of 20 readings ruling out the basis of the repeatability of the profile and any transverse variations that might be present. After five readings the work material was rotated to present a new microgeometry for analysis.

Experiment 2 Discussion: Influence of Frequency Upon Crest-Root Height

Unlike the first experiment, this test devoted specific attention to the influence of the frequency upon the crest-root height. Figures 21, 22, and 23 provide the technical data in the form of graphs. Two frequencies, 4 and 10 cps, were optimum. The data, statistically significant, indicated that the best fit curve would be a quartic, which confirms the shape of the curve and minimum points at 4 and 10 cps.

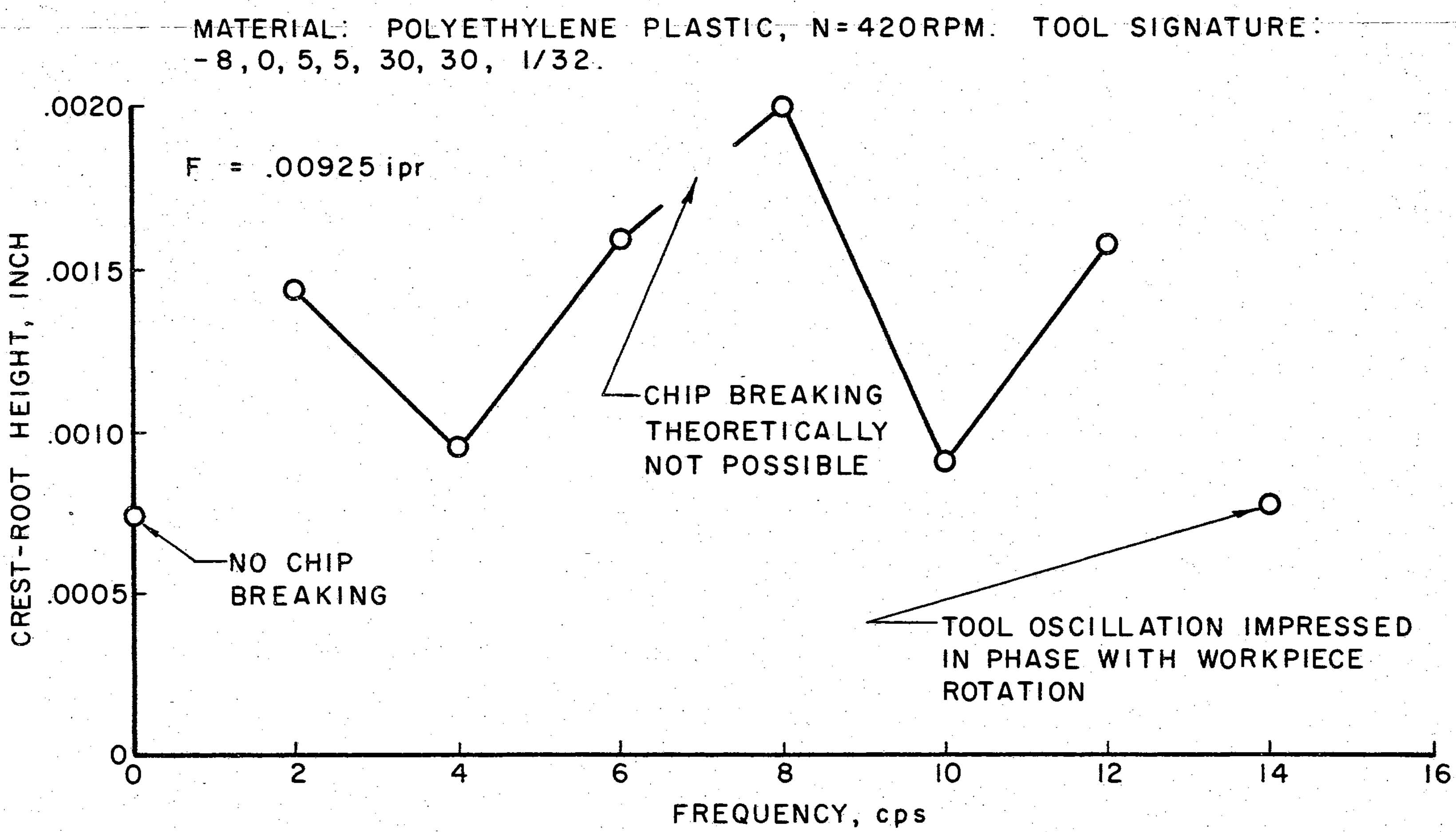


Figure 21. Response of Surface Height to Frequency

These points are 20% greater than the control point at 0 cps. At the other extreme, 8 cps, the increase in roughness amounts to 180%.

When replotting the data against a different abscissa, the points of 4 and 10 cps transform to new quantities relating the tool speed to work material speed, or a measure of their relative speed. This indicates that the optimum was at approximately .5 and 1.5 relative speed. When the relative speed index = 1, dynamic chip breaking does not take place.

The next figure gives an indice of the feed maximum-amplitude for crest-root height. Operation of this test proved the optimum value of this index to be about .72.

Experiment 3 Discussion: Influence of Frequency and Amplitude Upon Free Chip Length

Chip breaking can be assured at certain frequencies provided the amplitude is adjusted to A^*. The stipulations first discussed in Chapter III, Theoretical Considerations, met with consistent results. The theoretical length, however, was not obtained. Figures 24 and 25 indicate the length obtained from testing and from theoretical considerations.

The difference between theory and test amounted to a 101% average reduction of chip length. The shear strain exerted upon the material and the free chip in the cutting action resulted in permanent deformation that altered the

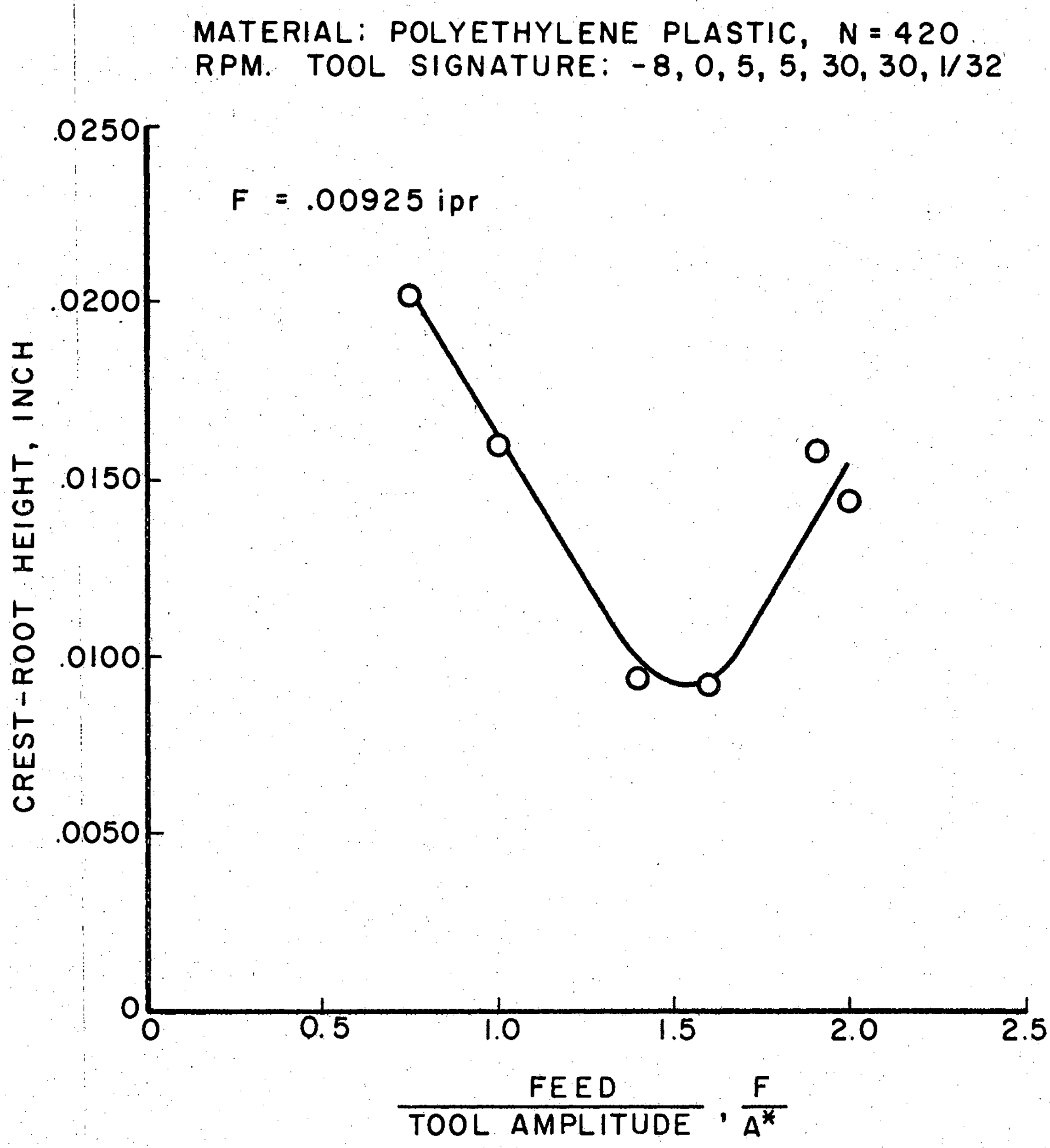


Figure 22. Response of Surface Height to Normalized Critical Amplitude

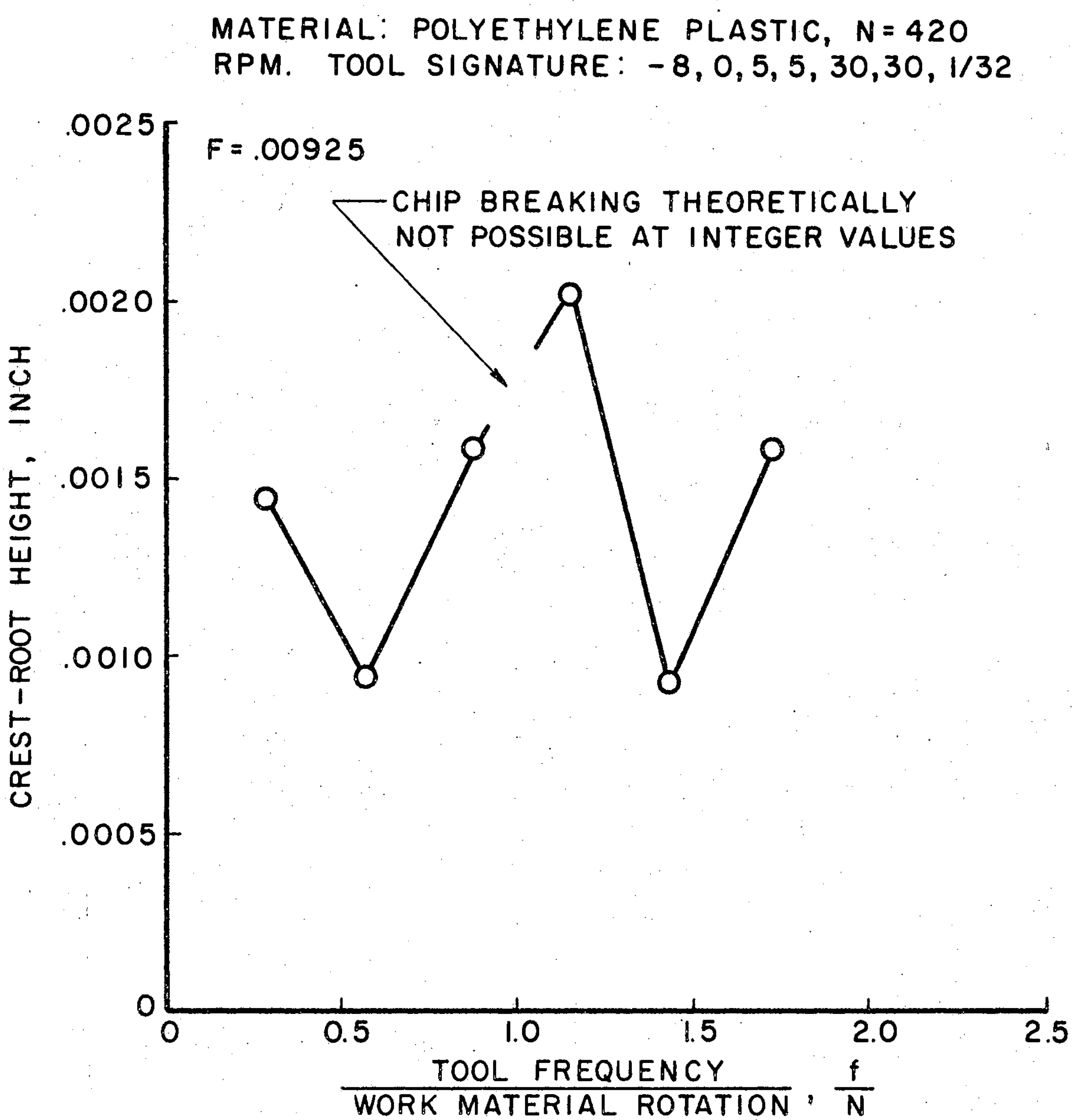


Figure 23. Response of Surface Height to Normalized Frequency

dimension of the free chip. The thickness was compressed and the length shortened while the width remained substantially constant.

In examination of the curves, it is noticed that at certain frequencies dynamic chip breaking does not occur. This corresponds to $N = Kf$ where K is an integer value. During this condition a phase difference between two consecutive tool paths does not exist. When operating at these ratios, the chip did not break and peeled off in a continuous string. In validating these ratios under dynamic chip breaking, the long continuous chip did not peel off from the workpiece in the same manner as it did when there was no tool perturbation. The continuous chip had a different wiggle when there was no movement of the tool. Figure 28 provides sample photographs of the chips.

A companion test was run similarly to the one previously reported but with one exception. Instead of the amplitude being just sufficient to break chips, it was set excessively at $\frac{3A^*}{2}$. The results of the comparison between the two tests found the following. There was no detectable difference in the length of the free chips produced. The crest-root height increased by 9% over the test where the objective was to impress an amplitude sufficient to provide chip breaking. This concurred with results of other tests.

The chips were of uniform length with a difference in measurement of ± 1/32" usually found in the specimens. The

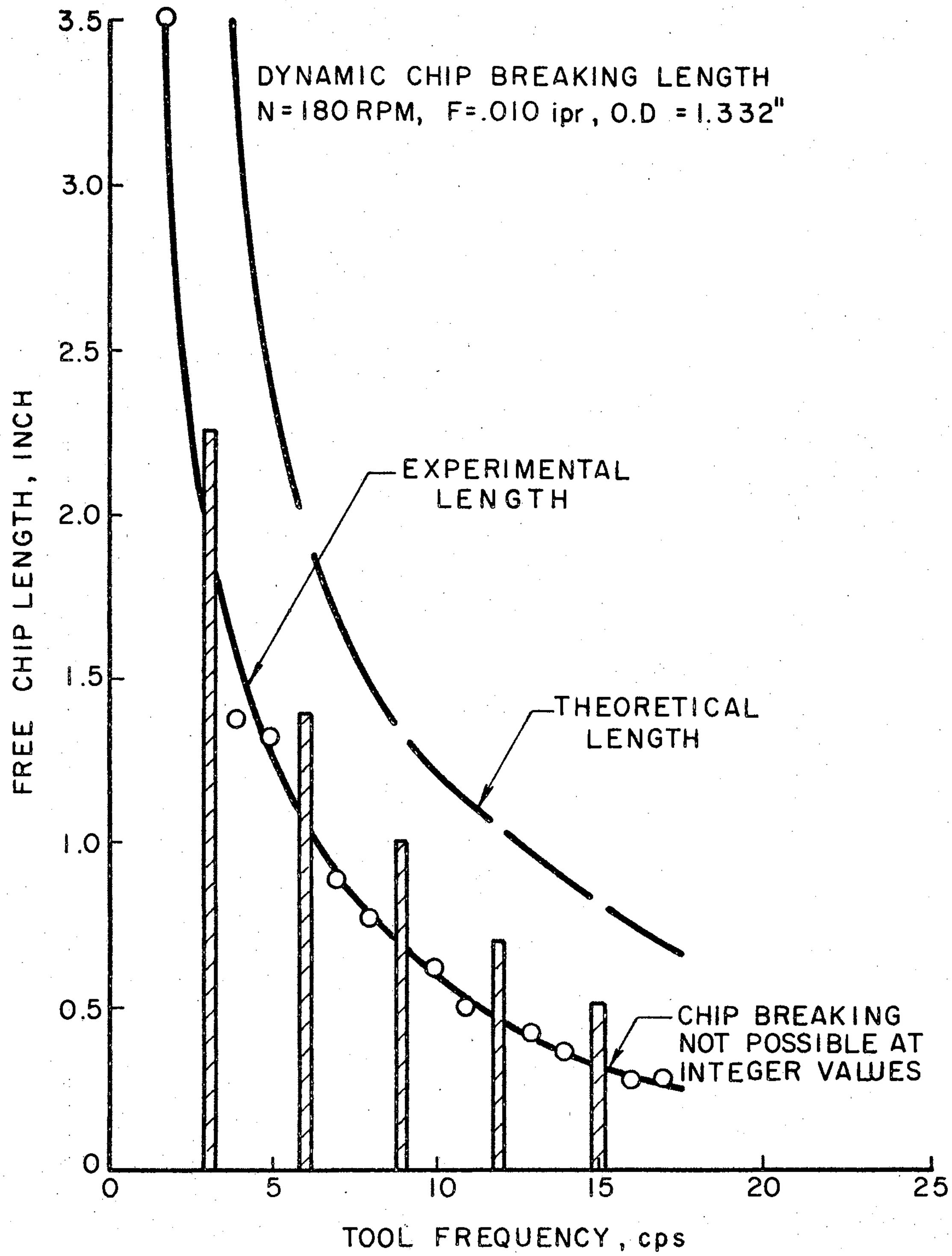


Figure 24. Response of Free Chip Length to Test Conditions

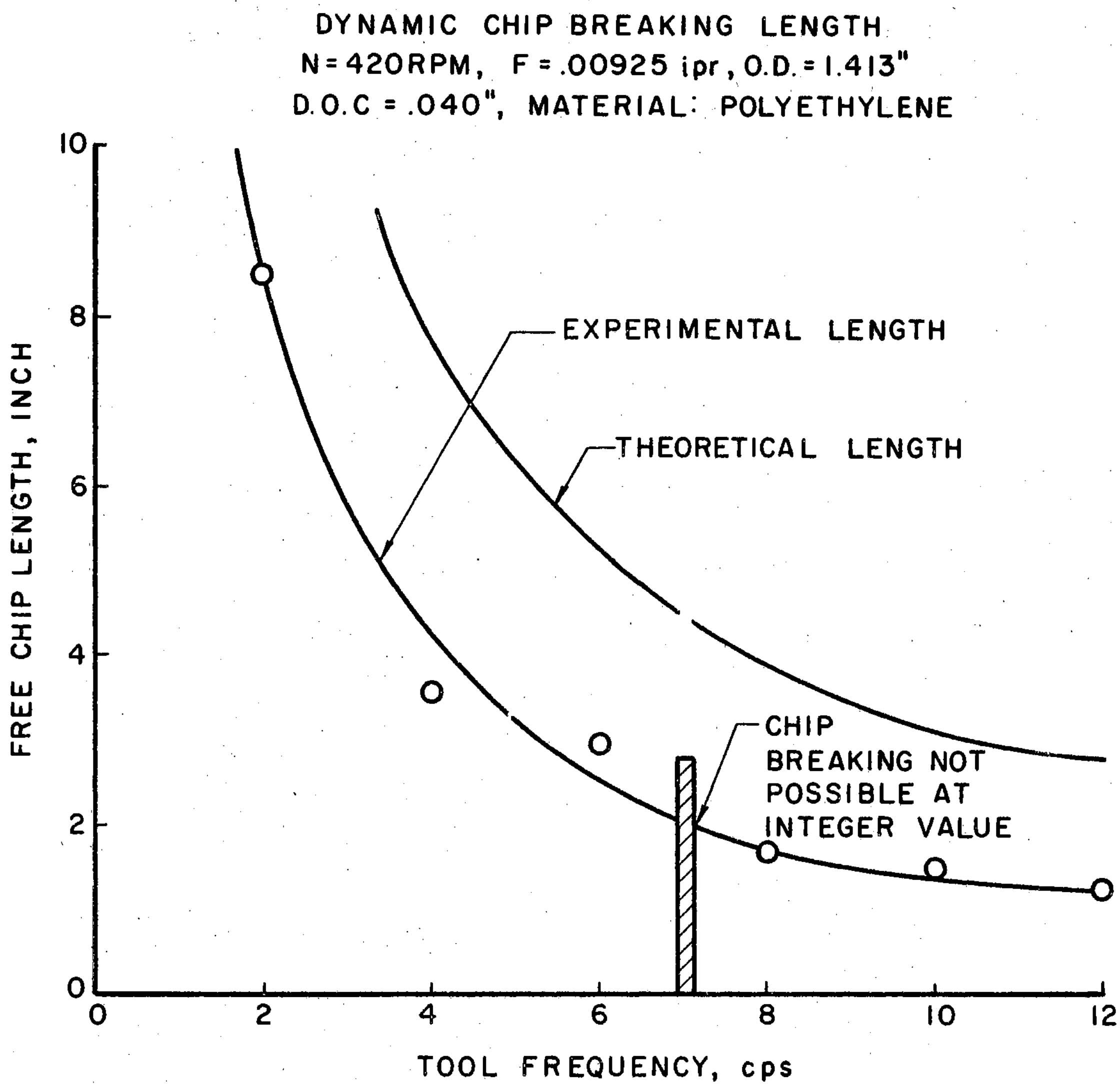


Figure 25. Response of Chip Length for One Test Condition with Critical Amplitude A^*

longer chips were inclined to curl, particularly at the ends while the shorter chips were stubby and more rigid, ideally suiting them to sluicing and control by chip disposal equipment.

Experiment 4 Discussion: Influence of Amplitude to Break Chips in Aluminum

The requirements for effective chip breaking amplitude depend upon the depth of cut in addition to tool frequency and work speed rotation. In a test of limited size these results were not statistically significant, however, one can make some practical remarks which tend to agree with other experience.

As is indicated by Table III the percentage of maximum amplitude to feed rises as the cross sectional area increases. In other words, as the amount of metal removal increases, the amplitude required to clip the chip responds to require greater energy. The cross section of a chip during conventional machining is a parallelogram. Increasing either feed or depth of cut will increase the area of the chip. As the depth of cut increases, a greater amplitude is required proportionally. As the feed increases the amplitude must compensate by increasing.

The values for effective chip breaking ranged from a minimum of 21% to a maximum of 69% for the larger cross section. The majority of tests indicated that the chip will shear across the thinest section without the ideally required critical amplitude.

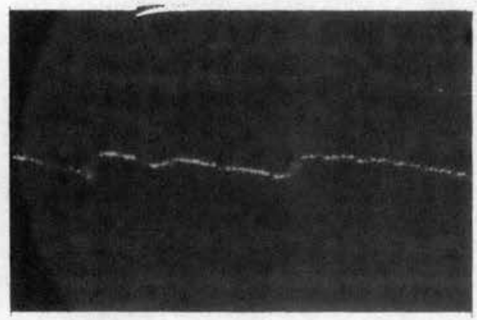
In alleging these results, it must be pointed out that a visual determination of the point at which chip breaking ensues was made difficult because of the propensity of this material to rupture and form chips prematurely through internal stresses arising from dynamic chip breaking. The evidence suggests that the amount of amplitude need not be as great as was required for the polyethylene. In terms of the order of magnitude for this material and the dynamic cutting conditions imposed, a maximum single-sided amplitude value of .35F would be sufficient to break chips. The phase lag between two consecutive tool paths was 180°, and these results pertain to this phase lag relationship only.

Experiment 5 Discussion: Influence of Tool Frequency and Material Workspeed Upon Roughness in Machining Aluminum

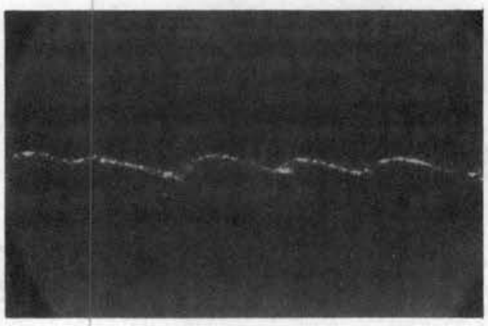
This test provided no worthwhile significant data, however, this does not imply that dynamic chip breaking is unsuccessful with aluminum. Rather, the errors of the response were large and replications were insufficient to cover the variability. Despite these shortcomings it is worthwhile to discuss some of the practical lessons that were gained during this experiment.

In some cases the motion pattern of the tool point failed to correspond to a harmonic trace. It could be determined from the recorder trace that the amplitude of the tool varied between oscillations; on one oscillation

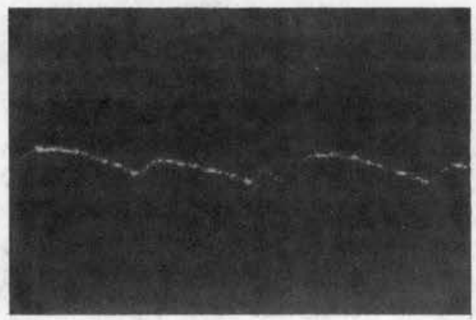
A. Period = 2



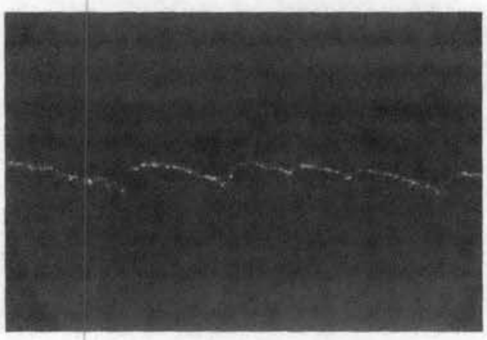
B. Period = 3



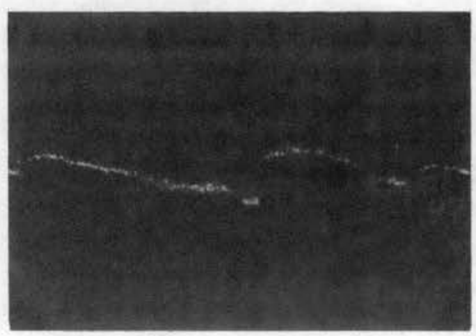
C. Included Angle = 120°



D. Pinch-Off Point in Middle

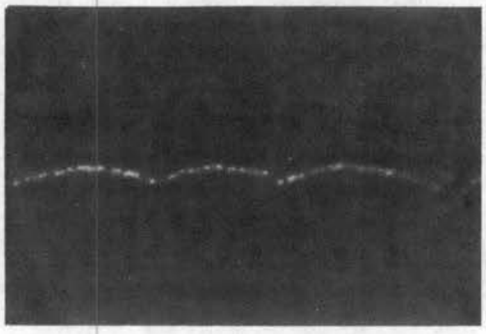


E. Foreshortened Height

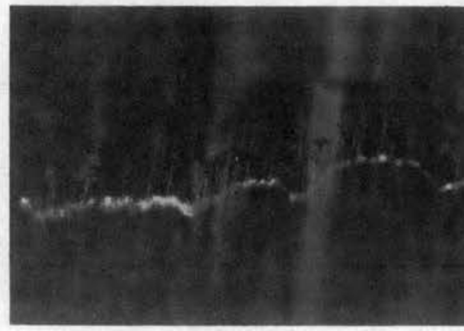


F. Foreshortened Height

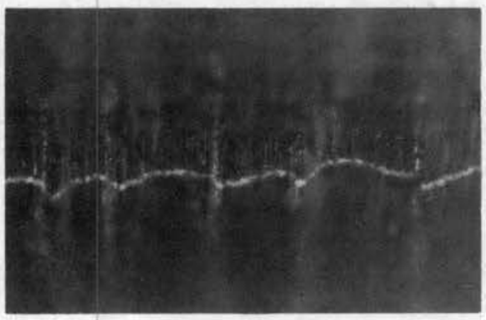
Figure 26. Light-Section Microscope Photographs of Surface Geometry. Plastic Material. 200X. Tool Radius = .005". Included Angle = 90°.



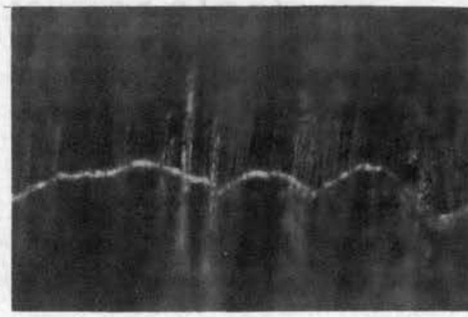
A. Plastic. Period = 2.



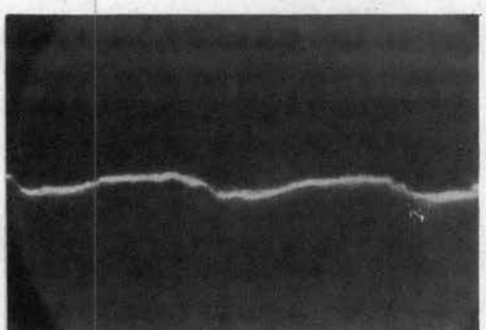
B. Aluminum. Non-Uniform Oscillation. 200X



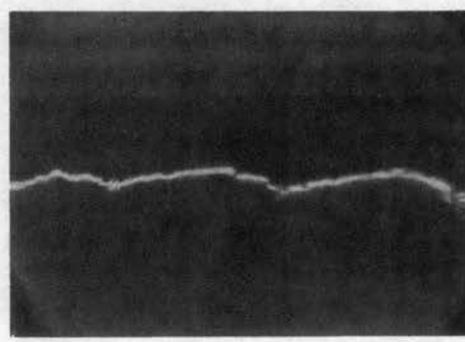
C. Aluminum. Uniform Oscillations



D. Aluminum. Non-Uniform Oscillation. 200X



E. Plastic. No Oscillation. 400X



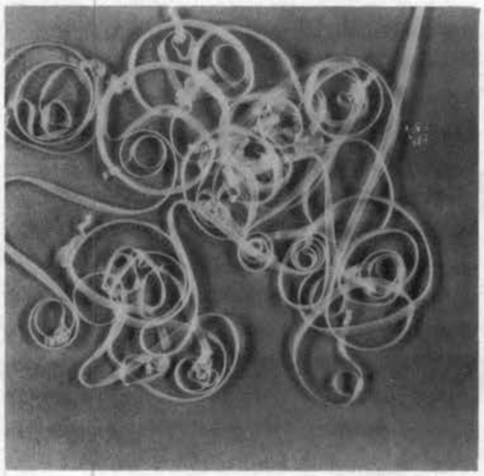
F. Plastic. Period = 3. 400X

Figure 27. Typical Light-Section Microphotographs for 1/32" Tool Radius.

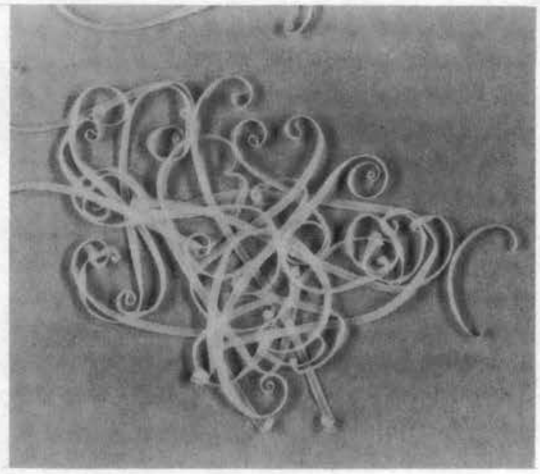
TABLE III

RATIO OF AMPLITUDE TO FEED NECESSARY FOR CHIP BREAKING OF ALUMINUM

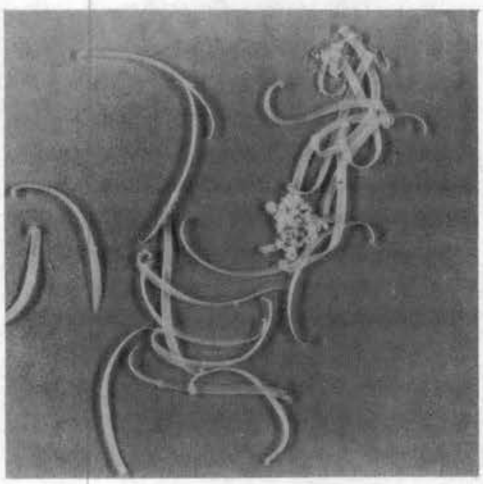
Fixed Amplitude, Inch	Fixed DOC, Inch	Chip Breaking Feeds, ipr	Ratio: Amplitude / Feed
.0016	.020	.0075	.21
.0016	.040	.0050	.32
.0023	.020	.0088	.25
.0023	.040	.0066	.33
.0038	.020	.0114	.33
.0038	.040	.0055	.69



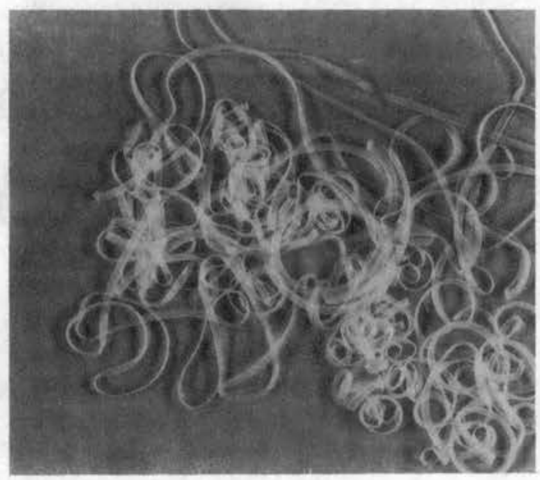
A. 2 cps. Length = 3.5"



B. 4 cps. Length = 1.4"



C. 8 cps. Length = .7"



D. 15 cps. Continuous Chip

Figure 28. Sample Photographs of Chips Resulting From Dynamic Chip Breaking Mechanism. Polyethylene Plastic. N = 3 cps.

the tool amplitude would be less than on a subsequent oscillation. This hammering of the tool on the material superimposed a Fourier series type oscillation upon the fundamental forced frequency. Impact problems resulting from entry into the material were a major source of error.

Contrary to anticipations, a build-up of aluminum fragments occurred on the point of the tool during the cutting operation and changed the geometry of the tool. This build-up was evident visually. It was not welded on the carbide surface as is the case when steel is machined with carbide. The build-up could be knocked off with a light side blow following machining of the test specimen. Very often during the cutting test the build-up would come off with a "ping" sounding its departure. This alternating build-up and "ping" resulted in periodic gouging of the surface.

The periodic feature of the dynamic chip breaker was evident on the surfaces as the alternating character of the surface from low to high crests confirmed the presence of the impressed tool motion. Frequent scratching due to the build-up and the non-harmonic motion contributed largely to the errors inherent in the test program. The tracer method substantiated the variation within the specimens. No trouble was found with the surface measurement tracer that would suggest that the tracer method contributed anything of importance to the error term.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This research proposition centers on the merits of dynamic chip breaking. If success of this endeavor is warranted, its industrial adoption rests upon overcoming serious faults which are suspect by the overwhelming evidence of decades of metal cutting experience. To cope with these problems the research was oriented in four directions: (1) Dimensions and properties of the free chip. (2) Nature of the microgeometry of the surface resulting from dynamic chip breaking. (3) Construction, operation, and limitations of the dynamic chip breaking mechanism. (4) Experimental procedures that might be exceptional to this process. This chapter provides the conclusions to these questions by examining the evidence as produced by experimental portions of the research. The path of model-determination, equipment-construction, and control-testing now assesses, where it is able, optimum points of operation for dynamic chip breaking.

As is traditional in metal cutting research, those findings which merit honest support have testimony in the three aspects of metal cutting: the tool, material, and chip. Dynamic chip breaking is no exception.

The Chip

Within the metal cutting field, discussion about the "chip" is usually considered irrelevant since the chip is destroyed and useless to all except the scrap dealer. However it should be recognized that long continuous chips offer disposal and storage problems and represent a hazard to the operator at high cutting speeds. As the long chip becomes increasingly obnoxious, ways must be considered to eliminate the problem.

1. The results of this research provide strong evidence that dynamic chip breaking will break the chips into shorter lengths convenient for disposal methods. It was found that chip breaking exists at any tool frequency where there is a phase difference between successive tool paths. The amplitude for effective chip breaking in plastic must be such that there is an intersection of tool paths. Given the out-of-phase and an intersection, chips of consistent length can be produced from ductile materials.

2. Some ferrous and non-ferrous materials may break randomly and prematurely due to stresses within the chip. This breakage will very likely exist at the narrowest section of the chip. Fortunately, this premature breakage due to the thin-section stress may be an asset to surface finish.

3. The length of the chip is shorter than theory would dictate which also benefits the goal of chip breaking.

In a search for causes that explain the variation between theory and fact, it is advanced that the property of compression of the thickness of the chip during cutting is the contributor to this effect. Under metal cutting action the shear stress exerted upon the material and the free chip results in deformation that compresses the thickness and shortens the length. Although this finding was shown for plastic, extensions of the same phenomenon to metal should cause no difficulty. In orthogonal metal cutting tests conducted by the writer and many others, this change of chip dimension has been frequently found. In terms of the order of magnitude, chip lengths in metal cutting reduce from 30% to 60% over the uncut length. The similarity between plastic and metal behavior leads one to conclude that metal will deform under chip breaking action and will be shorter by similar percentages as found during orthogonal metal cutting tests.

4. Chip length was unaffected by amplitudes in excess of the intersecting amplitude. There was no detectable difference in the length of chips when the amplitude was increased beyond that barely required for chip breaking. In extending this to metal cutting, one may venture to say that the same observation would be accurate with ductile materials.

Surface Finish

The fact that a variety of chip lengths can be selected by the method of dynamic chip breaking is a worthy benefit. Although broken chips are the goal, once this has been accomplished it becomes vital that the surface finish be given special considerations. The compromise between adequate chip length and satisfactory surface finish would permit the chip length to vary an inch or so, for example, in search for the optimum surface finish.

5. The method developed here whereby the critical value of amplitude is found, either empirically or analytically, and adjusted with the frequency is the operational procedure ideally suited to finding the optimum value of the surface finish. This adjustment process is in keeping with the versatility required in dynamic chip breaking. This advantage takes on greater significance as the tool wears, thus altering the original conditions under which the chip breaking was established. Batch to batch variations and the general capriciousness of metal machining dictate that the dynamic chip breaking methods be changeable.

6. The most favorable surface height in machining plastic was found when the amplitude was set to the critical value A^*. For amplitudes in excess of A^* the surface height deteriorates. In extending this observation to metal, the critical amplitude may or may not be less than the value A^*. It depends upon the willingness of the material to shear across the narrowest section between two consecutive traces. In those cases where the metal frac-

tures when the tool amplitude is less than the intersecting value, the surface finish is further improved. For ductile metals the minimum amplitude that will break the chips into uniform lengths is the optimum value. This extension was substantiated with the ideal material, plastic, in the case where the amplitude was smaller than critical. Although chip rupture did not occur with plastic at $\frac{A^*}{2}$ the surface was lower than when the oscillation was A^*.

7. Surface height is sensitive to changes in frequency of the oscillating tool. On the basis of the experiments described in this dissertation, the optimum frequency was found to be at 4 and 10 cps. Although 10 cps was significantly lower, the practical difference is immaterial.

8. In all cases of dynamic chip breaking, the surface finish deteriorated. This statement collaborates the findings of other investigators who studied the low frequency range of chip breaking. But the amount of deterioration can be limited to possibly tolerable values if the right combination of feed, work material speed, amplitude, depth of cut, tool geometry, and other of the many ramifications of the metal cutting process are carefully selected. The influence of tool frequency is an extremely vital factor. Rather than 180% reduction the test indicated that only 20% roughing could be expected at the optimum points.

9. Although optimum operation existed at 4 and 10 cps (test Number 2) it is worthwhile to question whether

there are dimensional parameters or indices that relate frequency to work-speed and if this index can be extended from the plastic material to metal. When evaluated against the test data, the parameter $(\frac{N}{f} - K)$ did not substantiate the theoretical consideration developed earlier. It is believed to be insensitive for the following reasons. The curve should have been a quadratic with the low point symmetically located at .5. However, the data displayed that the optimum points were close together after normalizing, (.7 and .75) but much higher values of roughness were found at the .25 region where two points were similarly associated in nearness. One could assume that the natural number K must have had some unexplained relationship to surface finish. The only purpose of the parameter $(\frac{N}{f} - K)$ is its procedural usefulness in understanding the phase angle and determining intersecting amplitudes. There was no evidence found to suggest that it is a worthwhile operating parameter.

10. Another possibility for a defining parameter is $\frac{N}{f}$ which was not confirmed for many of the same causes. Its inverse $\frac{f}{N}$, Figure 23, suggested that the two optimum points would be .57 and 1.44 which corrobrates closely Poduraev and Zakharov (3) who found optimum operation points for their chip breaking experiments at .5 and 1.5.

The Russians arbitrarily selected the parameter $\frac{f}{N}$ to display their results.

11. What inferences can be made regarding the surfaces resulting from dynamic chip breaking? The results of these tests point out that at low frequencies surface roughing is to be expected. Damage to the surface may be so extensive that the usefulness of the dynamic chip breaking process is limited to "roughing operations" where depths of cut and large feeds are commonplace. A fine finish is not normally expected in this type operation. Of course during roughing operations the continuous chip is a greater problem and dynamic chip breaking becomes more useful.

Equipment, Materials, and Testing Practices

12. The principle of positioning an oscillation parallel to the direction of feed may be successfully employed to break chips. Other directions of forced vibrations would require greater energy and introduce other complications. The features of adjustable frequency and amplitude are necessary for effective chip breaking.

13. The polyethylene plastic with its low surface friction and tenacity in forming chips was an ideal substitute for other ductile materials. Handling a continuous chip from this material is comparable to unwinding a string from a ball. The plastic permitted the research to be concentrated on the surface and broken chip lengths without complication from the diverse factors of cutting ductile

materials.

14. Whenever there is a need to have surface quality remain untransformed by a diamond tracer point, the light section microscope is a useful instrument. Insofar as this research was concerned, the choice of plastic for the work material would have been more difficult without the non-touching surface measuring instrument.

Extensions of the Work

This dynamic chip breaking research leaves many of the questions that surround the applicability of dynamic chip breaking unresolved. The emphasis herein was on surface and free chip length. Along these lines a better operating parameter more thoroughly developed along broader lines of the metal cutting operation would be important. This model should attempt to predict surface height while considering the feed, depth of cut, curvature of the work material, in addition to frequency and amplitude. It would be a prudent investigation if this predictive model were tested with the idealized material used throughout this investigation.

Dynamic chip breaking will be deemed successful only if it can be justified economically. There is little evidence to indicate the cost of continuous chips. What payoff and return might be expected while using equipment similar to that designed in this research and commercially marketed?

Other aspects associated with dynamic chip breaking such as improved lubrication, tool life, accuracy, reduction in work hardening, etc. were not considered. There can be no doubt that dynamic chip breaking alters these operating conditions.

It would seem wise to suggest a more practical tool geometry for equipment designed and manufactured to aid the achievement of dynamic chip breaking. As the clearance, rake, and other angles are constantly changing, the established geometries may not be optimum under these new conditions.

Only harmonic pulsations were considered in this research. Other types of pulsations where the displacement is triangular or square, for example, may offer advantages. Nor do these displacements have to be periodic, as random or aperiodic frequencies could be used to control the chip length and possibly be less drastic upon the surface finish.

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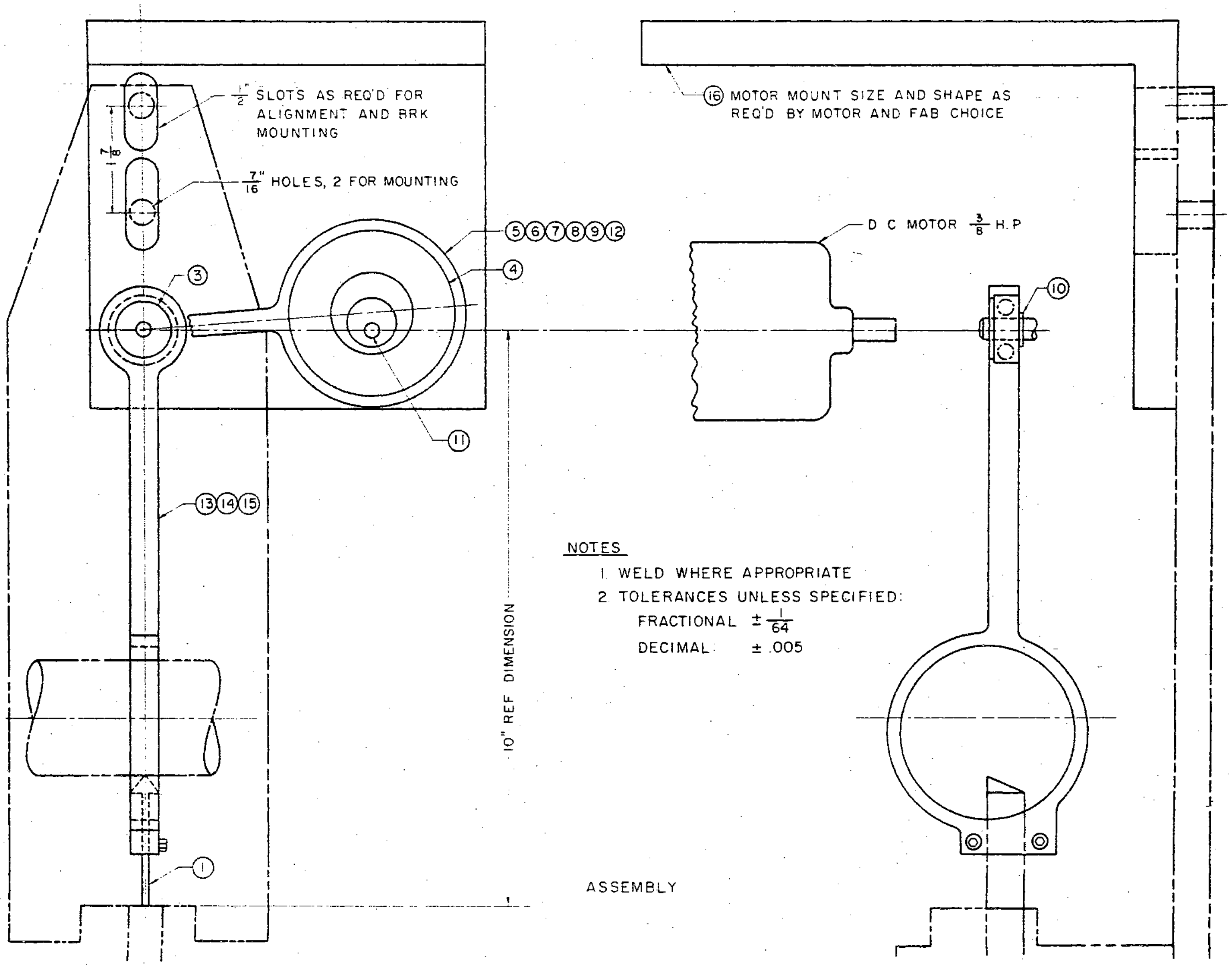
APPENDIX A

CONSTRUCTION DRAWINGS FOR DYNAMIC CHIP BREAKER

BILL OF MATERIAL FOR DYNAMIC CHIP BREAKING MECHANISM

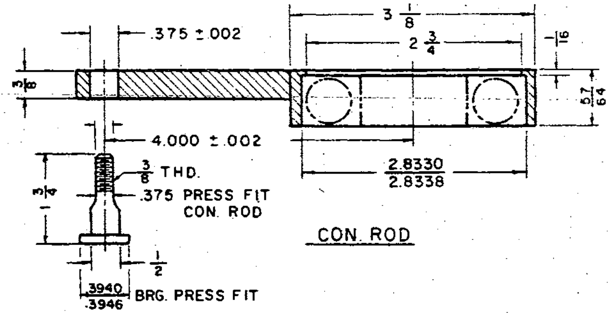
No.	Item	Qty.	Material
1	Tool	2	2024-T4 Aluminum
		2	1018 Steel
		3	General Electric Tools
2	Motor	1	3/8 H.P., Sears Hand Drill Portable, $50
3	Bearing	1	Bore 3937; OD, 1.1811; $3.40
4	Bearing	1	Bore 1.3780; OD, 2.8346; $13
5	Con Rod	1	1035 Steel
6	Con Shaft	1	1018 Steel
7	Disc	1	1035 Steel
8	Eccentric	1	1035 Steel
9	Set Screws	2	As Required for Disc
10	Shim	1	As Required
11	Coupling	1	As Determined by Fabrication
12	Drive Shaft	1	1035 Steel
13	Tool Arm	1	1035 Steel
14	Latch	1	1035 Steel
15	Allen Head Machine Screws	2	As Required by Fabrication
16	Motor Bracket, Straps		Material as Required by Fabrication



NOTES

1. WELD WHERE APPROPRIATE
2. TOLERANCES UNLESS SPECIFIED:
   FRACTIONAL $\pm \frac{1}{64}$
   DECIMAL $\pm .005$

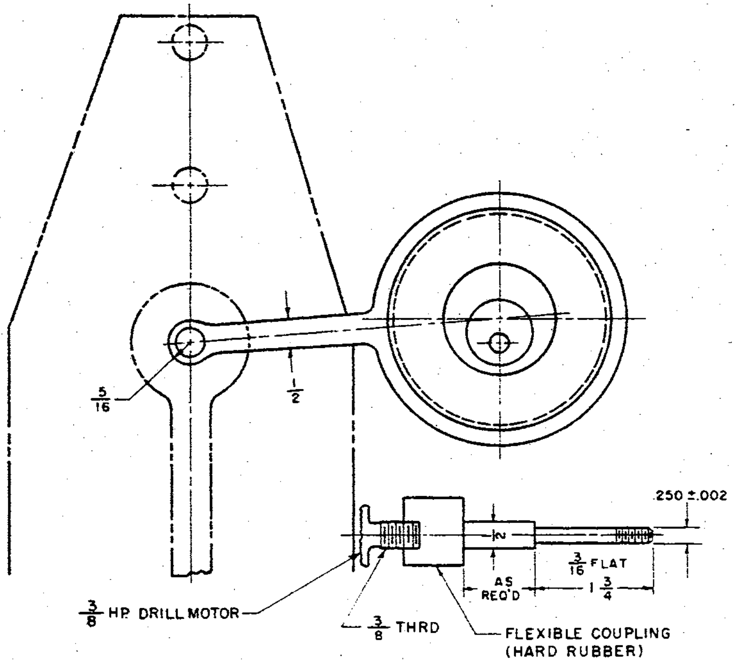
ASSEMBLY



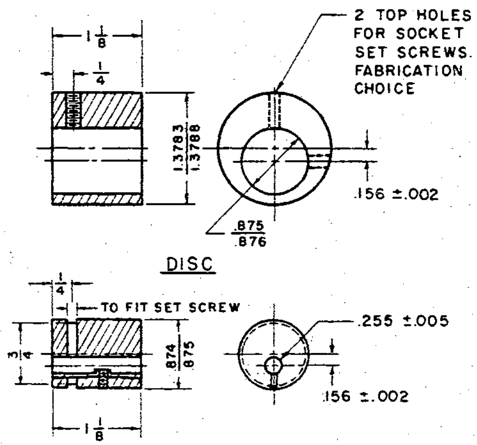
CON. ROD

CON. SHAFT

	BEARING	SHAFT
BORE	.3934 / .3937	.3940 / .3946
BORE	1.3775 / 1.3780	1.3783 / 1.3788
O. D.	2.8341 / 2.8346	2.8330 / 2.8338



COUPLING AND DRIVE SHAFT



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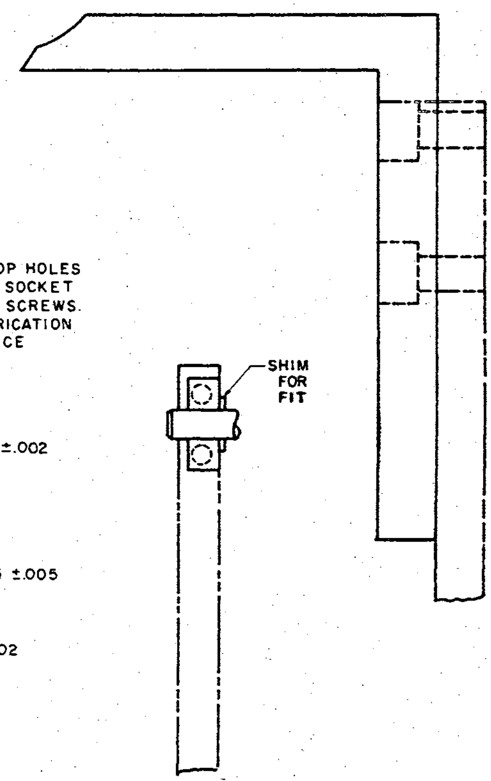
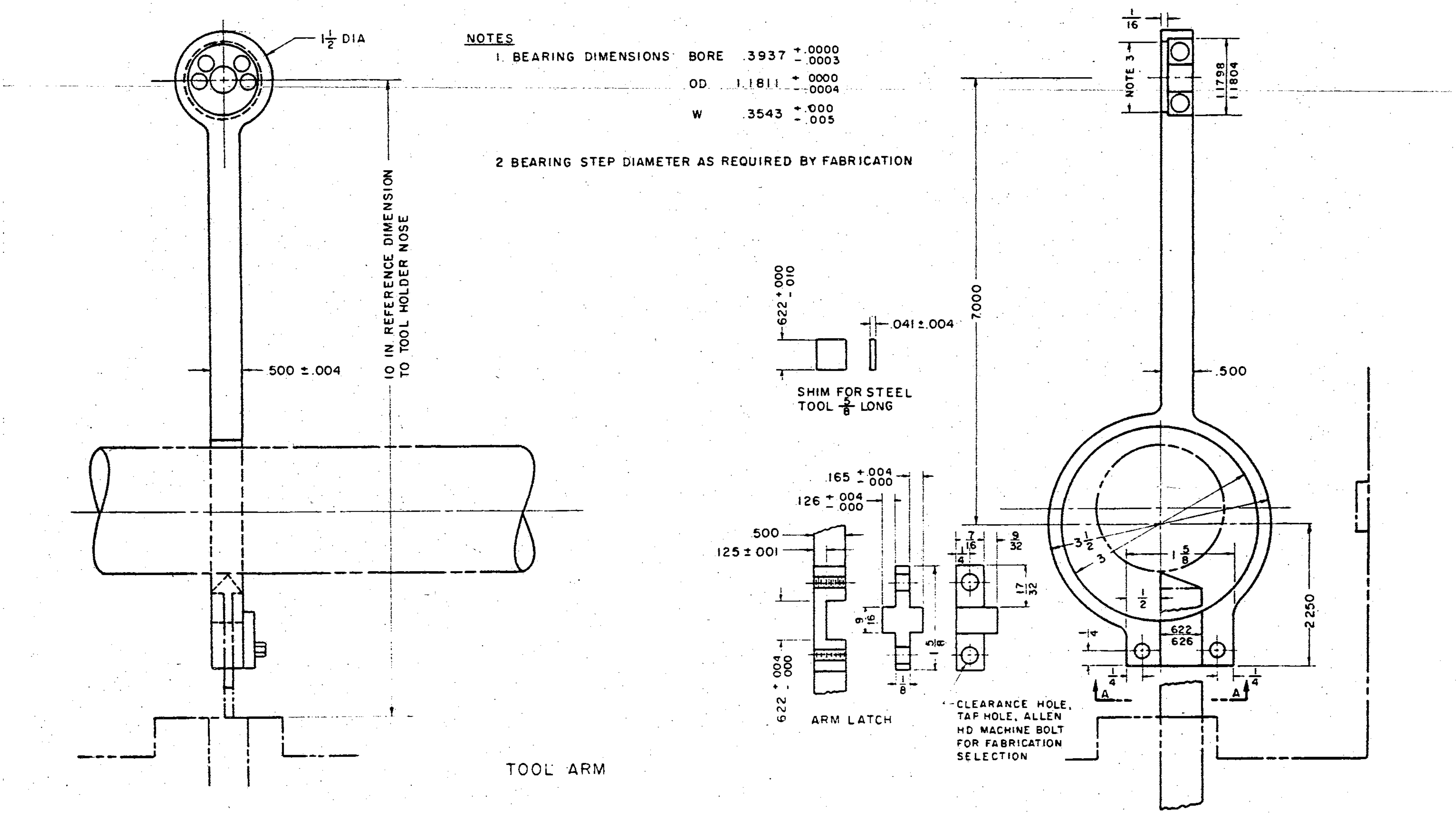
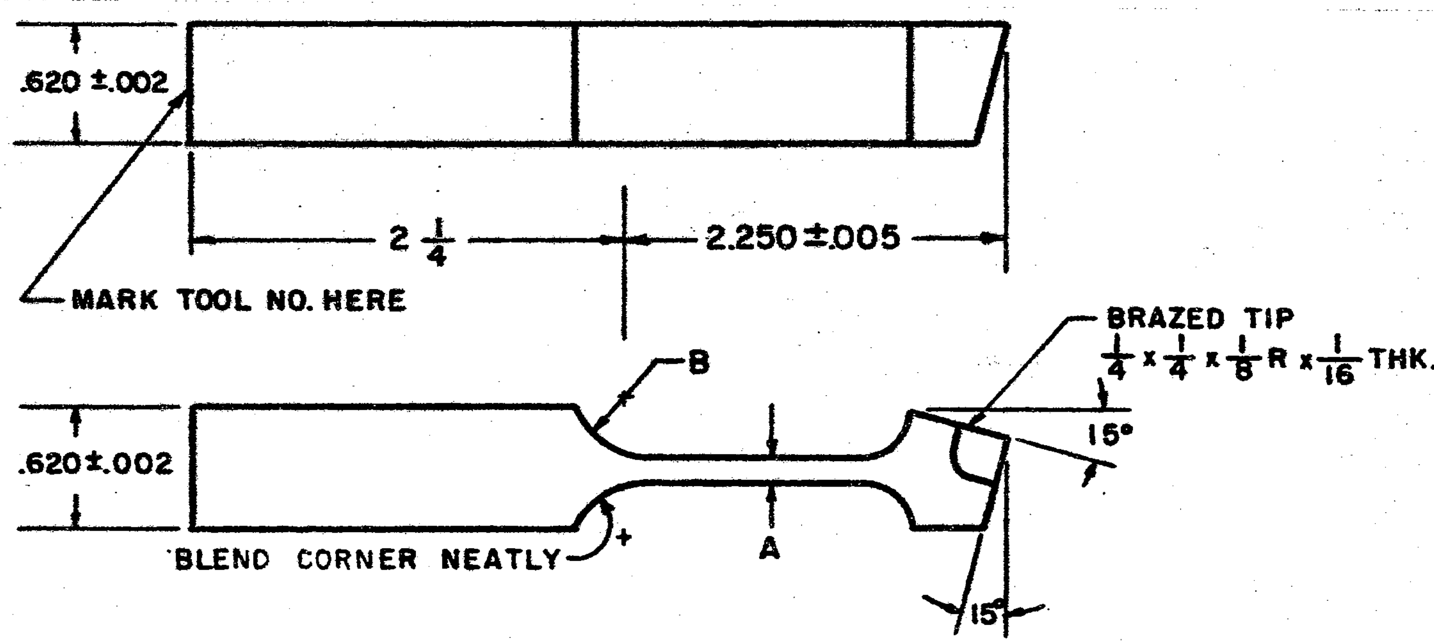




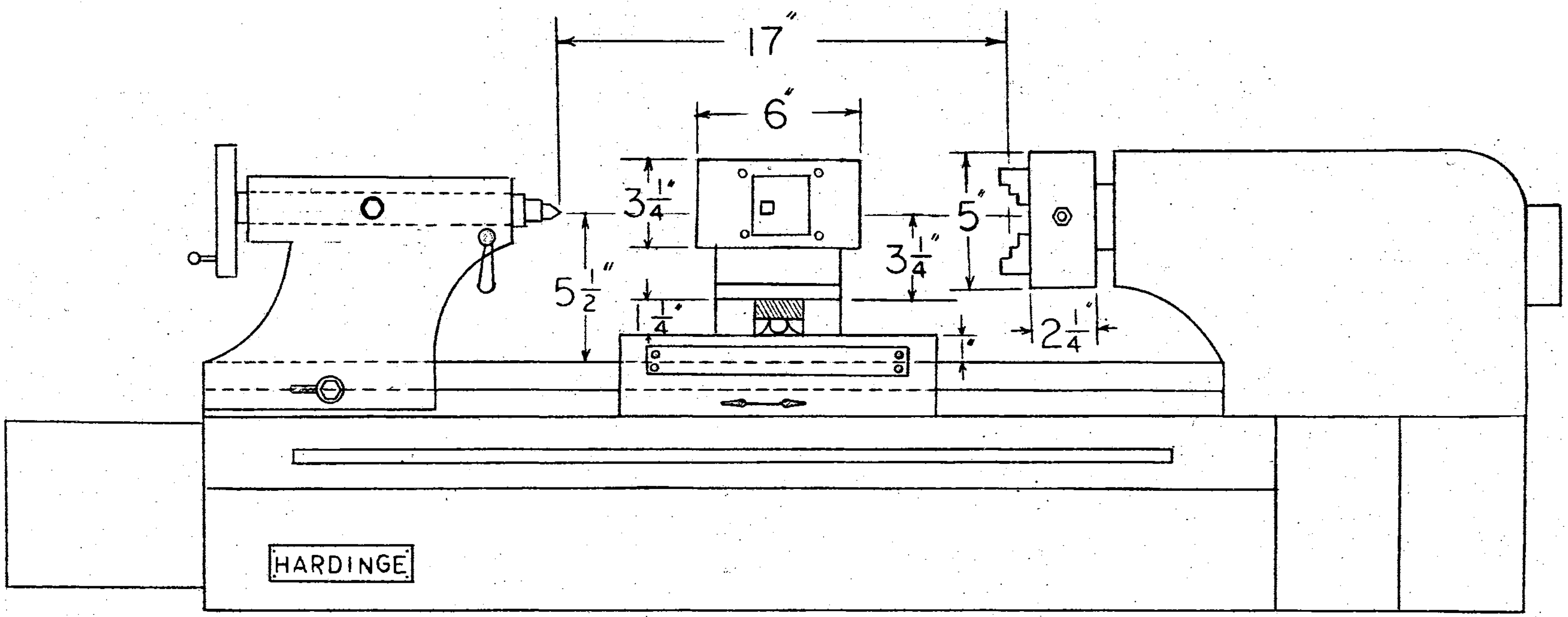
1½ DIA
NOTES
1. BEARING DIMENSIONS BORE .3937 +.0000 -.0003
OD 1.1811 +.0000 -.0004
W .3543 +.000 -.005
2 BEARING STEP DIAMETER AS REQUIRED BY FABRICATION
10 IN. REFERENCE DIMENSION TO TOOL HOLDER NOSE
.500 ±.004
.622 +.000 -.010
.041 ±.004
SHIM FOR STEEL TOOL 5/8 LONG
7.000
.500
NOTE 3
1.1798
1.1804
1/16
.165 +.004 -.000
.126 +.004 -.000
.500
.125 ±.001
.622 +.004 -.000
ARM LATCH
7/16
9/32
1/4
17/32
9/16
5/8
1/8
3 1/2
3
1 5/8
1/2
.622
.626
2.250
1/4
A
CLEARANCE HOLE, TAP HOLE, ALLEN HD MACHINE BOLT FOR FABRICATION SELECTION
TOOL ARM



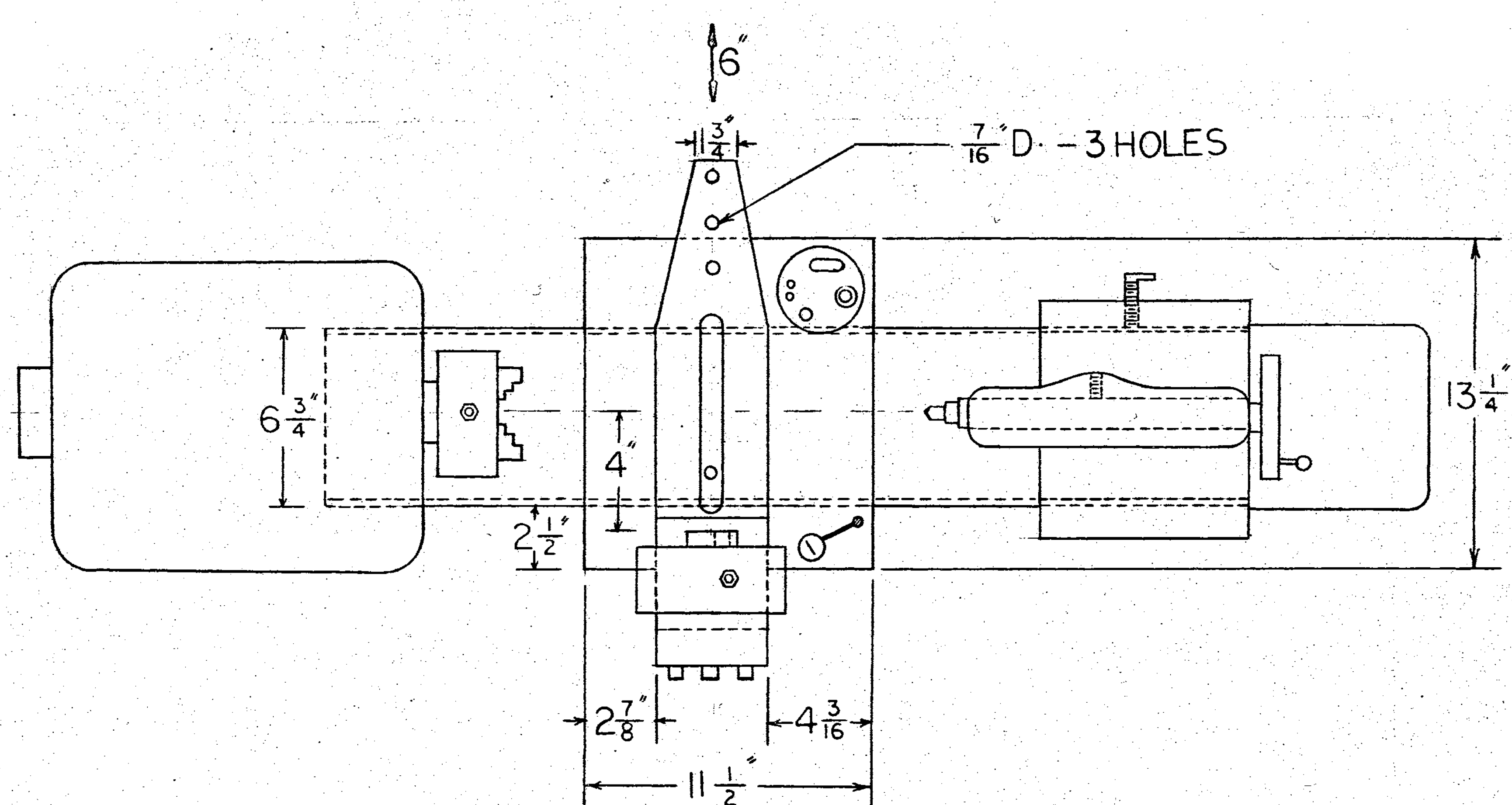
NOTES

MARK TOOLS 1,2,3,4. TOOLS 1 AND 2 MADE FROM 2024-T4 ALUMINUM. TOOLS 3 AND 4 MADE FROM SAE 1018. EXTRA STOCK LEFT ON POINTED END FOR STATIC LOAD CALIBRATION. TO BE REMOVED AFTER TESTING.

	DIMENSION	
MAT'L	A	B
2024	.250 ±.002	3/16
1018	.172 ±.002	1/4



Side Layout of Engine Lathe Showing Important Details Necessary for Dynamic Chip Breaking Mechanism



Top Layout of Engine Lathe Showing Important Details Necessary for Dynamic Chip Breaking Mechanism

APPENDIX B

SAMPLE DATA SHEET, CALIBRATION DATA EXPERIMENTAL DESIGNS, AND EXPERIMENTAL ANALYSES

Date________________ Treatment Combination__________

Serial Test No:______________
Specimen No:________________
Run No:_____________________

Part: Material__________ Diameter: Before______ After_____

Lathe: Feed_____________ RPM_______________CPS_____________

Tool No: 3, 4, or 5

Vibration: yes or no Lathe/tool Phase:_______________

Tool CPS: (Before)__________________ During________________

Tool Deflection A: (Before)_________ During________________

Sketch of Surface (Typical)

Zeiss Picture No:___________ Width______________ Height_____

Zeiss Readings

Width: Units___________ Height: Units___________

____	____	____	____		____	____	____	____
____	____	____	____		____	____	____	____
____	____	____	____		____	____	____	____
____	____	____	____		____	____	____	____
____	____	____	____		____	____	____	____
		Total	____				Total	____
		Average	____				Average	____

TYPICAL CALIBRATION DATA FOR LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

(1) Sanborn 321 Recorder

Right-hand channel, 100 attenuator setting

(2) Tool Number 4

(3) L.V.D.T., Sanborn Model 595DT-100

Approximate Eccentric Setting	Total Tool Deflection, 2A (Inch)	Recorder Deflection (mm)
$\frac{1}{2}$	.0024	2.1
1	.0044	4.0
$1\frac{1}{2}$	.0053	4.7
$1\frac{1}{2}$	.0056	5.0
2	.0093	8.3
$2\frac{1}{2}$	.0097	8.4
$2\frac{1}{2}$	.0094	8.4
3	.0103	9.4
3	.0112	9.8
3	.0115	10.4
4	.0148	14.2
5	.0180	17.2

Least Square Equation

$$2A = .00058 + .00103(\text{mm.})$$

The total deflection was determined by a dial gage where the nose of the gage pressed against the side of the tool. For a particular tool deflection (2A), the strip chart deflection was measured. Before any calibration the recorder and the transducer were balanced for all attenuator settings.

EXPERIMENTAL DESIGN 1: INFLUENCE OF FREQUENCY, FEED, AND AMPLITUDE UPON CREST-ROOT HEIGHT

Plot A

	f F A	f F A	f F A
Block 1	0 0 1	2 0 1	1 0 1
	0 0 2	2 0 2	1 0 2
	0 0 3	2 0 3	1 0 3
Block 2	0 1 1	2 1 1	1 1 1
	0 1 2	2 1 2	1 1 2
	0 1 3	2 1 3	1 1 3
Block 3	0 2 1	2 2 1	1 2 1
	0 2 2	2 2 2	1 2 2
	0 2 3	2 2 3	1 2 3

Plot B

Block 4	1 0 1	0 0 1	2 0 1
	1 0 2	0 0 2	2 0 2
	1 0 3	0 0 3	2 0 3
Block 5	1 1 1	0 1 1	2 1 1
	1 1 2	0 1 2	2 1 2
	1 1 3	0 1 3	2 1 3
Block 6	1 2 1	0 2 1	2 2 1
	1 2 2	0 2 2	2 2 2
	1 2 3	0 2 3	2 2 3

Levels
f: 2, 4, 8
F: .0060, .00925, .0125
A: $\frac{A^*}{2}$, A^*, 3/2 A

Constant Conditions
N = 5 cps, D. O. C. = .040"
Tool: -5,-5,5,5,13.6,13.6,.005
Material: Polyethylene

Frequency f	Feed F	$A^* = xF$	Amplitude $A^*/2$	A^*	$3/2\ A^*$
2	.0060	$A^* = .5F$	.0015	.0030	.0045
	.00925		.0023	.0046	.0069
	.0125		.0031	.0063	.0094
4	.0060	$A^* = .71F$	.0021	.0042	.0063
	.00925		.0032	.0065	.0097
	.0125		.0044	.0088	.0132
8	.0060	$A^* = .55F$	.0016	.0033	.0049
	.00925		.0025	.0051	.0076
	.0125		.0034	.0069	.0103

EXPERIMENT 1 DATA: INFLUENCE OF FREQUENCY, FEED, AND AMPLITUDE UPON CREST-ROOT HEIGHT OF SURFACE

Run	Experimental Unit	Treatment Combination			Crest-Root Height, Inch
I	1	0	0	1	.000916
		0	0	2	.001072
		0	0	3	.001484
	2	0	1	1	.001184
		0	1	2	.001456
		0	1	3	.002372
	3	0	2	1	.001392
		0	2	2	.002088
		0	2	3	.002764
	4	1	0	1	.000800
		1	0	2	.000936
		1	0	3	.001140
	5	1	1	1	.001024
		1	1	2	.001192
		1	1	3	.001992
	6	1	2	1	.001504
		1	2	2	.002228
		1	2	3	.003176
II	1	2	0	1	.001172
		2	0	2	.001100
		2	0	3	.001380
	2	2	1	1	.001368
		2	1	2	.001572
		2	1	3	.002064
	3	2	2	1	.001500
		2	2	2	.002804
		2	2	3	.003276
	4	0	0	1	.000892
		0	0	2	.001204
		0	0	3	.001400

EXPERIMENT 1 DATA (Continued)

Run	Experimental Unit	Treatment Combination			Crest-Root Height, Inch
	5	0	1	1	.001308
		0	1	2	.001480
		0	1	3	.002000
	6	0	2	1	.001688
		0	2	2	.002472
		0	2	3	.002968
III	1	1	0	1	.000700
		1	0	2	.000916
		1	0	3	.001388
	2	1	1	1	.001084
		1	1	2	.001572
		1	1	3	.001884
	3	1	2	1	.001880
		1	2	2	.002992
		1	2	3	.002912
	4	2	0	1	.000976
		2	0	2	.001364
		2	0	3	.001280
	5	2	1	1	.001420
		2	1	2	.002108
		2	1	3	.002288
	6	2	2	1	.001672
		2	2	2	.002764
		2	2	3	.002664

EXPERIMENT 1 ANALYSIS: INFLUENCE OF FREQUENCY, FEED, AND AMPLITUDE UPON CREST-ROOT HEIGHT OF SURFACE

	D.F.	S.S.	M.S.
Total	53	25,216,832	
Groups	1	2,244	2,294
f	2	361,409	180,704
F	2	14,375,708	7,187,854*
A	2	7,096,156	3,548,078*
fXF	4	366,787	91,696
fXA	4	175,923	43,980
AXF	4	1,585,501	396,375
fXFXA	8	82,132	10,266
fX Groups	2	127,858	63,929
FS Groups	2	14,751	7,376
AX Groups	2	209,308	104,690
fXFX Groups	4	291,256	72,814
fXAX Groups	4	302,259	75,564
FXAX Groups	4	66,550	16,638
fXFXAX Groups	8	158,868	19,859
Pooled Error	27		4,345,244

F Confounded With Blocks

f Confounded With Runs in Each Group

A Confounded With Intra Run-Block Errors

*Denotes Significance

EXPERIMENTAL DESIGN 2: INFLUENCE OF FREQUENCY UPON CREST-ROOT HEIGHT

Treatment	Frequency, cps	Tool Amplitude, 2A*
1	0	0
2	2	.0093
3	4	.0131
4	6	.0185
5	8	.0242
6	10	.0114
7	12	.0096
8	14	.0093

Constant Conditions

F: .00925 cpr

Depth of Cut: 0.040 Inch

Tool: -8,0,5,5,30,30,1/32 Tungsten Carbide Insert

Workspeed: N = 7 cps

Specimens: Six Polyethylene Plastic Bars

EXPERIMENT 2 DATA: INFLUENCE OF FREQUENCY
UPON CREST-ROOT HEIGHT

Test Piece	0	2	4	6
1	.000662	.001256	.000998	.001240
2	.000780	.001416	.000958	.001600
3	.000768	.001244	.000972	.001414
4	.000760	.001590	.001146	.001615
5	.000730	.001588	.000844	.002107
6	.000740	.001608	.000842	.001620
Average	.000740	.001450	.000960	.001599

Test Piece	8	10	12	14
1	.002124	.000930	.001604	.000592
2	.001958	.001110	.001800	.000738
3	.002214	.000778	.001392	.000916
4	.001862	.001024	.001482	.000700
5	.001850	.000804	.001862	.000970
6	.002006	.000802	.001427	.000692
Average	.002002	.000908	.001595	.000768

EXPERIMENTAL DESIGN 3: INFLUENCE OF FREQUENCY AND AMPLITUDE UPON FREE CHIP LENGTH

Specimen No.	Frequency	Condition One Amplitude, A*	Condition Two Excessive Amplitude
1	0	0	0
2	2	.0050	.0083
3	4	.0070	.0083
4	5	.0052	.0083
5	7	.0052	.0083
6	8	.0054	.0083
7	10	.0062	.0083
8	11	.0068	.0083
9	13	.0077	.0083
10	14	.0082	.0083
11	16	.0085	.0090
12	17	.0090	.0090

N_1 = 3 cps, OD_1 = 1.332, F = .010 ipr

N_2 = 3 cps, OD_2 = 1.192, F = .010 ipr

Tool: -5, -5, 5, 5, 13.6, 13.6, .005 Carbide

Material: Polyethylene Plastic

EXPERIMENTAL DESIGN 5: INFLUENCE OF TOOL FREQUENCY AND MATERIAL WORKSPEED UPON ROUGHNESS IN MACHINING ALUMINUM

Factors	Levels
f	2, 4, 6, 8, 10, 12,
N	3, 5, 7

Block	f	N	f	N	Nested Double Amplitude
1, 7, 13	0	0	2	3	.0093
	0	1		5	.0093
	0	2		7	.0093
2, 8, 14	1	0	4	3	.0131
	1	1		5	.0131
	1	2		7	.0131
3, 9, 15	2	0	6	3	.0093
	2	1		5	.0185
	2	2		7	.0185
4, 10,16	3	0	8	3	.0100
	3	1		5	.0100
	3	2		7	.0242
5, 11,17	4	0	10	3	.0115
	4	1		5	.0093
	4	2		7	.0114
6, 12,18	5	0	12	3	.0131
	5	1		5	.0096
	5	2		7	.0096

Constant Conditions

Material: 2011-T3 Aluminum, 1" Diameter

Tool: -8, 0, 5, 5, 30, 30, 1/32 Tungsten Carbide Insert

Depth of Cut: .050"

Feed: .00925 ipr

VITA

Phillip Frederick Ostwald

Candidate for the Degree of

Doctor of Philosophy

Thesis: "DYNAMIC CHIP BREAKING" - AN EVALUATION OF THE EFFECTS UPON SURFACE MICROGEOMETRY AND FREE CHIP DIMENSION

Major Field: Engineering

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