THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

A STUDY OF HIGH-SPEED MILLING OF TITANIUM ALLOYS

L. V. Colwell
L. J. Quackenbush

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NOMENCLATURE

Chip	That part of the workpiece, or any part thereof, removed by a single cutting edge of the tool as the edge moves once across the surface being machined.
Crest Length	The minimum distance across the top of a V-type machining specimen in the direction of cutting.
Cutting Time	Nominal time required to do a particular machining operation.
Cutting Time Per Chip	Actual time required for one cutting edge to separate one chip from the workpiece; usually the time for a single cutting edge to move the depth or length of cut.
Cutting Time Per Pass	Total time the tool and workpiece are in contact as the tool traverses the entire surface being machined once.
Cutting Velocity	The velocity of the cutting edge as it moves across the surface being machined; usually expressed in surface feet per minute or fpm.
Depth of Cut	The amount of penetration into the workpiece by the tool; usually measured from the outer surface in inches.
Feed Rate	Relative motion of the workpiece with respect to a fixed position of the cutting tool, or vice versa; usually expressed in inches per tooth, inches per revolution of the tool or workpiece, or inches per minute.
Microsecond	A millionth of a second, abbreviated as μsec.
Millisecond	A thousandth of a second, msec.
Pass	One movement of entire surface being machined past the cutting tool.

Time Rate of Metal Removal	The rate at which metal is being removed from the workpiece; usually expressed in cubic inches per minute.
Tool	A cutting device, which upon contact with a workpiece, removes metal by generating chips.
Tool Life	That interval of time during which a cutting tool is efficiently removing metal; usually expressed in minutes but often expressed in terms of the time for a certain amount of cutting edge wear.

ABSTRACT

An exploratory study was made to determine the feasibility of increasing rates of metal removal in milling by cutting at higher than normal speeds for shorter cutting times per chip. The results indicate the possibility of milling even titanium at feed rates up to 100 feet per minute for shallow cuts where the cutting time per chip is limited to less than a millisecond. Studies of temperature, tool wear, vibrations, and chip formation were made in exploring the boundaries within which this process is workable.

INTRODUCTION

This project was carried out to establish whether it is feasible to increase rates of metal removal by milling at relatively high rates of cutting speed. It was assumed at the outset that, if such a result were possible, it would occur at some combination of high cutting speed and very short exposure of the cutter teeth to the high temperatures associated with high speeds.

Accordingly, numerous tests were made in which the duration of a single cut varied from as little as 5 microseconds (millionths of a second) to several milliseconds (thousandths of a second). Cutting speeds ranged from 600 fpm (feet per minute) to 14,000 fpm. Several metals were cut at various combinations of these conditions. The metals ranged from aluminum through ingot iron, copper, low-carbon steel, stainless steel, Inconel-X, NIVCO-10, and three alloys of titanium designated as A-110, B-120, and C-120, respectively.

The results indicate that it is feasible to increase current rates of metal removal for high-strength materials like titanium and stainless steel alloys. This can be accomplished with carbide cutting tools when the cutting conditions are selected so as to keep the cutting time per chip under one thousandth of a second. With such combinations it was possible to use the experimental equipment up to its maximum feeding capacity, 230 inches per minute. In other words, titanium alloys were milled with the work feeding past the cutter at nearly 20 fpm. It is possible to extend this even further as illustrated in the following example.

AN EXAMPLE OF THE FEASIBILITY

The results of this study indicate that the following cutting conditions are workable for milling titanium alloys.

Cutter:

A 1-in.-diam carbide end mill with 30 teeth.

Type of Cut:

Cutting on the perimeter with a climb or "in-milling" type of slab-milling cut.

Cutting Conditions:

(a) Cutter speed = 3600 rpm = 950 fpm.
(b) Depth of cut = 0.010 in.
(c) Feed per tooth = 0.010 in.
(d) Maximum thickness of undeformed chip = .002 in.
(e) Length of undeformed chip = 0.096 in.
(f) Cutting time/chip = 530 μsec.
(g) Number of teeth per minute = 108,000.

Performance:

(a) Feed rate = 1,080 in./minute = 90 fpm.
(b) Metal removal rate = 10.8 cu in./minute per in. of cutter engagement.
(c) Tool life: Possible as long as one hr/regrind.

Similar cuts were made experimentally as reported in Series H of the Appendix. The operation has been called micromilling because of the relatively small size of individual chips. The depth of cut is limited for two reasons:

(1) To provide short cutting time per chip.
(2) To minimize the length of the chips.

Short cutting time is most essential. This can be reduced at any given depth of cut by increasing peripheral speed and decreasing cutter diameter, within limits; the useful working depth appears to lie between 0.005 and 0.030 in. However, greater depths can be removed by successive cuts at the very high traverse rates. Thus a 0.050-in. depth could be removed in successive passes at a rate equivalent to a feed rate of 200 in./minute where the cut was made in a single pass.

These operating conditions resemble grinding but the depths of cut, chip size, and removal rates are considerably greater. In addition, the cutting speeds can be even higher than for grinding with work materials like aluminum, copper, and low-carbon steel. The reason for the latter is that the chips are thicker and the effective rake angles are more positive with milling.

It is known that chip thickness and length are critical. The chip may be too thin and too long. Thin chips greatly increase the incidence of rubbing and frictional heating. Chips that are too long for the available chip space will also cause overheating. Consequently, rigidity, vibration, cutting temperature, and tool wear are factors that should be examined in evaluating any process. All these were investigated to some extent in this feasibility study.

TEMPERATURE AS A FACTOR

All the experimental studies were carried out on the combination lathe-milling machine shown in (a) of Fig. A. Figure A(b) is a close-up of the arrangement for studying cutting temperatures with a thermocouple embedded in a hole on the underside of the stationary cutting tool. Details of procedure and set-up are presented in Series F of the Appendix.

Only relative temperature data were obtained because of limited time and funds. The results are summarized in Figs. B, C, and D and also in Figs. 18-29 of the Appendix.

Temperature data for the A-110 titanium alloy for three different sets of cutting conditions are plotted in Fig. B. Temperature rise during a complete pass is plotted versus the cutting time per chip in microseconds which remained constant during each pass but increased on successive passes. The temperatures were calculated as the step-function impulse which persisted as an average during the entire pass. These are not the temperatures which actually existed between the chip and tool, as will be explained later.

The data in Figs. B, C, and D are comparable regardless of errors arising out of simplifying assumptions since the passes for all cutting conditions required the same total cutting time of 3.4 seconds. The temperature rise is shown to be greater for the higher speeds although the rate of metal removal is the same at all three speeds. This leads to the conclusion in all cases that it is better to cut at low speeds and heavy cuts than vice versa. This is true for all types of metal cutting in general where temperature, tool life, and rate of metal removal are considered. However, tool wear and temperature rise become critical and unstable when certain threshold levels are exceeded. This appeared to occur when the cutting time per chip exceeded one millisecond at the heavy-feed, low-speed cut in Fig. B.

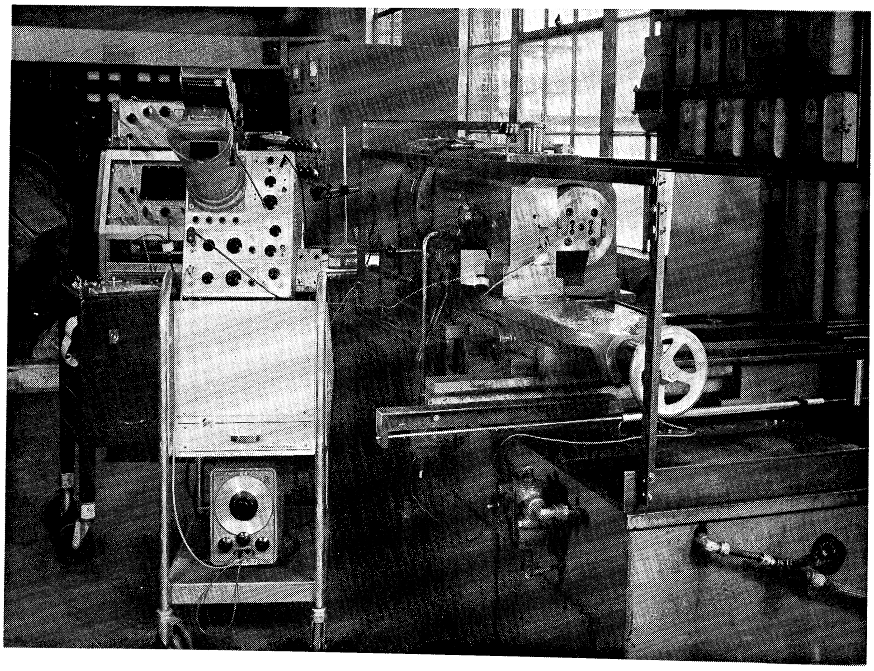
A comparison of the sensitivity of temperature rise per pass to changes in cutting speed and feed rate is given in Eqs. (1) and (2) below.

$$\theta = K_f f^{.37} \tag{1}$$

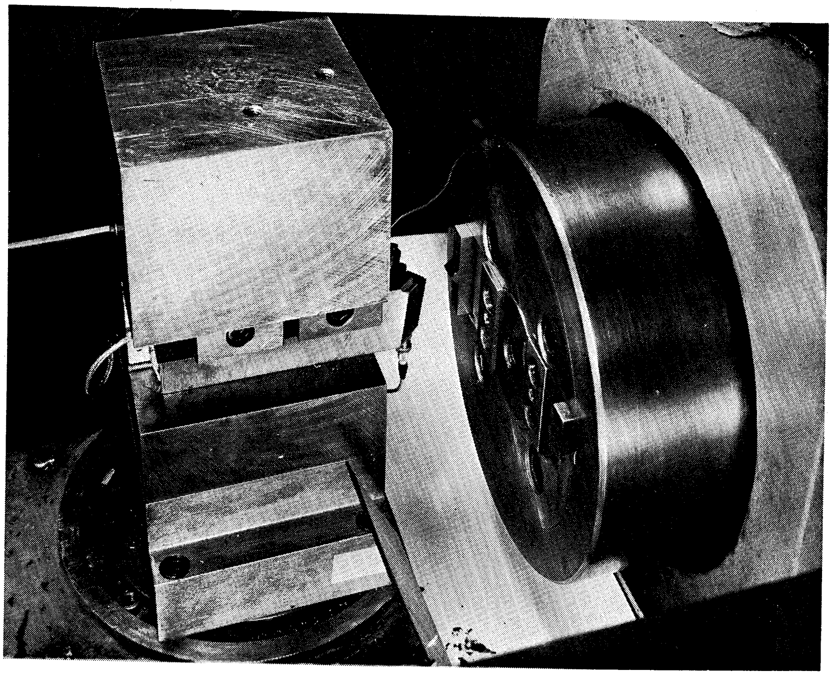
$$\theta = K_V V^{2.6} \tag{2}$$

where:

θ = temperature rise
f = feed in in./tooth
V = cutting speed in fpm
K_f, K_V = proportionality constants.



(a) Combination lathe-milling machine and instrumentation.



(b) Close-up cutting tool for temperature measurements.

Fig.-A.

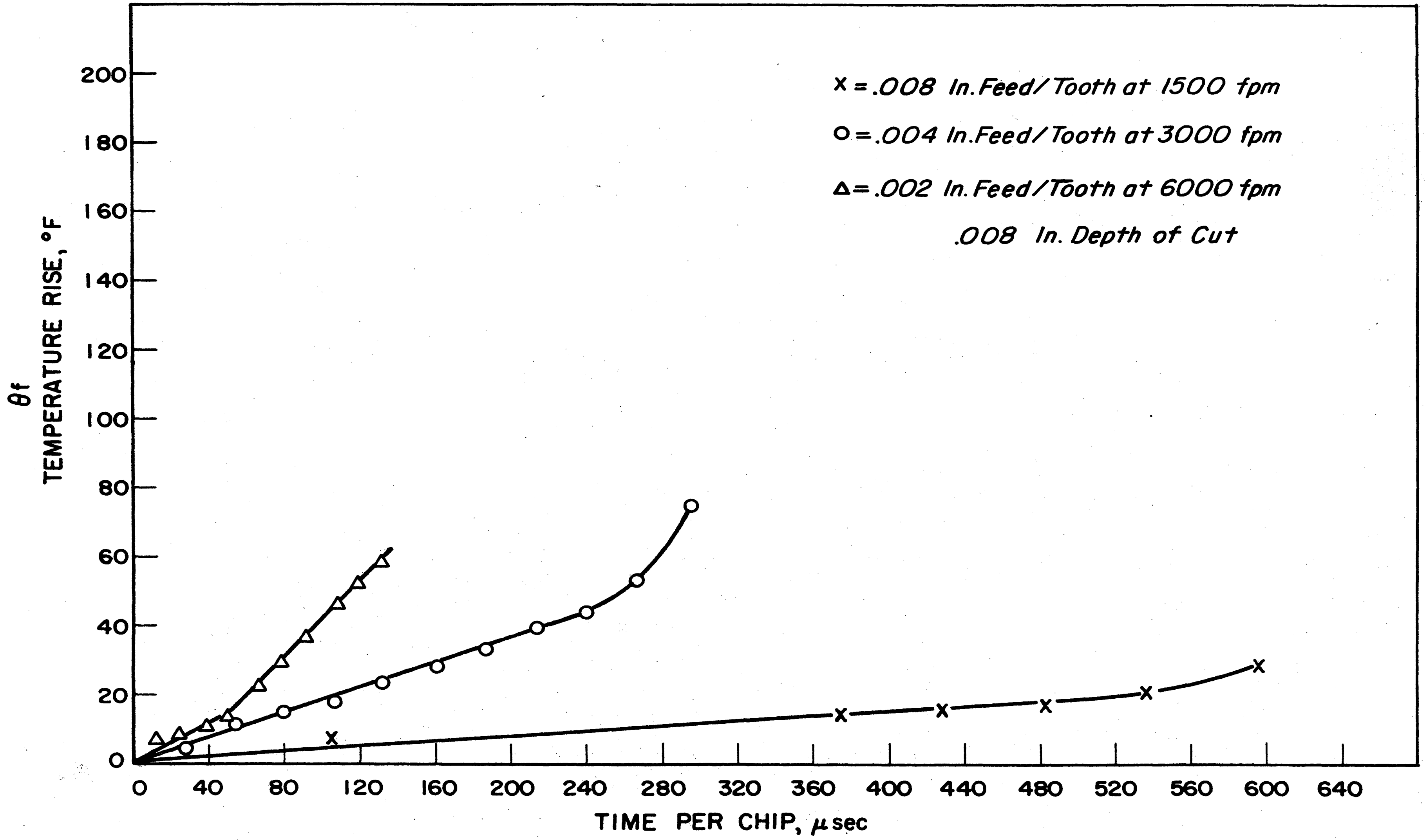


Fig. B. Temperature rise vs. time per chip at the same metal removal rates: A-110.

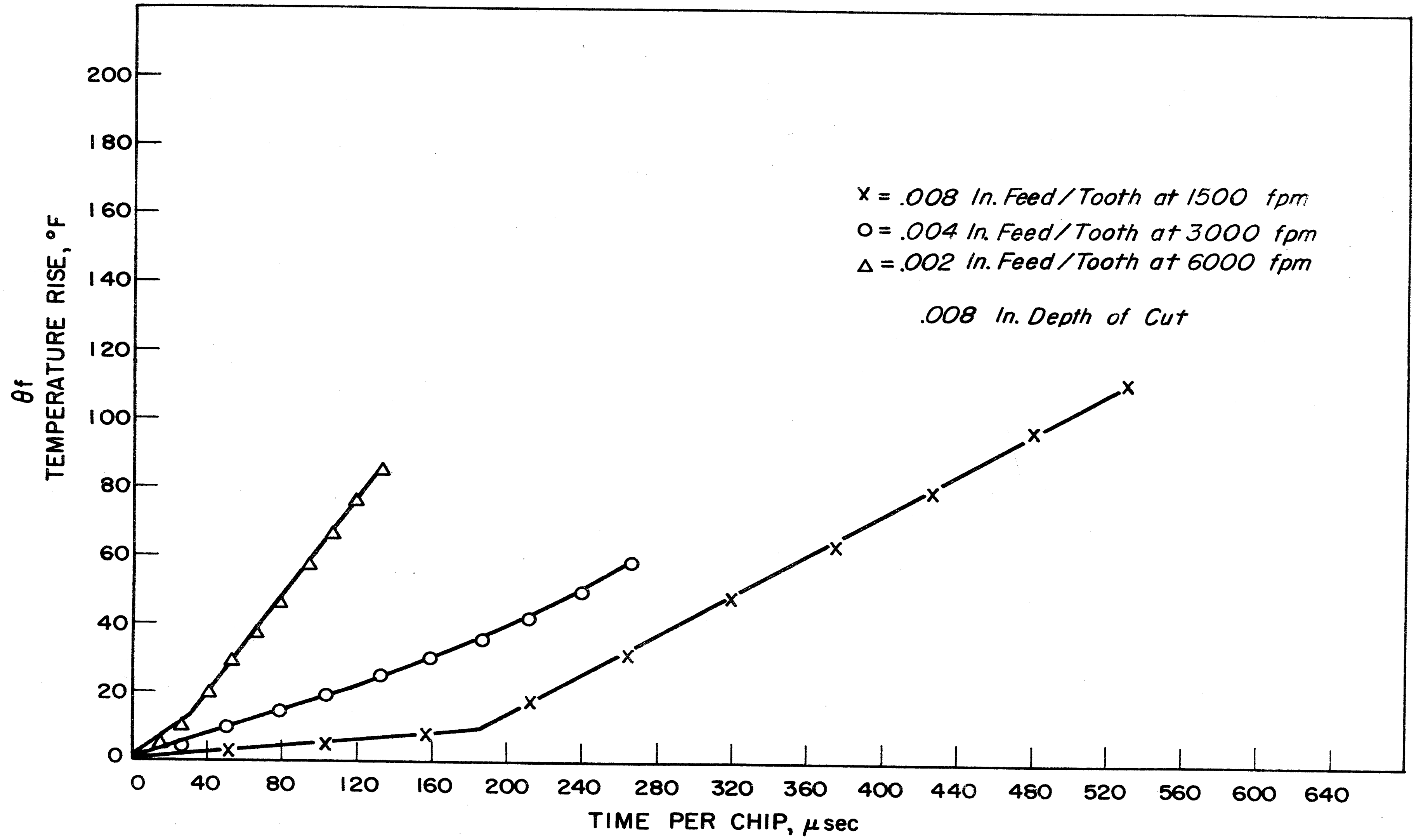


Fig. C. Temperature rise vs. time per chip at the same metal removal rates: B-120.

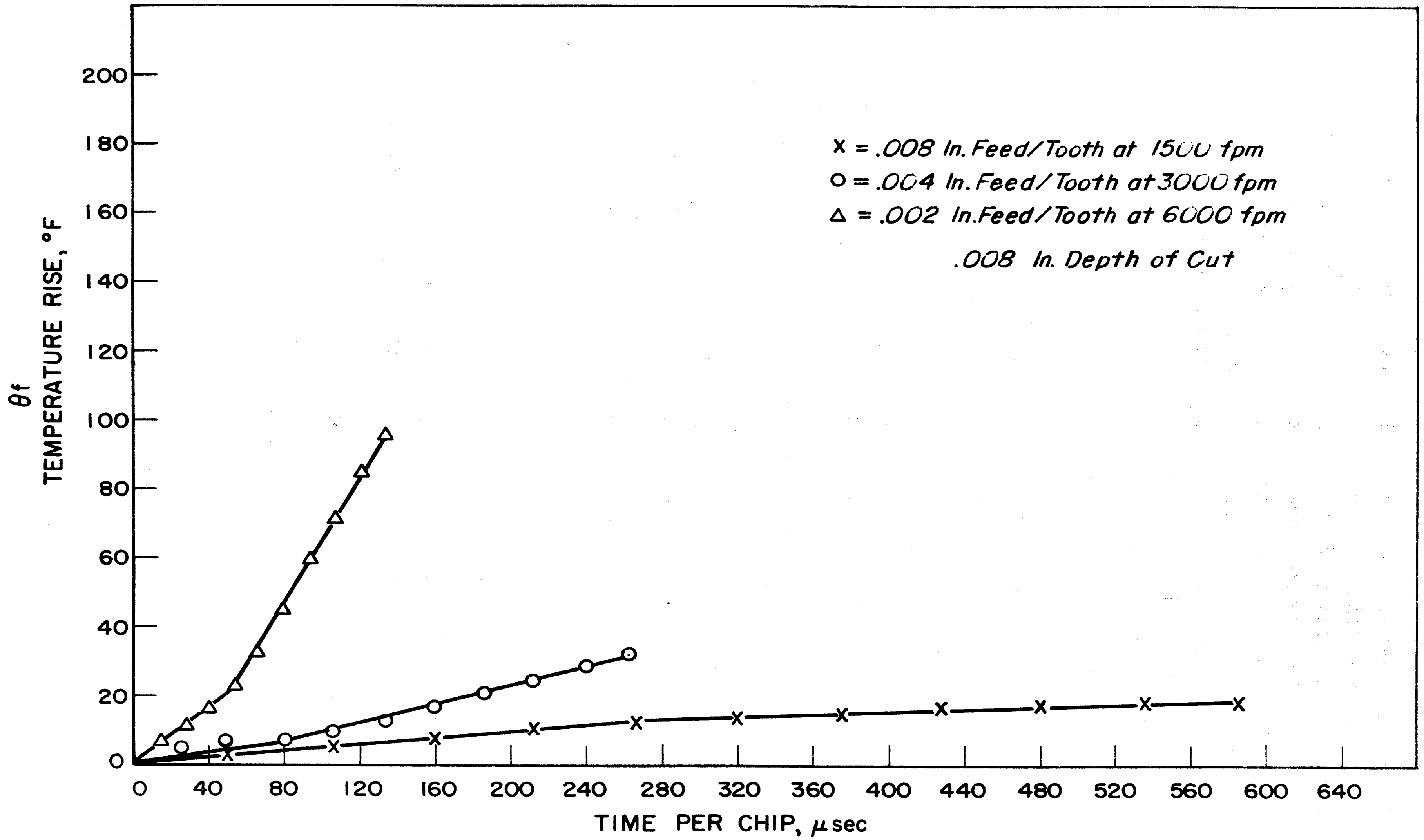


Fig. D. Temperature rise vs. time per chip at the same metal removal rates: C-120.

Both of these equations were obtained by comparing temperatures for passes wherein the cutting time per chip was 120 μsec. Equation (1) is for a constant cutting speed of 6000 fpm; Eq. (2) is for a constant feed of 0.008 in. per tooth. The equations are almost equally valid for all three titanium alloys with the exception that the proportionality constants appear to be somewhat higher for the A-110 alloy than for the B-120 and C-120. Note that the actual maximum thicknesses of the undeformed chips are somewhat less than the feeds, as shown in the following table:

Maximum Undeformed Chip Thickness-t_{max}

Feed-inches per tooth:	.002	.004	.008
t_{max}-inches:	.0011	.0026	.0045

It will be recalled that the maximum undeformed chip thickness and cutting speed in the feasibility example were 0.002 in. and 950 fpm, respectively. Also, the cutting time per chip was only 530 μsec. Consequently, the temperature behavior should fall below the lower lines in Figs. 21, 22, and 23 in the Appendix. This appears to be a workable condition since the measured temperature rise in the lower lines of Figs. 21, 22, and 23 appeared to have reached at least 85% of an equilibrium level in about 7 seconds of cutting time. Therefore it is highly probable that prolonged cuts of several minutes duration could be sustained without overheating. Even so, this remains to be proven through actual test and a further study of actual tool-chip interface temperatures.

TOOL-CHIP INTERFACE TEMPERATURE

No direct measurements were made of the actual temperatures at the tool-chip interface, but some deductions can be made from further analysis of the experimental results. If one assumes that the temperature at the interface reaches equilibrium within a very short time and remains substantially constant, then the temperature at some point remote from the interface can be calculated from the conditions illustrated in Fig. E.

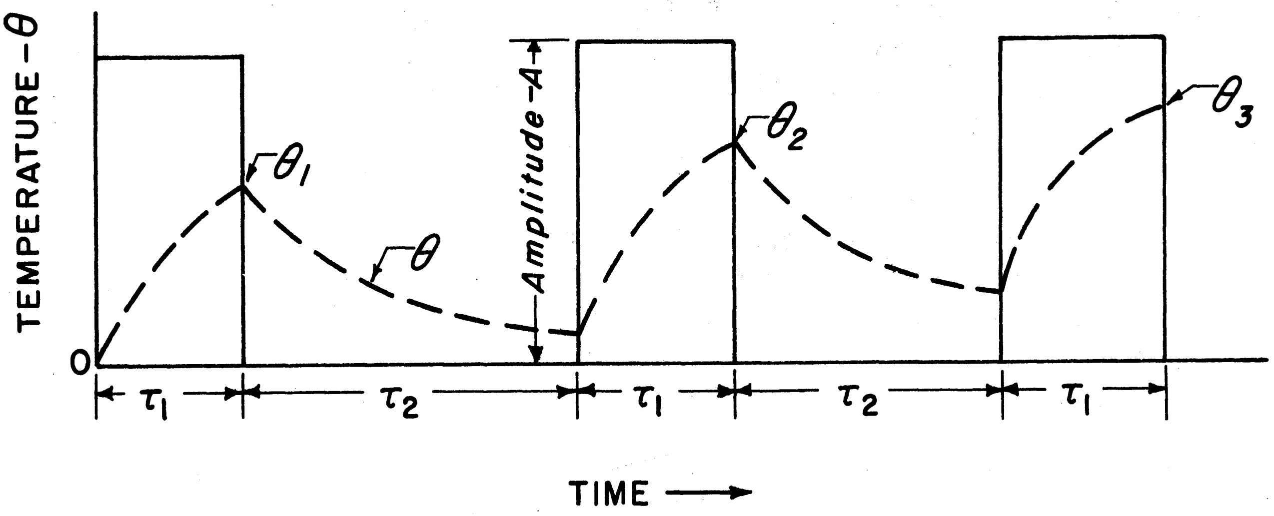


Fig. E. Temperature relationships in interrupted cuts: τ_1 = cutting time per chip; τ_2 = cooling time between cuts; A = interface temperature; and θ = temperature at some point outside the interface.

It can be shown that the peak temperature reached at some point outside the interface after "n" cuts will be:

$$\theta_n = A(1-K_1)(1+K+K^2+K^3+\ldots+K^{n-1}) \tag{3}$$

where:

θ_n = peak temperature at point outside interface
A = interface temperature during cutting
$K_1 = e^{-\tau_1/T}$
$K = (e^{-\tau_1/T})(e^{-\tau_2/T}) = e^{-(\tau_1+\tau_2)/T}$
n = number of cuts
T = system time constant.

For the experimental conditions the time $\tau_1+\tau_2$ is the time for a single revolution of the spindle and varies with the rpm. The number of cuts is a function of the feed rate and varied from n = 57 to n = 228. At these conditions, the second term $(1-K_1)$ is almost linear with τ_1 while the last term in Eq. (3) is similar to first-order response to a step-function impulse.

Using Eq. (3) to calculate interface temperatures from the results of this study leads to ridiculously high temperatures when the time constant "T" is taken as 3.5 sec, as derived from the assumption that the temperature records approximated first-order response. Actually, the geometry of the system indicates a combination of step-function and ramp-function characteristics so that the real time constant for Eq. (3) must be somewhat less than 3.5 seconds.

If it is assumed that the time constant is one second, then the interface temperatures for the three different speeds in Fig. B would be 825°F, 2050°F and 2200°F, respectively, for 1500 fpm, 3000 fpm, and 6000 fpm. It is probable that the actual temperatures are somewhat higher since the chips from the highest speed indicate that the melting point of the alloy had been reached.

In view of the importance of working at relatively high temperatures and substantial differences in sensitivity of temperature to changes in speed and size of cut, it is desirable to refine this type of information further as a guide for the selection of optimum cutting conditions.

TOOL WEAR

Tool life and tool wear have been matters of concern throughout this project, but one of the several series of tests was devoted solely to this problem area. The details of procedure and conditions are recorded in Series D of the Appendix. This study was restricted to the A-110 titanium alloy.

Plots of tool flank wear versus cumulative cutting time are shown in Fig. F for three different speeds at a relatively heavy cut. The effect of speed is evaluated by comparing the times for the same amount of wear to take place, as in Fig. G where the cumulative cutting time to failure is plotted against the corresponding cutting speeds. Failure or the flank wear at which regrinding is advisable has been considered at two different levels, 0.030 in. and 0.021 in.

For a terminal wear land of 0.030 in., the tool-life equation is:

$$VT^{.2} = 1320. \tag{4}$$

For a terminal wear of 0.021 in., the corresponding equation is:

$$VT^{.16} = 1375 \tag{5}$$

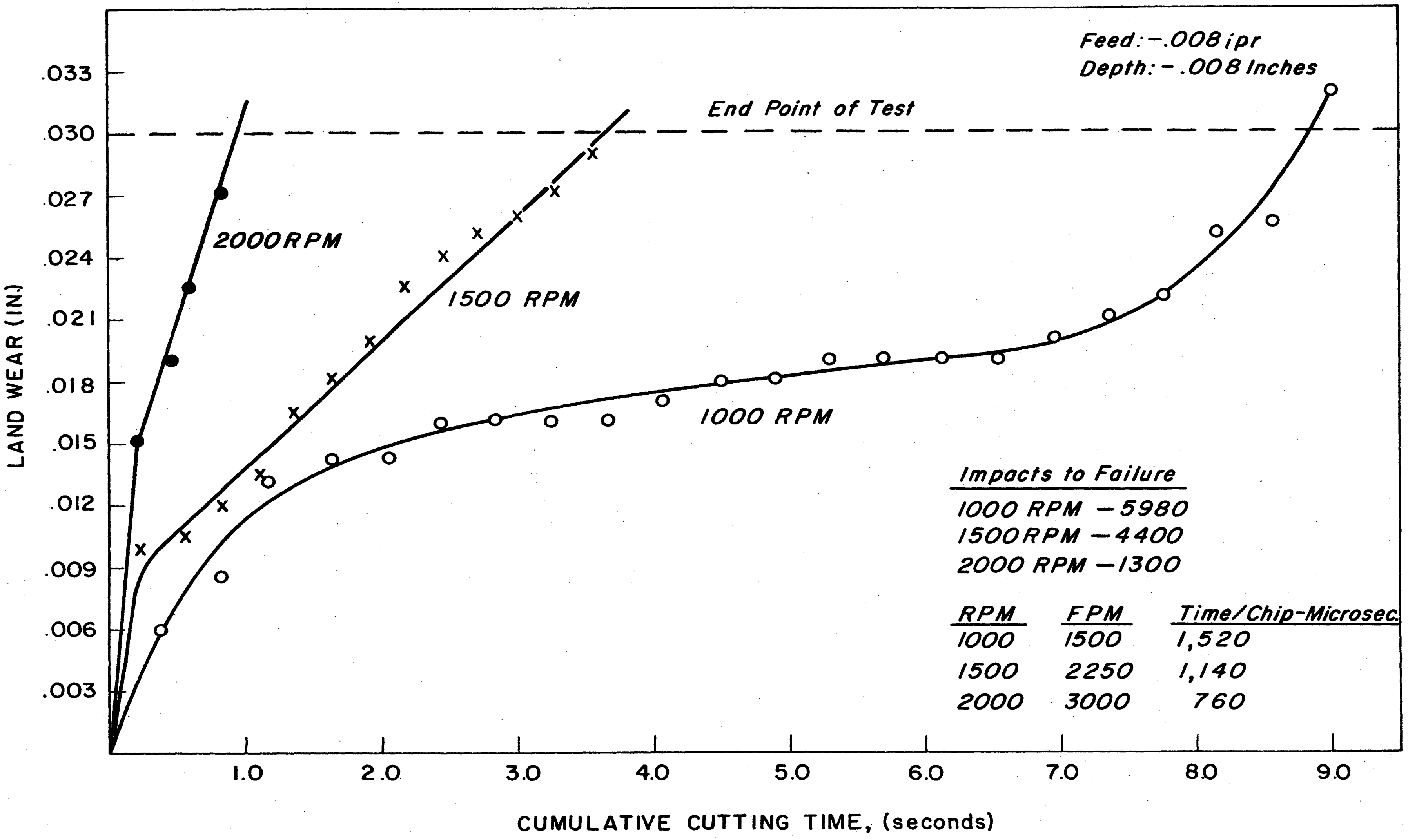


Fig. F. Land wear vs. cumulative cutting time: A-110 titanium cut with carboloy 883.

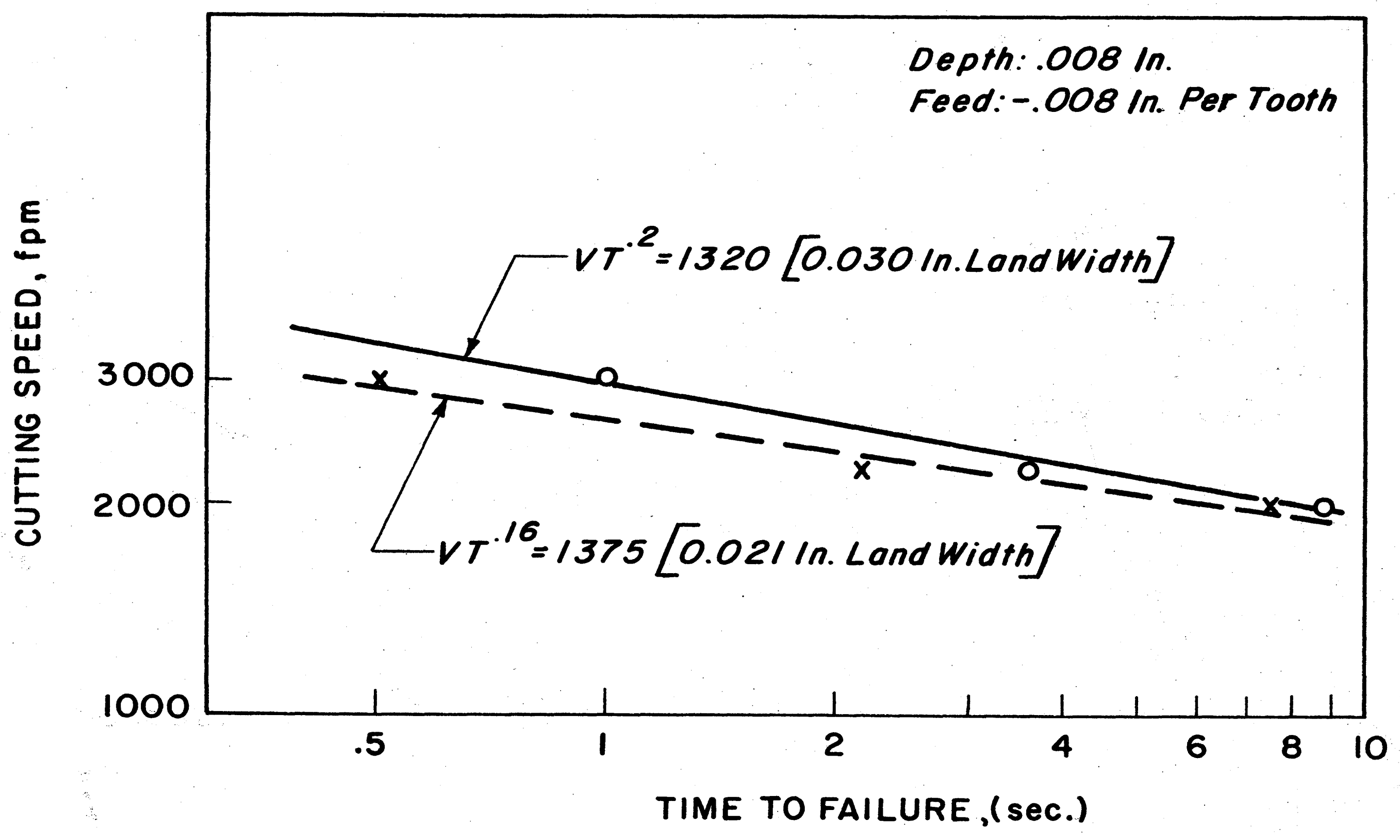


Fig. G. Cutting speed vs. time to failure: A-110 titanium.

where:

V = cutting speed in fpm
T = tool life per regrind, in minutes.

When one substitutes the cutting speed of the feasibility example (950 fpm) into Eq. (5), one gets a tool life of 10 minutes. The ten minutes is cumulative cutting time which corresponds to a total of 314 minutes or over 5 hours of continuous cutter use. In view of the uncertainties involved, this prediction was reduced to one hour although the cut thickness was more than twice that of the aforementioned example.

Equation (4) is the more conservative at lower speeds and, when transformed to amount of metal "Q" removed per regrind, it gives

$$Q = \frac{1320^{5.0}(12\ fd)}{V^{4.0}} \tag{6}$$

where:

Q = cubic inches removed per regrind
V = cutting speed in fpm
f = average chip thickness, in.
d = depth of cut, in.

Again, this equation emphasizes the economic importance of heavier cuts at lower speeds since doubling the size of cut and reducing the speed to one-half increases the tool life in terms of metal removed by 2^5 or 32 times.

FORCES AND VIBRATIONS

Forces and vibrations are always matters of concern in metal cutting. Forces are relevant to size control and power requirements. Vibrations can be beneficial if they lead to lower forces and friction. On the other hand, they can aggravate problems associated with surface finish, tool life, energy requirements, and temperature. Therefore two series of studies were devoted to these problems. Details of procedure and some of the results are given in Series E and G of the Appendix.

Vibration studies were made both with the cutting tool stationary and the workpiece stationary. Both accelerometer and force-transducer data were obtained although forces, per se, were measured only with a stationary tool and rotating workpiece. In addition, samples of the chips were analyzed for possible dependence on vibration characteristics.

Typical test records are shown in Fig. H for single cuts on C-120 titanium alloy. The records are photographs of single sweeps of a dual-beam oscilloscope. The lower trace is a time-base record of cutting force with force plotted in the vertical direction and with time increasing from left to right. The more rapidly varying trace in (b) is the output of the accelerometer mounted under the front end of the tool holder. The top trace is a sinusoidal timing of reference wave of 10 kilocycles which indicates that each centimeter or square of horizontal oscilloscope traverse represents 100 μsec.

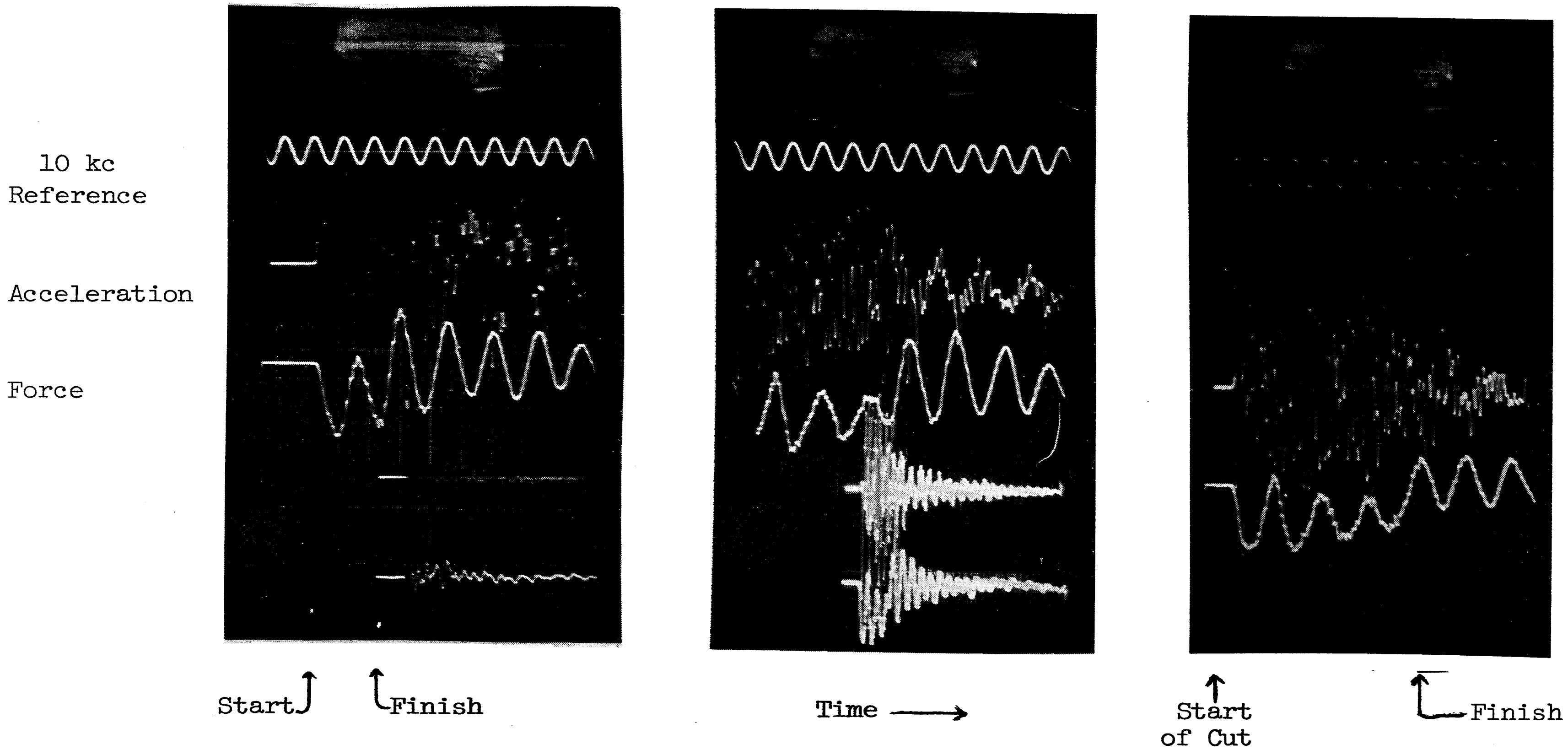
The cutting time for Pass No. 4 at (a) was 214 μsec or a little more than two squares. The cutting tool was deflected downward during the cut, but it also oscillated or vibrated at a frequency between 6 and 7 kc even during the cut.

The accelerometer record indicates force variations of even higher frequency. These are evident also in the force record, particularly during cutting. It appears that the higher frequency is of the order of 50 kc. The forces in these records are at the rate of 27.5 lb/cm so that the peak force in the first cycle of Pass No. 4 is about 70 lb.

It can be seen clearly in Fig. H(b) that the accelerometer record also reflects the tool motion, particularly after cutting is complete and the higher frequencies are dying out. The accelerometer record rises vertically when the accelerometer is being accelerated upward. The scope was triggered by the accelerometer so that the initial downward excursion represents the first shock wave from the impact of the work on the tool. These higher frequencies are complex wave forms and undoubtedly result from a mixture of resonant frequencies of both the workpiece and the tool, as will be demonstrated later.

Figure J shows a chip of C-120 titanium obtained at the same speed but at a lighter feed than that used in Fig. H. The coarse segments or notches in the lower edge of the chip correspond to a frequency of about 53,000 cps, which roughly approximates the highest frequency indicated by the accelerometer. The finer segments, which are evident over the entire top surface of the chip, occur at a frequency over 200,000 cps. This is well beyond the frequency limit of the accelerometer, which could explain why they did not show up in the oscilloscope records.

Figure K shows chips from the tenth pass when milling A-110, at (a), and B-120 titanium, at (b) at a speed of 1500 fpm, a depth of 0.008 in., and the heavy feed of 0.008 in. per tooth. The coarse segmentation dominates at the heavy feeds and corresponds to frequencies between 37,000 and 50,000 cps. There also is evidence of melting on the slip planes as shown by the rounding of the edges of the segments. This can be seen clearly in (a) in Fig. K.

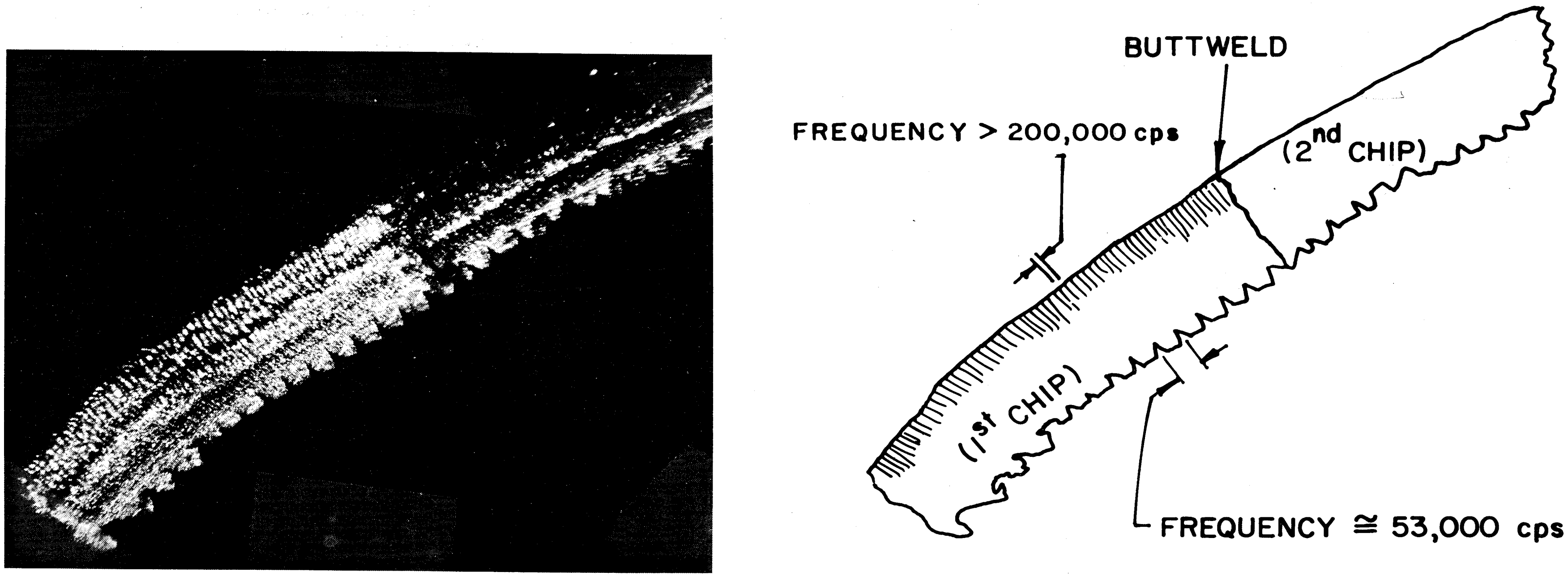


(a) 214 μsec/chip
(Pass No. 4)

(b) 535 μsec/chip
(Pass No. 10)

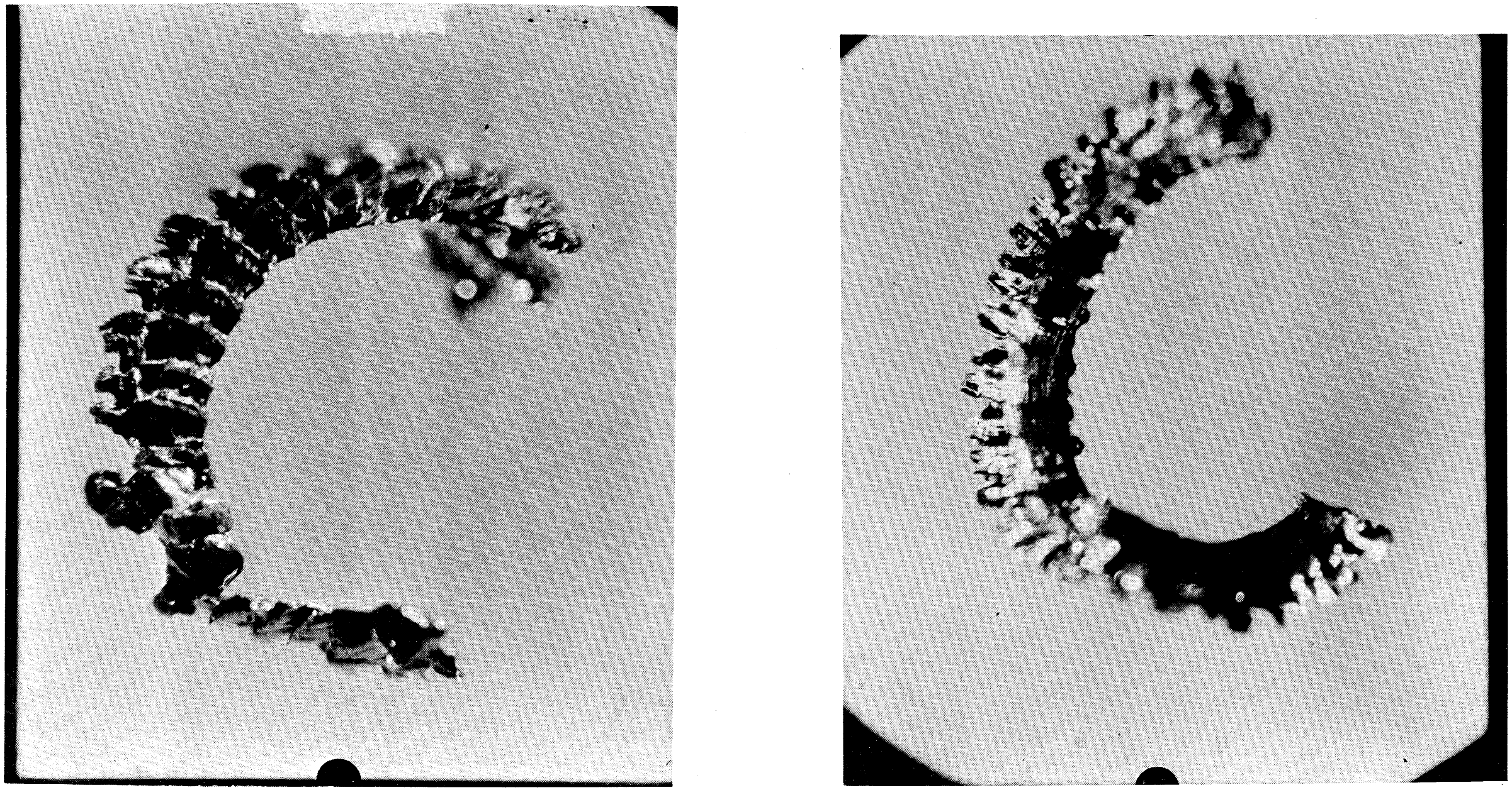
(c) 588 μsec/chip
(Pass No. 11)

Fig. H. Cutting forces and tool accelerations while cutting C-120 titanium at 1500 fpm, 0.008 in. depth of cut and 0.008 in. per tooth feed. Sine wave at top is 10-kc time reference. Cutting force and tool deflection is downward under load. Force = 27.5 lb/cm of trace deflection.



Actual Chip

Fig. J. Chips from Pass No. 5 when milling C-120 titanium at 1500 fpm at a feed of 0.002 ipt and a depth of 0.008 in. The 14 coarse segments occur at a frequency of about 53,000 cps, which corresponds to highest frequency shown by accelerometer.



(a) A-110 Titanium
(Top surface)

(b) B-120 Titanium
(Underside)

Fig. K. Single chips from Pass No. 10. Cutting speed = 1500 fpm; feed = .008 ipt; depth = 0.008 in. Segment frequency between 37,000 and 50,000 cps. Rounded edges of segments in (a) indicate melting.

Figure L illustrates another significant behavior characteristic. The oscilloscope traces represent force and acceleration for B-120 titanium milled at 6000 fpm with a feed of 0.004 in. per tooth. At this speed the flank of the tool can readily become smeared, thus bringing about an increase in the effective spring constants of both the tool and the workpiece when the two are in rubbing contact. The net result is a brief increase in resonant frequency of the tool as shown at (b) in Fig. L. The record at the left, (a), is normal.

Figure M shows chips and oscilloscope records for copper and 1018 steel. It is significant that chip segmentation is less than for titanium and that the higher frequencies are absent from the accelerometer record for copper and of low amplitude for steel. This could indicate that titanium has very low damping at high frequencies, and that it also is more notch-sensitive than steel and copper.

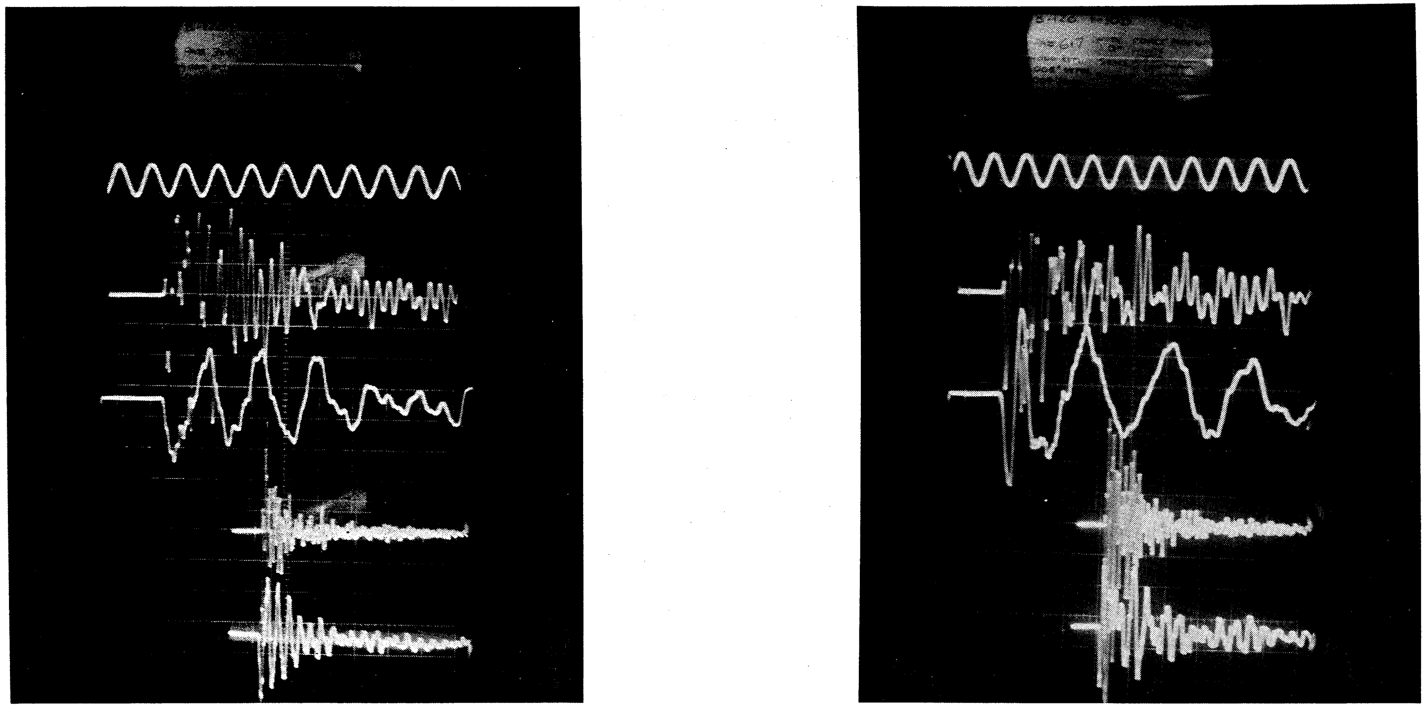
RESONANT FREQUENCIES IN THE WORKPIECE

Vibrations in the workpiece are also possible causes of segmentation of the chips. This possibility was explored by milling with a rotating tool so that an accelerometer could be mounted on the workpiece. Details of the set-up and procedure are outlined in Section E of the Appendix. The length and location of the workpiece in the holder were varied and both horizontal and vertical vibrations were measured.

For vertical vibrations, the accelerometer was mounted under the workpiece on the overhanging portion as shown in (a) of Fig. N. Typical records are shown in (b) and (c). Two cuts are shown on each record. The bottom trace is for Pass No. 5 and the upper trace which was made at a faster sweep rate was for Pass No. 6. The corresponding cutting times per chip and time per revolution are shown in the following table.

		Microseconds	
Pass No.	Cutting speed, fpm	Time/chip	Time/revolution
5	3000	134	30,000
6	3000	160	30,000
5	4500	89	22,500
6	4500	107	22,500

The expand sweep with Pass No. 6 traverses the scope tube in about one millisecond or 1000 μsec. The traverse time for Pass No. 5 is 5 msec, so neither trace represents one full revolution, and it is evident that all vibrations decay to zero before the next revolution. The records at (b) and (c) in Fig. N supplement those shown in Fig. P where the length of the workpiece was held constant at 2-1/4 in. and the overhang or free length was increased in two steps from 5/8 in. to 1-1/4 in.



<u>Normal Behavior</u>

(a) 214 µsec/chip

<u>Substantial Rubbing</u>

(b) 374 µsec/chip

Fig. L. B-120 titanium. Increase of resonant frequency of tool due to rubbing contact between tool flank and workpiece. Force and acceleration records for cuts made at 6000 fpm, .008 in. depth, and 0.004 ipt.

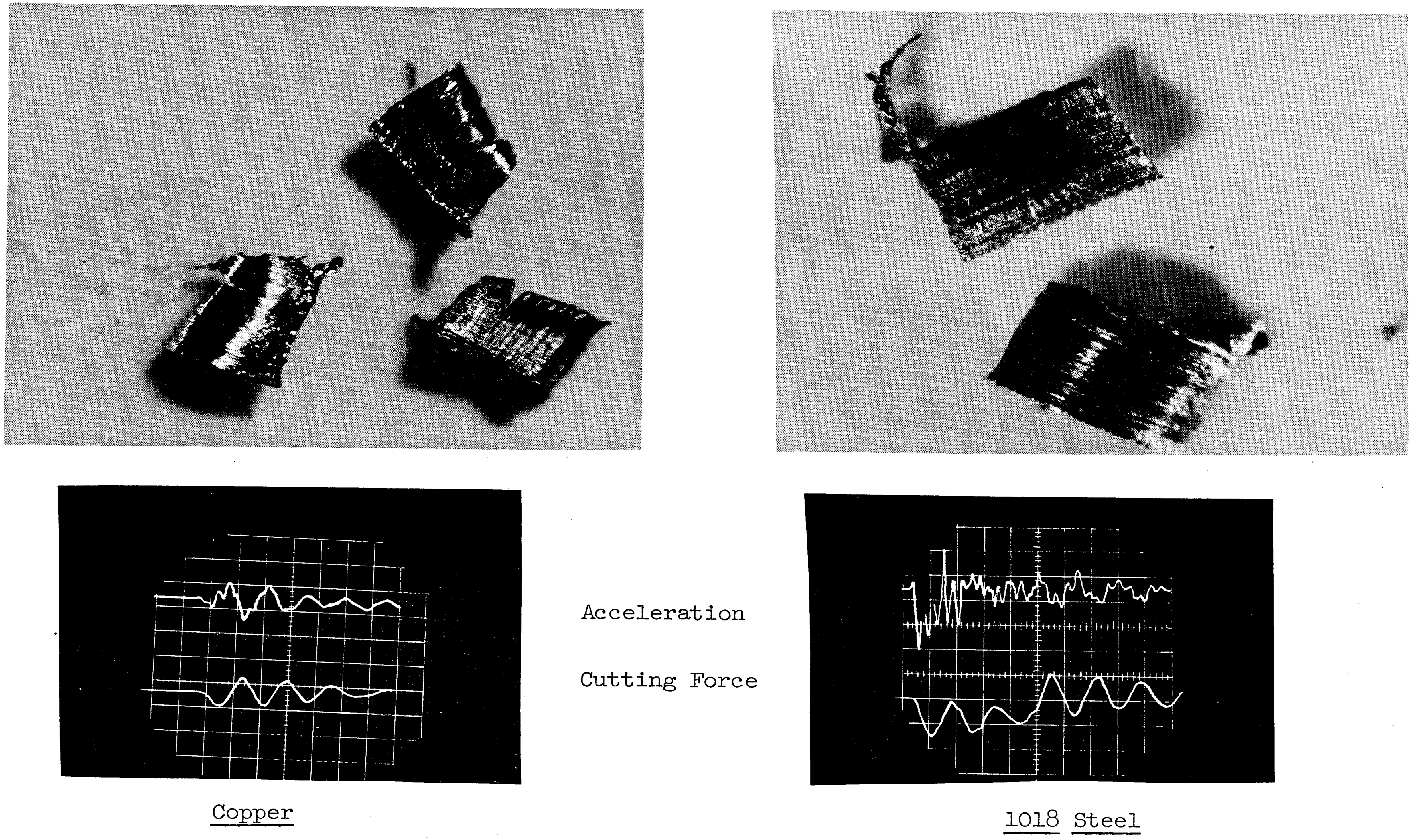
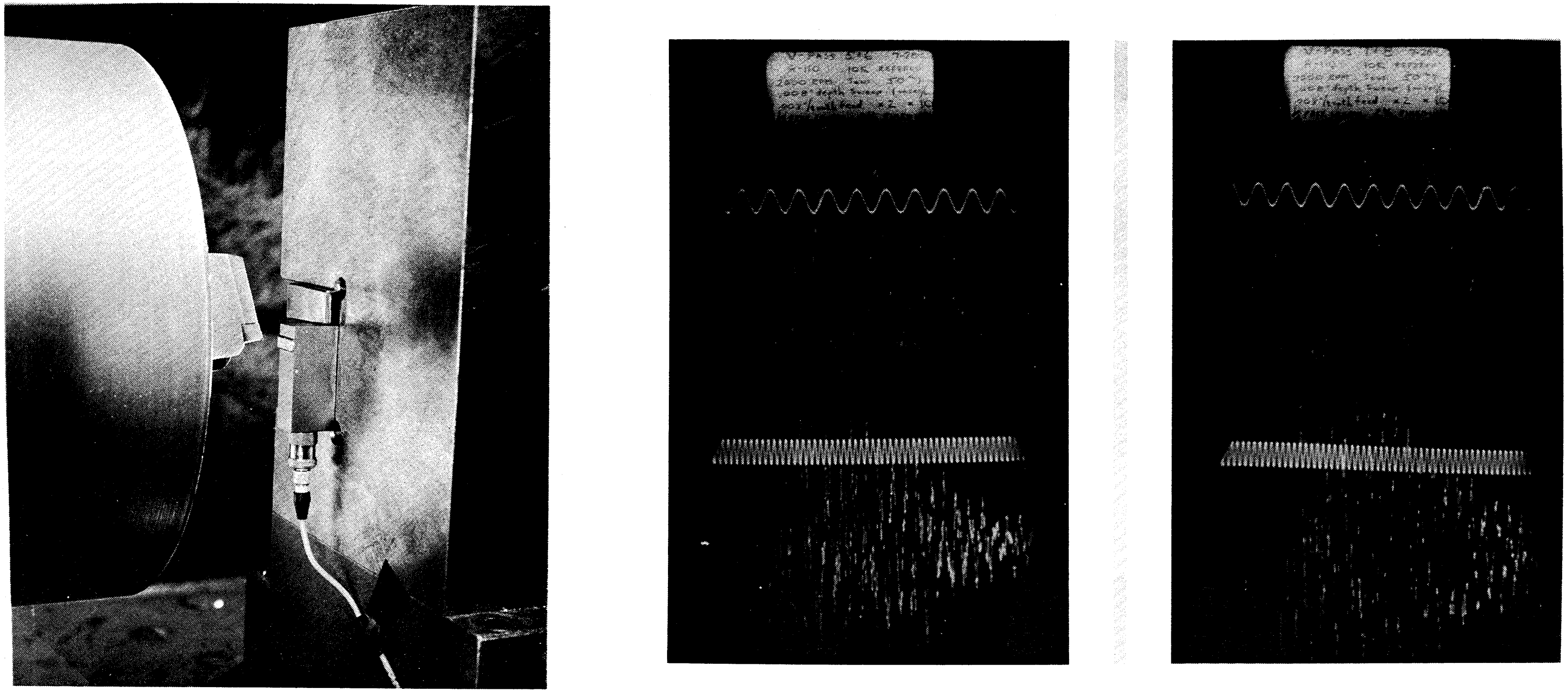


Fig. M. Relative freedom from segmentation compared to titanium. High frequencies are absent from accelerometer trace for copper and are of lesser magnitude in steel. Cutting speed = 1500 fpm; depth of cut = 0.008 in.



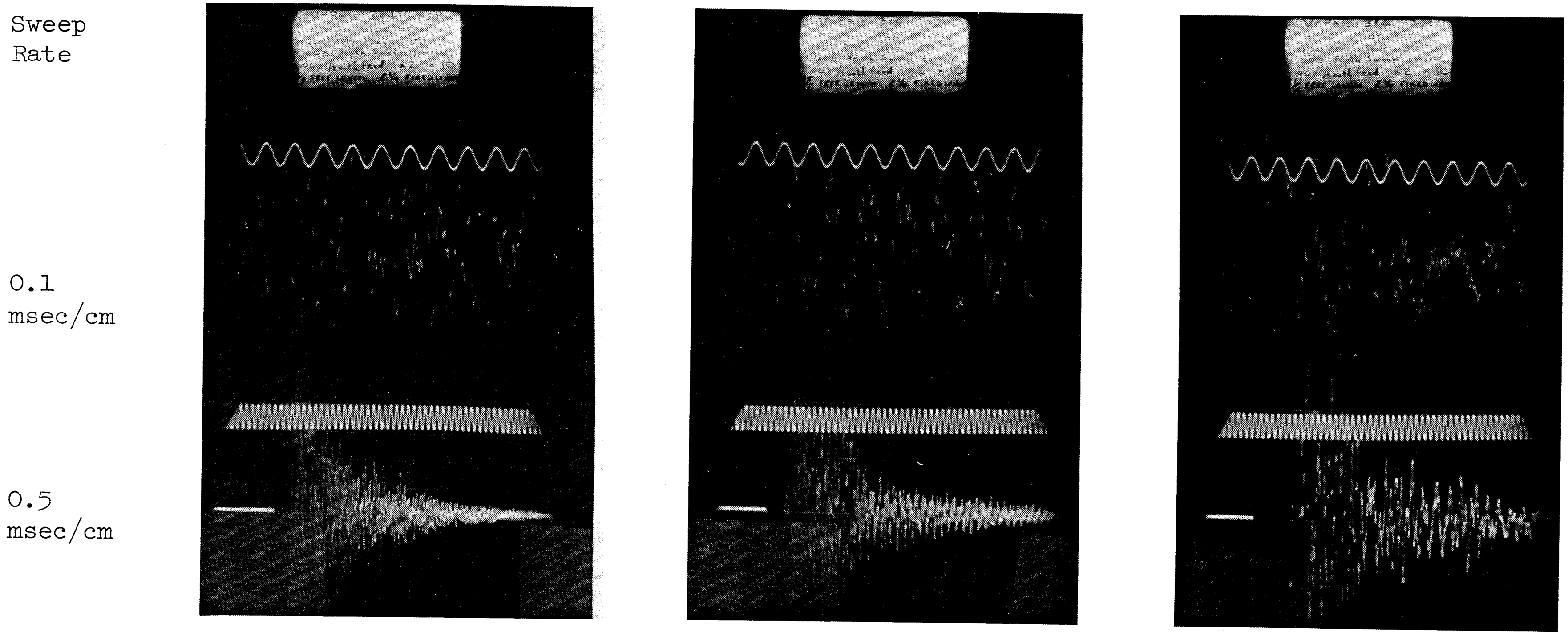
(a)

(b) 1-1/4-in. overhang
Cutting speed: 3000 fpm

(c) 1-1/4-in. overhang
Cutting speed: 4500 fpm

A-110 Titanium

Fig. N. Typical accelerometer records obtained with set-up shown in (a). Overhang of the stationary workpiece was varied from 5/8 to 1-1/4 in. (see Fig. P). Note that the higher impact at higher speed increases amplitude of lower-frequency vibrations.



(a) 5/8-in. overhang (b) 15/16-in. overhang (c) 1-1/4-in. overhang

(Time wave is 10 kc at both sweep rates)

A-110 Titanium (Vertical Vibrations)

Fig. P. Shows the effect of increasing overhang on the frequency of vibration in the shear mode. Note increasing amplitude and decreasing frequency with increase in overhang. Cutting speed = 1500 fpm; depth = .008 in.; feed = .008 ipt. (See Fig. N for higher speeds.)

It can be seen in Fig. P that the amplitude of the vibrations is increased with increased overhang and that the frequency is decreased. This is graphic evidence that the higher frequencies are resonant modes which are unique to the shape and size of the workpiece as well as the manner in which it is supported. The records in Fig. N indicate that the effect of greater overhang is aggravated by higher speeds and consequently by higher rates of impact.

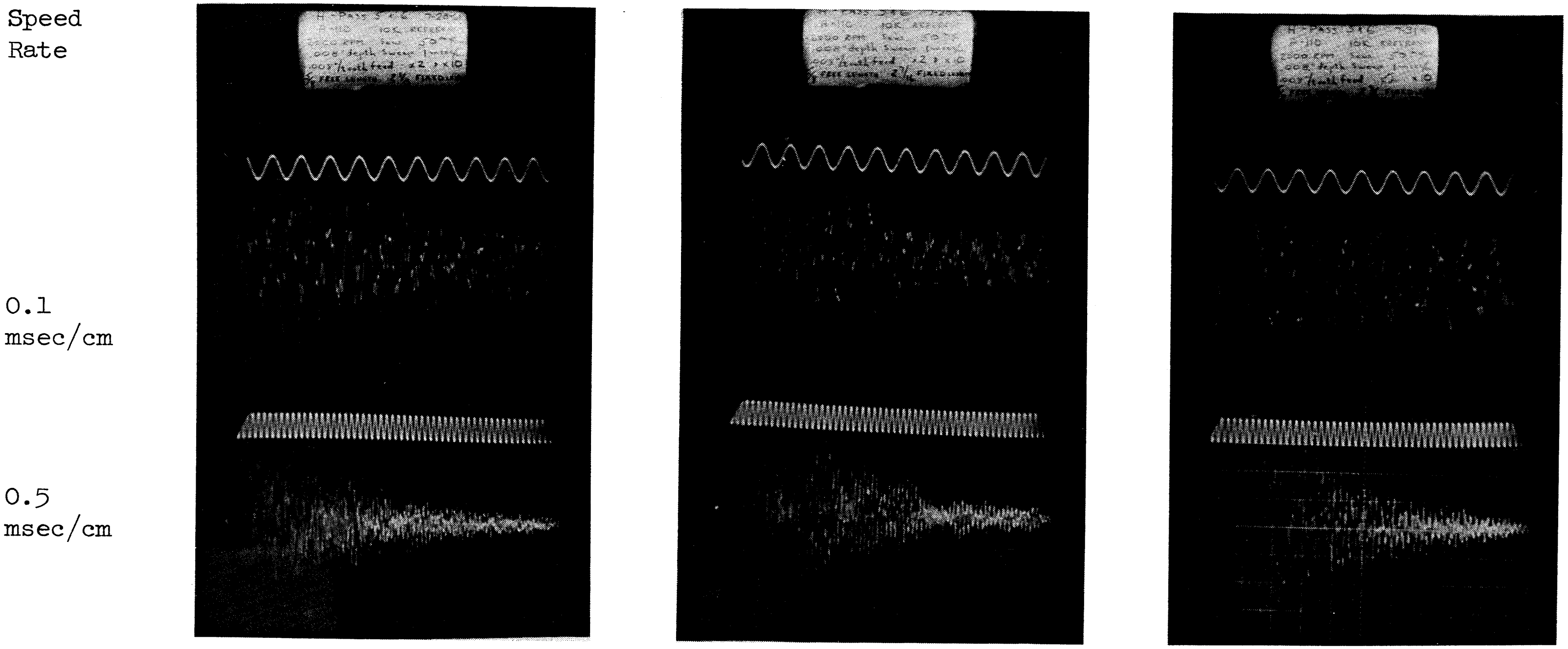
Similar information on horizontal vibrations is shown in Fig. Q where the accelerometer was mounted on the far end of the workpiece directly opposite the surface being machined. It is significant that substantial vibration was observed at this point despite very high clamping forces. These are not vibrations of the work holding block but are internal to the workpiece itself. The latter conclusion is substantiated by the fact that the predominant frequency was reduced by an increase in the length of the workpiece. This is clearly indicated in the lower traces at (a), (b), and (c) in Fig. Q. The overhang of the workpiece was held constant at 5/8 in.

Figures R and S compare titanium with other metals with respect to both horizontal and vertical vibrations. Once more it is evident that high-frequency vibrations are much stronger with all three titanium alloys machined in this study. Further, it is highly probable that resonant frequencies of the system determine the frequency of chip segmentation, rather than the segmentation frequency being the initial determinant. A further possibility is that the fine segmentation might be caused by shock waves which travel at the speed of sound in which case the shear velocities in forming the segments may also approach the speed of sound.

CONCLUSIONS

Considering that a feasibility study is essentially exploration and lacks a certain degree of refinement and sophistication, the following conclusions must also be considered as somewhat speculative since they lack absolute proof at this stage. However, they are stated as conclusions because they constitute definite results and provide the direction for further study which can be expected to result in improved and usable machining practices.

1. Higher rates of metal removal by milling can be achieved through optimizing cutting speed and size of cut in relation to cutting temperatures, time per chip, length of chip and chip segmentation as affected by vibration characteristics.



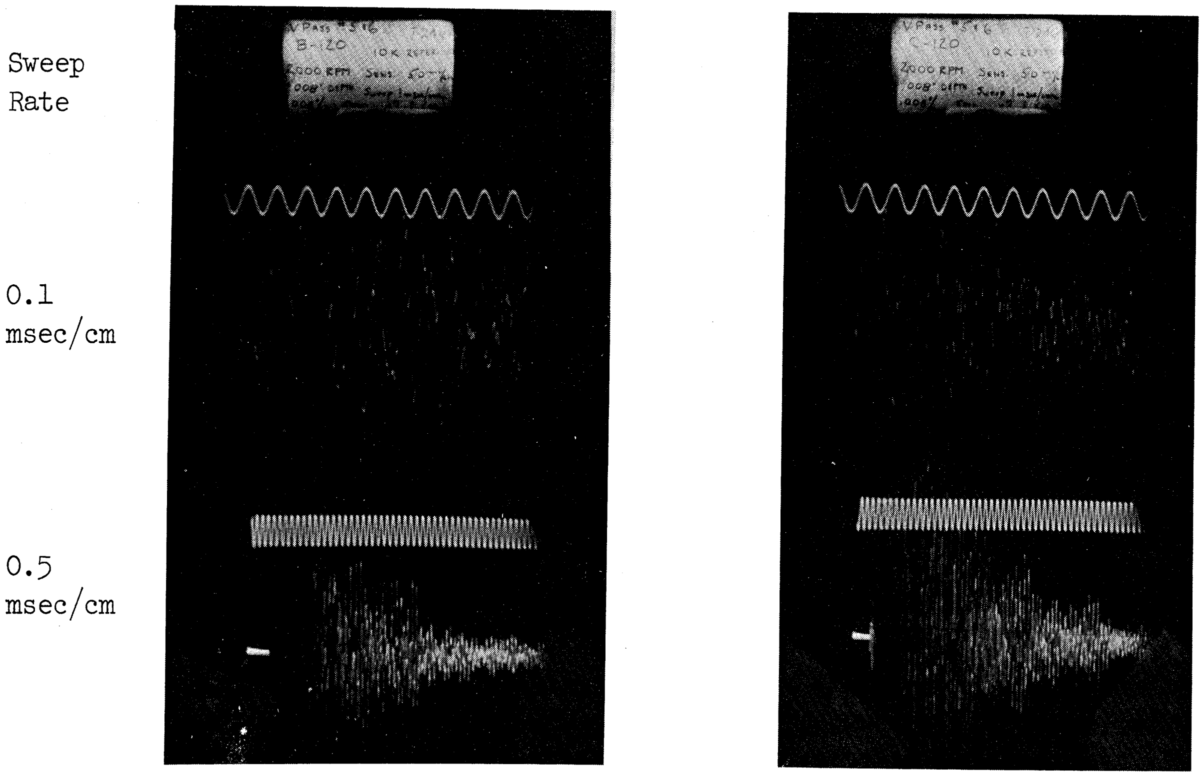
Length of workpiece:

(a) 2-1/8 in. (b) 2-7/16 in. (c) 2-3/4 in.

(Time wave is 10 kc at both sweep rates)

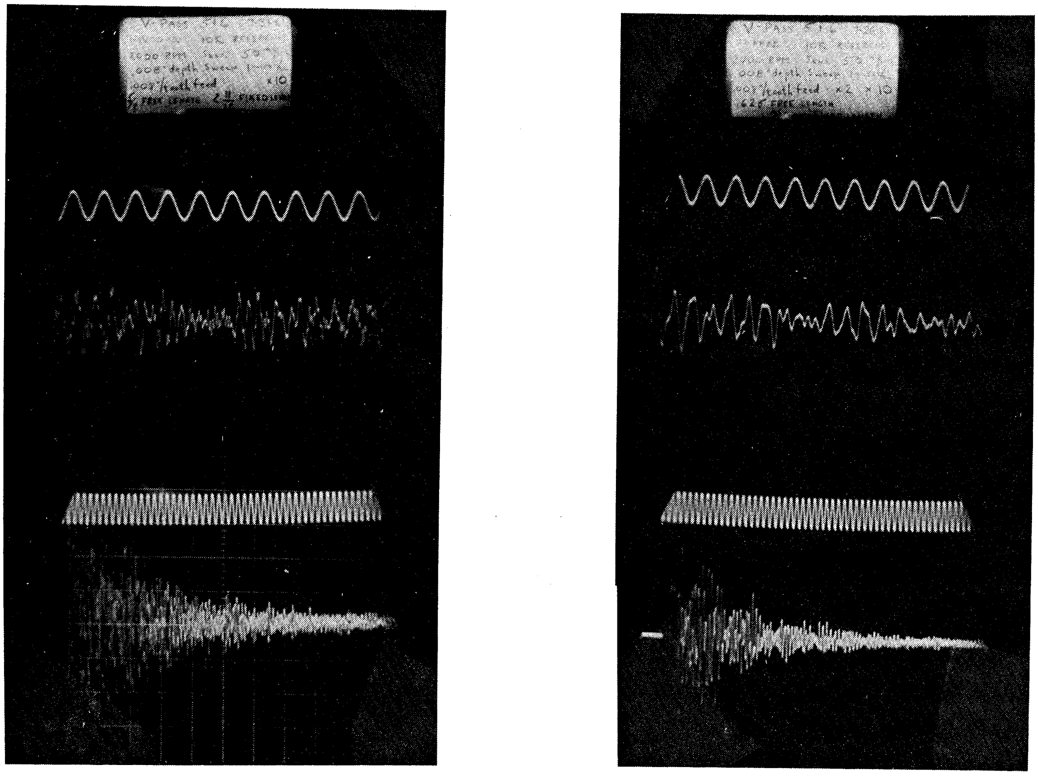
A-110 Titanium (Horizontal Vibrations)

Fig. Q. Change in frequency of horizontal shock waves as length of workpiece is increased. Cutting conditions same as in Fig. P except cutting speed = 3000 fpm. Workpiece overhang = 5/8 in. Accelerometer mounted on end of workpiece opposite the cut.



B-120 Titanium

C-120 Titanium



NIVCO-10

Copper

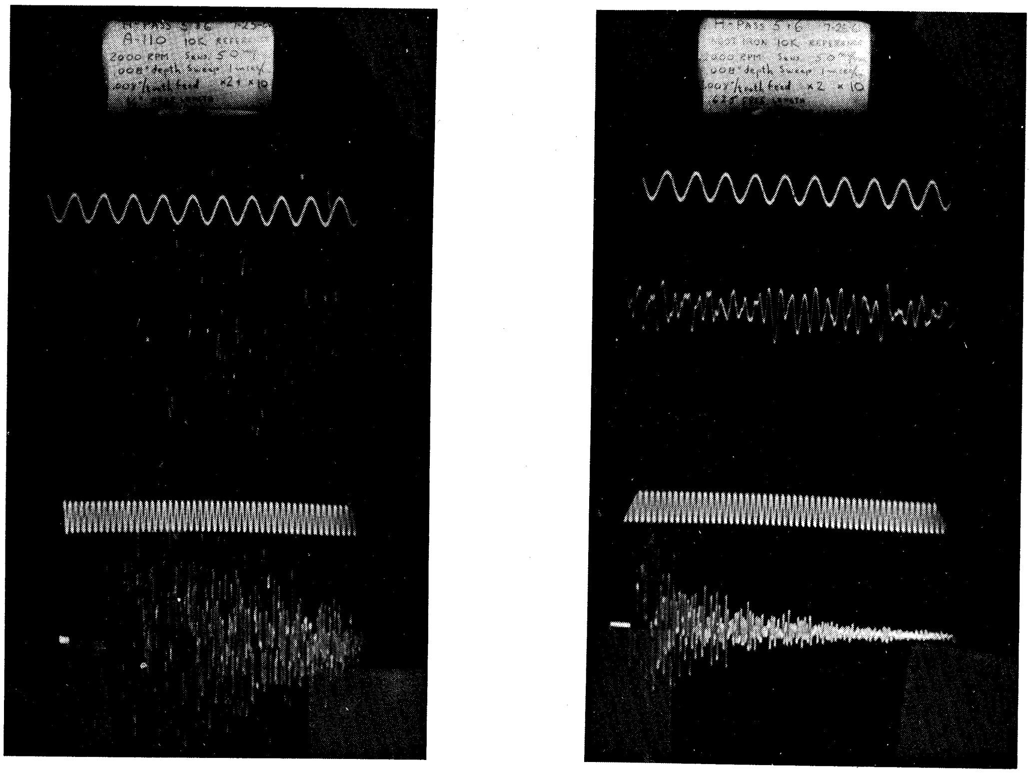
Vertical Vibration

Fig. R. Comparison of vertical vibrations in different metals cut at identical conditions. Speed = 3000 fpm; depth = .008 in.; feed = 0.008 ipt. Cutting time/chip = 267 μsec for lower trace; 321 μsec for upper expanded trace.

Sweep
Rate

0.1
msec/cm

0.5
msec/cm



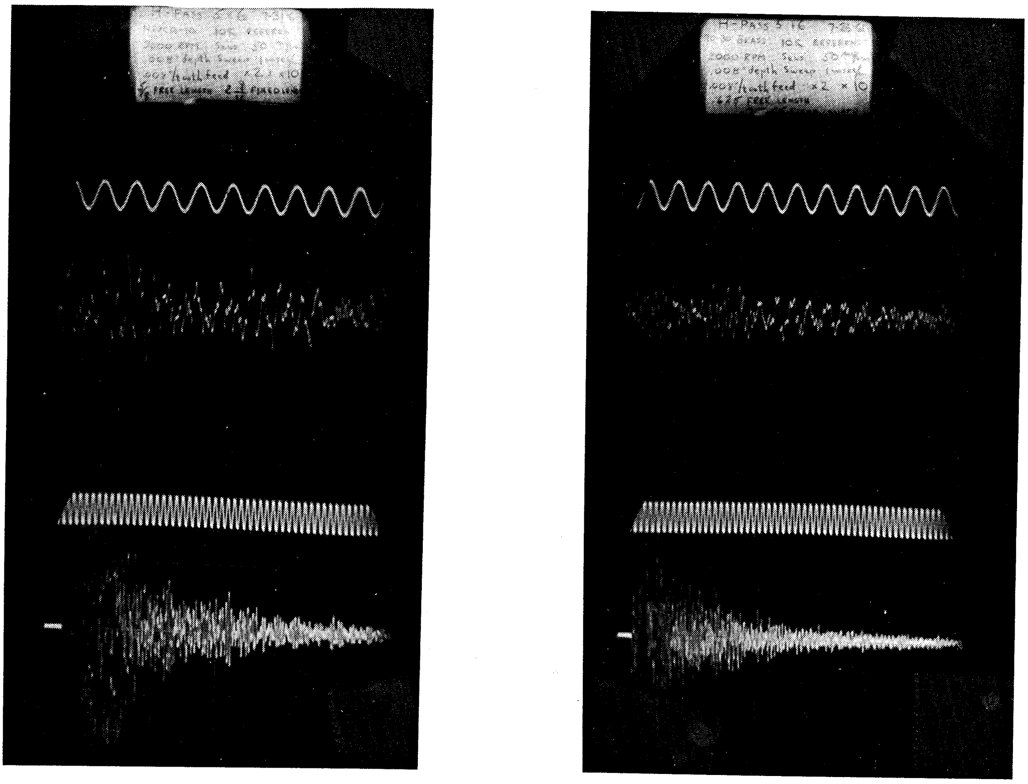
A-110 Titanium

Ingot Iron

Cutting
time/chip

321
µsec

267
µsec



NIVCO-10

70-30 Brass

Horizontal Vibration

Fig. S. Comparison of horizontal vibrations in different metal milled at identical conditions. Cutting conditions same as in Fig. R.

2. Feed rates as high as 100 fpm are possible in milling titanium with depths of cut of the order of 0.010-0.015 in.

3. Cutting time per chip should be held below one millisecond. The shorter the time the better. Increased cutting speed may be used to accomplish this, providing critical temperatures are not exceeded as a result.

4. Within certain limits it is better to increase the rate of metal removal by taking heavier cuts at lower cutting speeds. One of the limitations is that the cutting time per chip cannot be permitted to increase indefinitely.

5. Measured temperatures were about six times more sensitive to changes in cutting speed than to corresponding changes in chip thickness for the same cutting time per chip.

6. Tool wear is somewhat less abrasive in nature and more sensitive to temperature at the high cutting speeds used in this study. This conclusion is derived from the smaller slope of the cutting-speed, tool-life lines shown in Fig. G.

7. Cutting tools and workpieces will vibrate at resonant frequencies even during continuous cutting although the frequencies are very high, 5-50 kc. Although resonant in nature, they are not reflected in the work surface like common "chatter."

8. Chip segmentation appears to be an effect and not a cause. Through excessive segmentation and rewelding, titanium chips can be longer than the actual cut. Vibrations or shock waves appear to be the cause of chip segmentation.

9. Titanium appears to be much more sensitive to vibrations than other metals, as reflected in the degree of chip segmentation and the strength of measured vibrations.

10. It is highly probable that micro-milling might prove to be an improvement over grinding for those high-ductility metals which are particularly difficult to grind readily. These include copper, low-carbon steel, brass, some aluminum alloys, and even stainless steel and other high-nickel alloys.

RECOMMENDATIONS

The results of this exploratory study justify further study and steps toward the development of plant applications. Therefore the following recommendations are suggested as the appropriate next steps in the development of this process for shop use.

1. Continue the study of temperatures, vibrations, tool wear, and chip formation with the objective of refining and sharpening up these important parameters which define the boundaries and limitations of the process. It is particularly important to measure the tool-chip interface temperatures and to develop a precise correlation with cutting speed and cutting time per chip. Further, it should be determined whether the high-frequency vibrations have deleterious effects on temperature and tool wear.

2. Chip disposal is a critical problem with titanium. It can be approached through cutter design and consideration of cutting fluids or even dry lubricants deposited on the cutter. It is recommended that steps be taken directly to design and evaluate micro-milling cutters. This will require a parallel development of precision sharpening or regrinding techniques since existing commercial products are not good enough, both functionally and economically.

3. Cutting fluids may have deleterious effects on the machined product even though the cutting process may be benefited. It is believed that this problem is tied in with and complicated by the residual stresses in the machined surface. Such stress can be caused by the cutting process as well as by other processes. Therefore it is recommended that a study be made of this facet of the cutting fluid problem as well.

APPENDIX

SERIES A(I-V)

PRELIMINARY STUDIES

Objective:

To explore various cutting conditions over ranges of cumulative cutting time, cutting velocity, and chip size while maintaining a satisfactory surface finish. All the titanium alloys, A-110, B-120, and C-120, were used for this study.

Test Conditions:

A specimen with a machined stand-out profile (see Fig. 4a) was used throughout this series of tests. The crest length, or the minimum length of the specimen in the direction of cutting, ranged in steps of .100, .200, .400, .800, and 1.600 in. The width was a constant .456 in.

For this entire series of tests, the work specimens were mounted in a special rotating chuck (see Fig. 1) at a working radius of about 3 in. The tool holders were Kendex SN 4 KSDR 85A and Kendex SN 4 KSFL 85A. (See Fig. 3.) The KSDR holder was used in Series A-I and II and the KSFL holder was used for the remainder of Series A. Figure 2 shows the method of holding the tool holders rigid.

Tungsten carbide insert or throwaway cutting tools were used throughout the test. The inserts were Vascoloy grade 2A5, style SQ-163P. These are 1/2-in.-sq by 3/16-in.-thick inserts. On tests A-I and II, these were altered by grinding a .010 inch flat 45° across each point and were used with the KSDR holder. (See Fig. 4b.) On the balance of the tests they were used as received in the KSFL holder.

Calculation Procedures

An explanation is in order about the method of calculating the short cutting times used throughout this program.

Cutting Time Per Chip:

The mean cutting circle described by the rotating specimen was 17.9 in. and was based on a mean diameter of 5.71 in.

The actual cutting time per chip is the time the tool and specimen are in contact while removing one chip.

$$\text{ACT/chip} = P \times \frac{L}{\text{cir}} \tag{1}$$

where:

ACT = actual cutting time
P = time in seconds for one revolution
L = crest length of the specimen in inches
cir. = circumference of circle of revolution in inches.

Cutting Time Per Pass:

The cutting time per pass (ACT/pass) varies with specimen size and the number of chips per pass. The number of chips increases as the work area increases in length (see Fig. 4a). For the .008/tooth feed, the .100- and .200-in.-long specimens had 57 chips per pass; the .400-in., 60 chips per pass; the .800-in., 70 chips per pass; and the 1.600-in., 80 chips per pass. The chips/pass for the other feed rates were proportionately greater in number.

$$\text{ACT/pass} = (\text{ACT/chip}) \times (\text{chips/pass}) \tag{2}$$

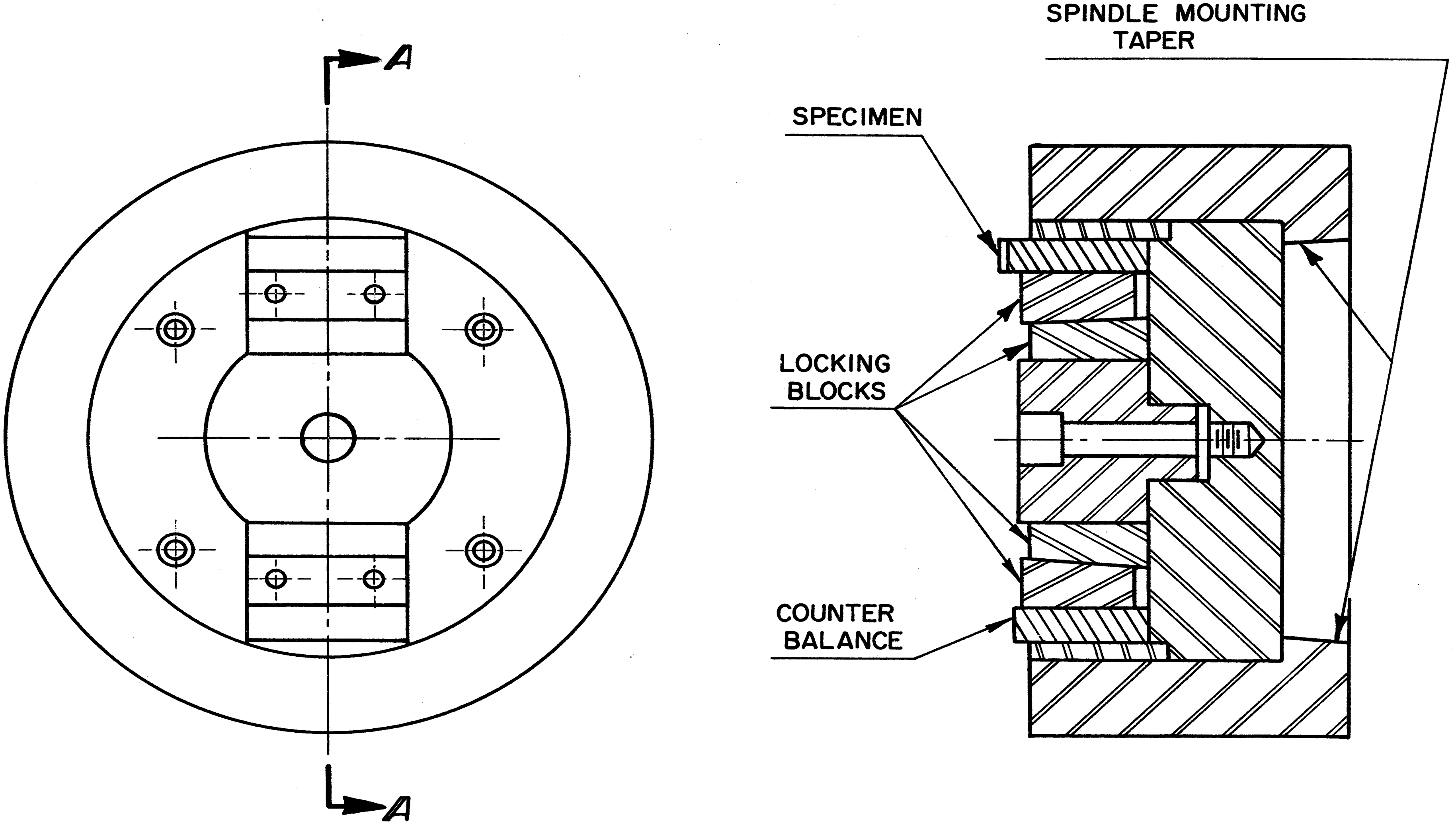
Cutting Time Per Specimen:

Since the standout profile had a 45° angle on the leading and trailing edges, each successive pass had a longer cut and the lengths increased with the depth of cut. In general the length of the cut increases by (2n-1) units per pass where n equals the pass number. For each pass, the crest length is added to the product of (2n-1) times the depth of cut. Consequently, the cutting time per specimen is:

$$\text{ACT/specimen} = \frac{P}{\text{cir}} \left[\Sigma(L + d(2n-1) \right] \tag{3}$$

where:

P = period of one revolution in seconds
cir. = circumference of work circle, inches
L = crest length of the specimen
d = depth of cut
n = the individual pass number



No Scale

Fig. 1. Rotating chuck.

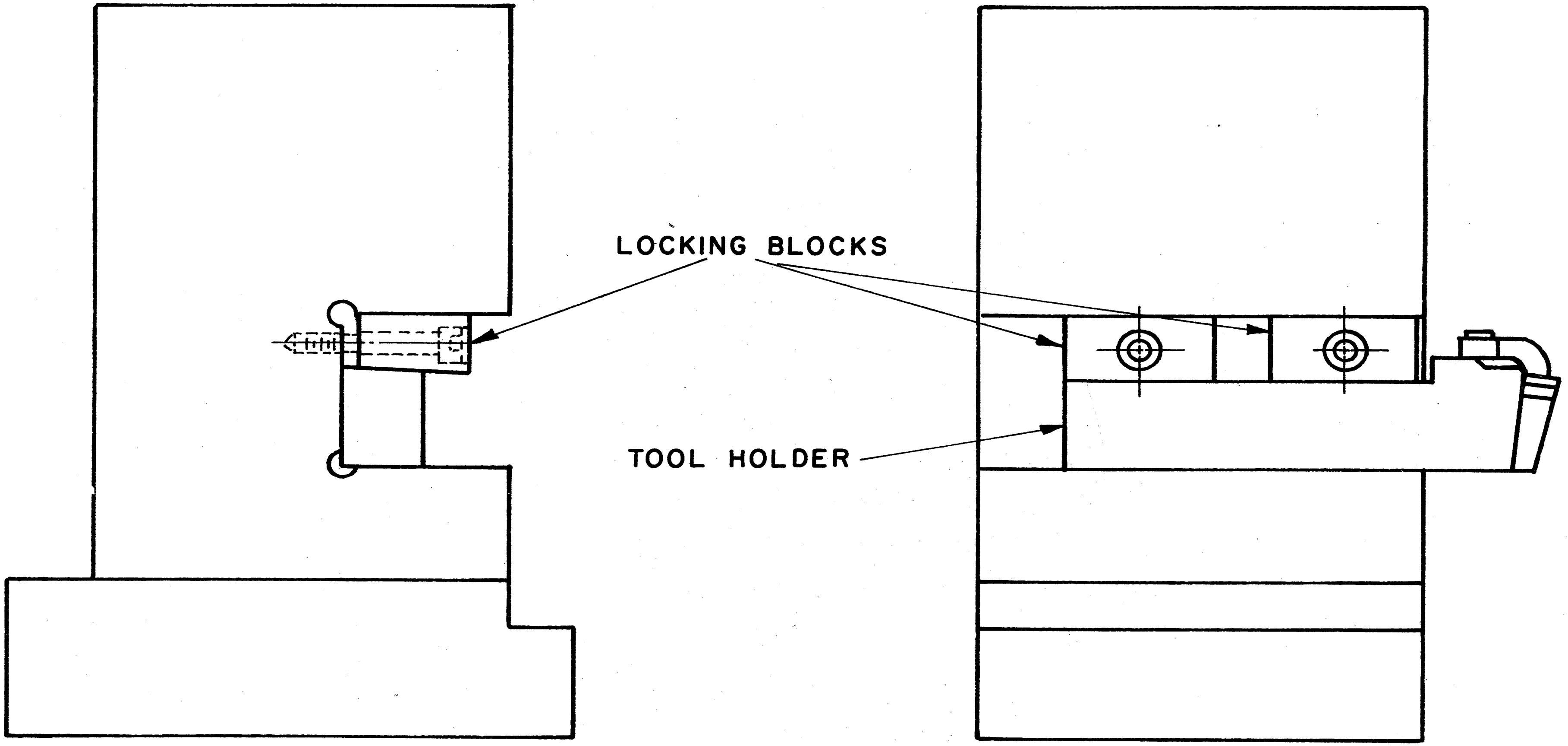
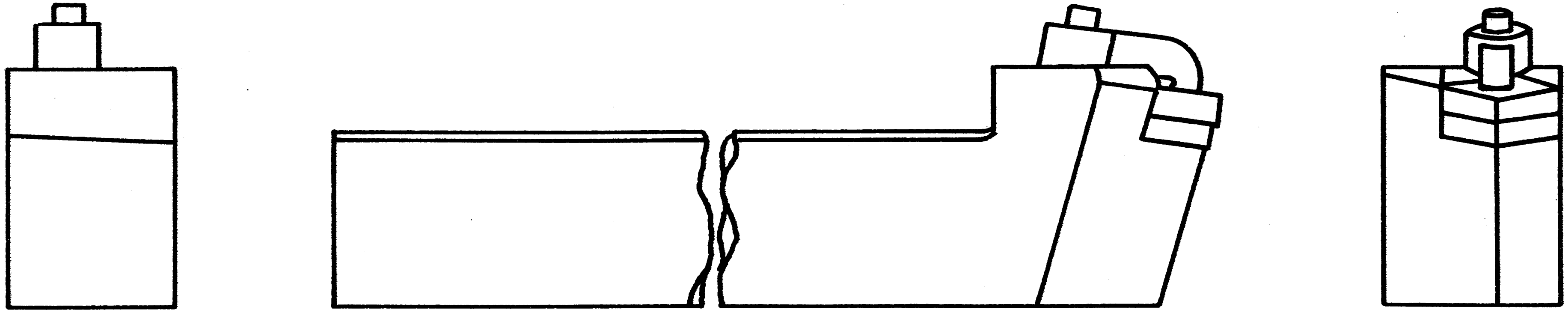
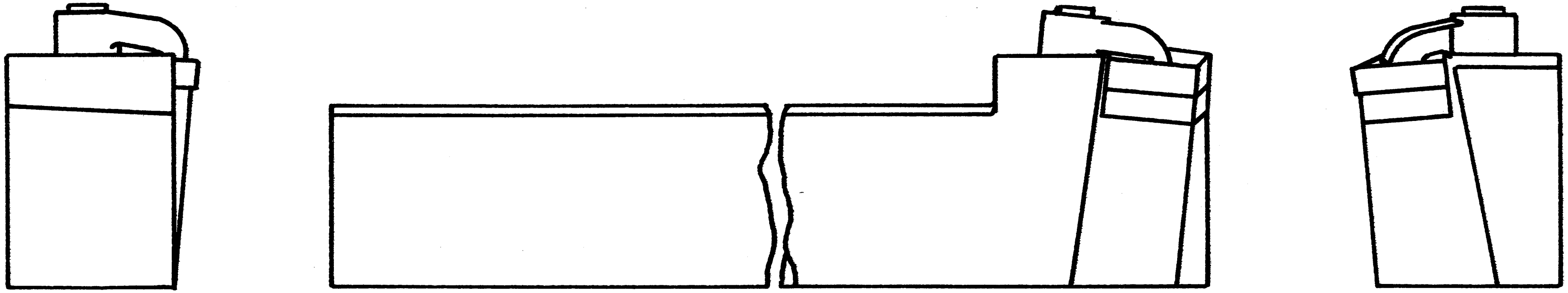


Fig. 2. Tool post: showing method of holding tool holder rigid.



KENDEX SN4 KSDR 85A



KENDEX SN4 KSFL 85A

Fig. 3. Tool holders.

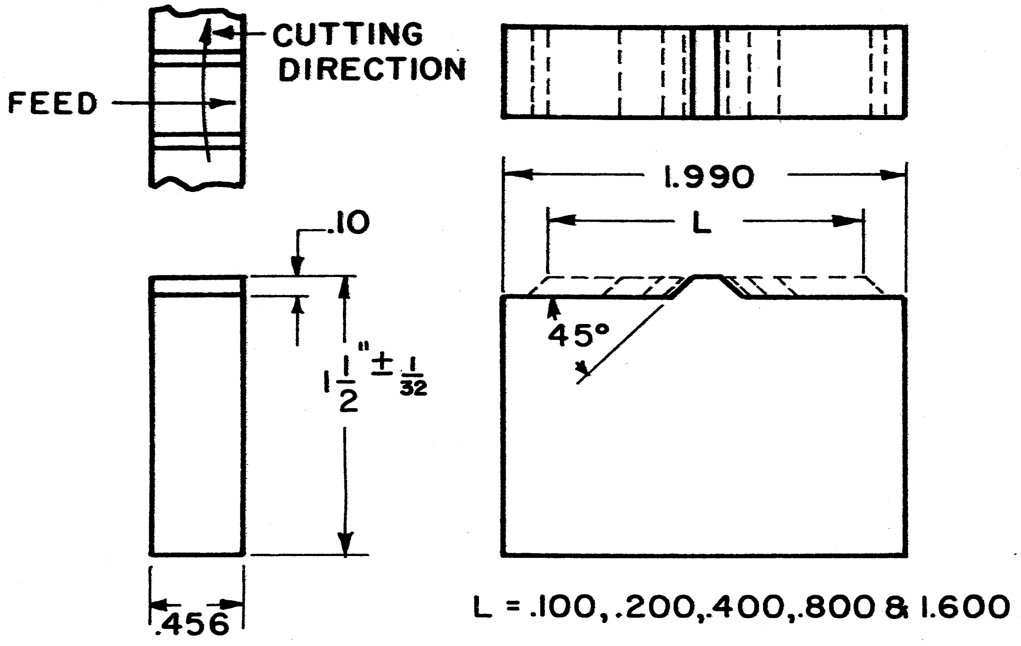


Fig. 4a. Standout specimen as used for Series A.

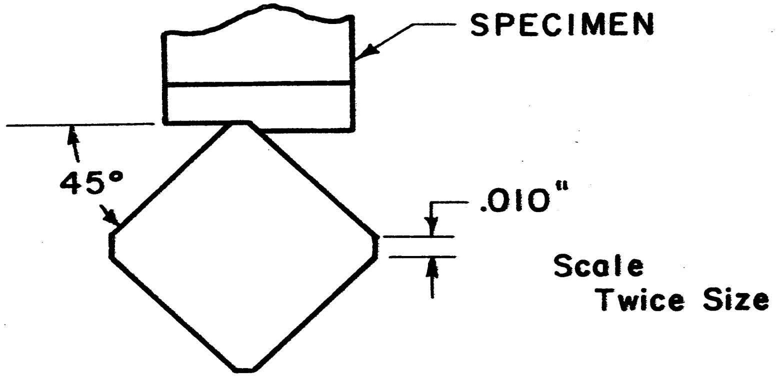


Fig. 4b. Tool geometry and orientation to specimen.

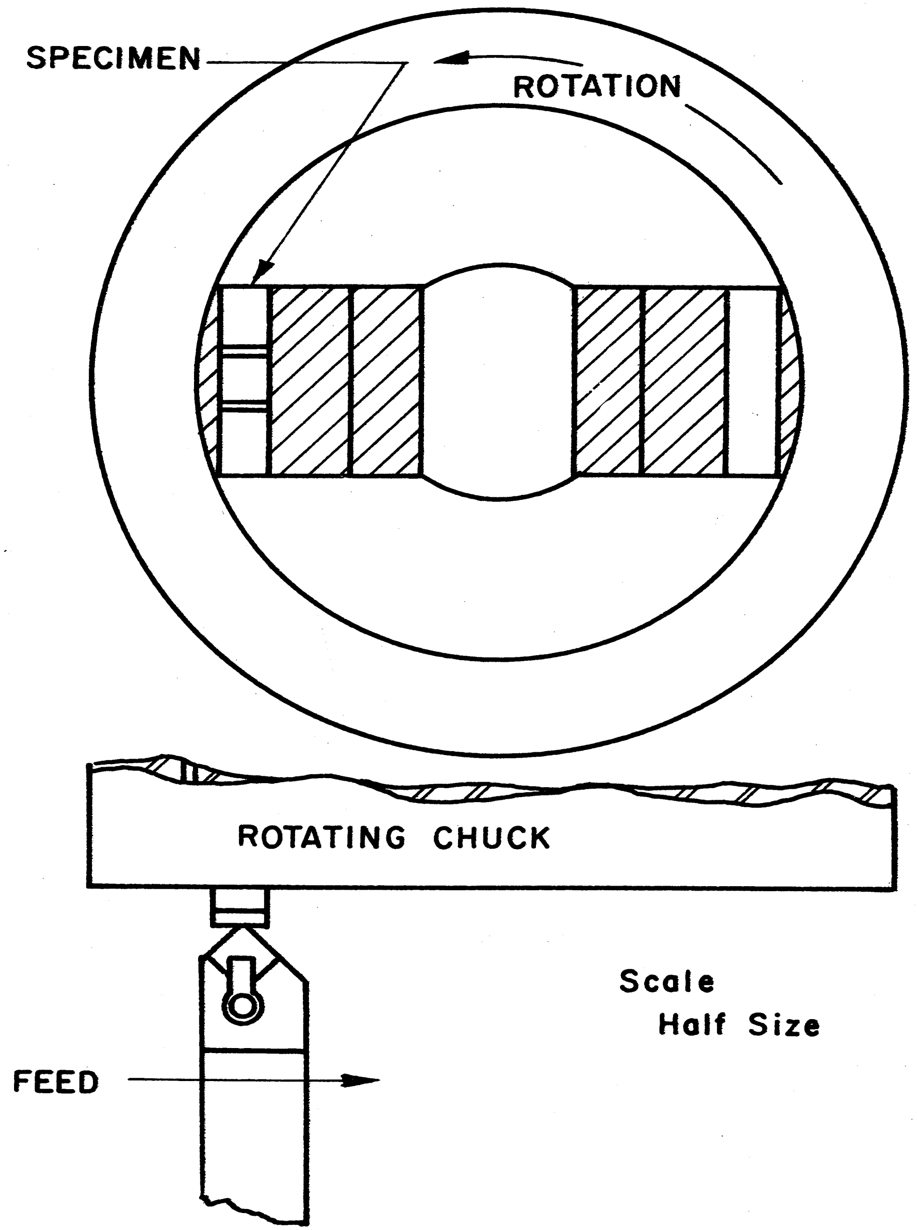


Fig. 4c. Tool holder, tool mounting, and specimen mounting.

Series A-I

Objective:

To observe the effects of varying the cutting time per chip.

Test Conditions:

On this series of tests, the following conditions were used:

Specimen:

1. A-110, B-120, and C-120.
2. Stand-out profile with crest lengths of .1, .2, .4, .8, and 1.6 inch (see Fig. 4a).
3. Width of specimen: .456 inch.
4. Specimen was rotated (see Fig. 4c).

Tool:

1. Tool holder No. SN 4 KSDR 85A.
2. Vascoloy 2A5 tungsten carbide insert.
3. Tool modified to .010 in. flat 45° diagonally across the point.

Cutting Conditions:

1. Velocity: 3000 fpm at 2000 rpm.
2. Cutting depth: .005 inch.
3. Feed: .008 in./tooth.

Results:

All the materials cut satisfactorily through the .100- and .200-in. specimens. The first tool failure occurred on the .400-in. CL[1] specimen of B-120 alloy. Tool failure occurred on the .800- and 1.600-in. specimens of all alloys.

The surface finishes of the .100, .200, and .400 specimens of the A-110 were acceptable. The .800 specimen had a little chip tearing but the 1.600 CL specimen had approximately 30% faulty surface. With the B-120 specimens, only the .100 CL specimen was acceptable; all others were unsatisfactory. There was smearing, tearing, and welding on the specimens. The C-120 alloy

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[1] Crest length.

looked good through the .400 CL specimen, but the .800 CL had a lot of chip weld and metal smear.

It was observed that the A-110 chips were quite normal up to the .400 specimen where sparking was observed. The B-120 gave discontinuous chips for all cuts; the chips burned in a shower of sparks generated at the tool point.

The C-120 had more red sparking than the other alloys and tended to weld into quite long chips up to 3 inches. The results are summarized in Table I and illustrated graphically, along with those for A-110 and B-120, in Fig. 5.

TABLE I

SERIES A-I. TEST DATA

Material Cut	Speed fpm	Crest Length of Specimen (in.)	Depth of Cut (in.)	Feed Per Tooth (in.)	Cutting Time Per Chip (sec)	Cutting Time Per Pass (sec)	No. Passes Per Specimen	Total Cutting Time Per Specimen (sec)	Total Metal Removal Per Specimen (in.^{3})	Total Failure	No. Chips Per Pass
A-110	3000	.1	.005	.008	.000175	.009520	5	.059565	.001400	No	57
		.2			.000342	.019600	5	.107200	.003110	No	57
		.4			.000677	.040620	5	.212500	.004820	No	60
		.8			.001345	.094300	3	.287000	.005560	Yes	70
		1.6			.002680	.214200	2	.431000	.007420	Yes	80
B-120	3000	.1	.005	.008	.000175	.009520	5	.059565	.001400	No	57
		.2			.000342	.019600	5	.107200	.003110	No	57
		.4			.000677	.040620	5	.212500	.004820	Yes	60
		.8			.001345	.094300	2	.189800	.003690	Yes	70
		1.6			.002680	.214200	3	.648000	.011050	Yes	80
C-120	3000	.1	.005	.008	.000175	.009520	5	.059565	.001400	No	57
		.2			.000342	.019600	5	.107200	.003110	No	57
		.4			.000677	.040620	5	.212500	.004820	No	60
		.8			.001345	.094300	5	.483000	.009400	Yes	70
		1.6			.002680	.214200	4	.867000	.014780	Yes	80

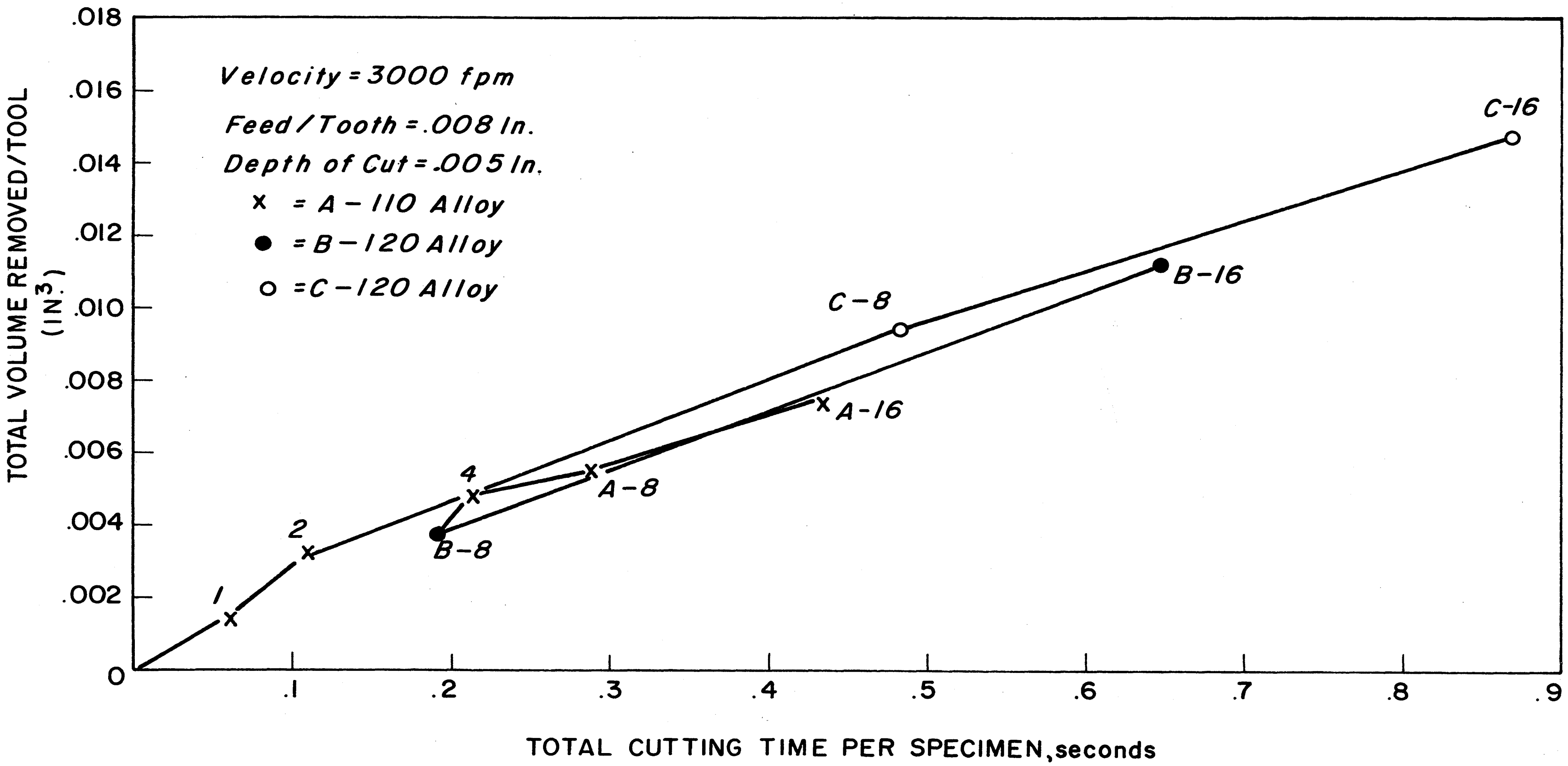

Fig. 5. Metal removal per tool vs. cutting time per specimen.

Series A-II

Objective:

To observe the relative effect of variable cutting speed.

Test Conditions:

On this test series, the following conditions were used:

Specimen:

1. C-120 alloy, only.
2. Stand-out profile with .400-in. crest length (see Fig. 4a).
3. Specimen width: .456 in.
4. Specimen rotated (see Fig. 4c).

Tool and Holder:

1. Kendex SN 4 KSDR 85A tool holder (see Fig. 3).
2. Vascoloy 2A5 tungsten carbide insert.
3. Tool bit set at 45° to cutting direction.
4. Tool nose modified to .010-in. contact length in direction of feed (see Fig. 4b).

Cutting Conditions:

1. Velocity: Varied in steps of 1500, 6,000, and 12,000 fpm.
2. Depth: .005 in. at 1500 and 6,000 fpm
   .003 in. at 12,000 fpm.
3. Feed: .008/tooth at 1500 and 6,000 fpm.
   .004/tooth at 12,000 fpm.

Observations:

At the 1500-fpm velocity, the cutting appeared normal with virtually no sparking and no chip burning. The cutting time per chip was 1335 μsec and the surface was entirely satisfactory.

At 6,000 fpm, velocity, burning chips and considerable tool pounding was observed on the second pass. The surface was not entirely satisfactory because it had some flecks of molten metal adhering to it. The ACT/chip was 340 μsec and the surface was not entirely satisfactory.

At 12,000 fpm, the feed and depth of cut were reduced. The feed was set at .004 in./tooth while the depth of cut was set at .003 in. At this velocity the chips were not collected because they were merely a shower of sparks. The specimen surface was not entirely satisfactory because it was rough and irregular in appearance. This test series was repeated twice with practically the same results. The ACT/chip was 170 μsec and the surface was fair or slightly less than satisfactory.

This series gave indications that velocity was more of a critical factor than ACT/chip. Sparking, chip burning, and surface deterioration increased with the increased velocities. The results are summarized in Table II.

TABLE II

SERIES A-II. VARIABLE CUTTING VELOCITY

Material Cut	Speed fpm	Crest Length of Specimen (in.)	Feed Per Tooth (in.)	Depth of Cut (in.)	Cutting Time Per Chip (sec)	Cutting Time Per Pass (sec)	No. Passes Per Specimen	No. Chips Per Pass	Total Cutting Time Per Specimen (sec)	Total Metal Removal Per Specimen (in.^{3})	Total Failure	Surface Finish
C-120	1500	.400	.008	.005	.001335	.080100	5	60	.426000	.004820	No	Very clean
C-120	6000	.400	.008	.005	.000340	.020400	2	60	.010960	.001860	Yes	Fairly clean
C-120	12000	.400	.004	.003	.000170	.020400	2	120	.010960	.001110	Yes	Streaked and uneven
C-120	12000	.400	.004	.003	.000170	.020400	3	120	.016440	.001670	Yes	Gouging and uneven

Series A-III

Objective:

To observe cutting characteristics when varying cutting velocity, length of cut, and feed rate in a sequence so as to keep the energy input substantially constant.

Test Conditions:

Specimens:

1. A-110, B-120, and C-120 alloys.
2. Stand-out profile of .100- and .200-in. crest length (see Fig. 4a).
3. Specimen width: .456 in.
4. Specimen rotated (see Fig. 4c).

Tool and Holder:

1. Kendex SN 4 KSFL 85A tool holder.
2. Vascoloy 2A5 tungsten carbide insert.
3. Zero radius inserts.

Tool holder set so as to allow a 4° clearance between workpiece and back edge of tool insert (see Fig. 6).

Cutting Conditions:

Two sets of conditions were used for making comparisons at the same input energy.

Velocity:	(1) 1500 fpm	(2) 3000 fpm
Feed/tooth:	.001 in.	.0005 in.
Depth of cut:	.012 in.	.012 in.
Spec. length:	.100 in.	.200 in.

Observations:

The A-110 alloy cut very satisfactorily at 1500 fpm with a good clean surface. With the slow (.0005-in.) feed per tooth, the surface had an rms reading of 9-11. On the longer specimen, the .0005-in. feed made an extremely thin chip that tended to ignite easily. Consequently the surface was blotched with molten metal. The surface beneath the blotches was very smooth.

The .100-in. specimen of B-120 formed a continuous chip but it curled off the face of the tool back into the surface. This action welded chip particles to the surface and made it unsatisfactory. This was the first con-

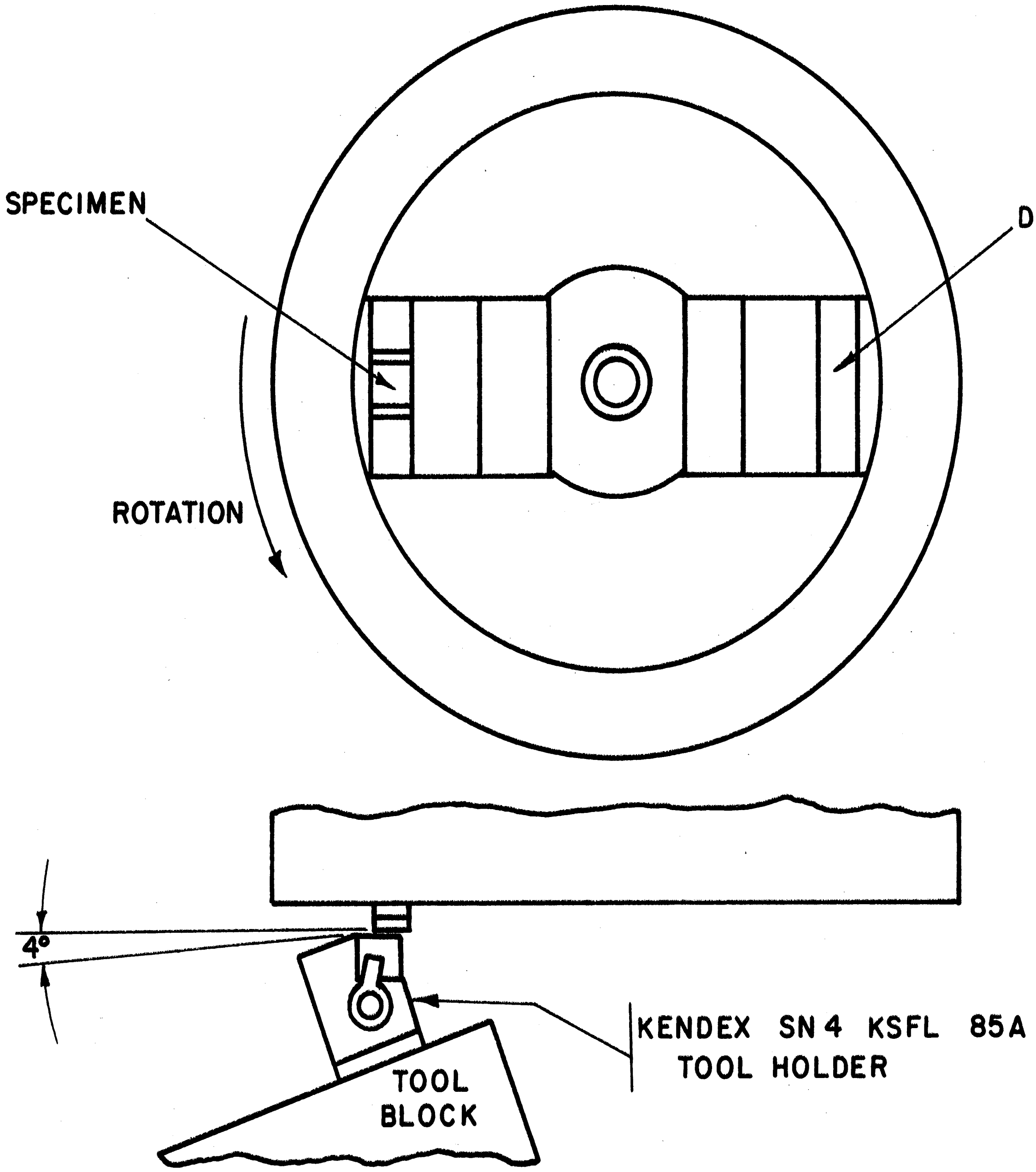

Fig. 6. Rotating specimen with 4° offset of cutting tool.

tinuous chip formed with B-120. The other series had only discontinuous chips. The chips from the .200-in. specimen were fused into a single mass at the light feed. There was no burning but the surface was smeared by the plastic flow of the metal.

The surface finish of the .100-in. specimen of the C-120 alloy was the best. It had a 6-8 rms finish. The chips welded together end to end but this did not influence the surface finish. The .200-in. specimen had a good basic finish, but it was marred by fused chips.

With energy levels and the ACT/chip equal for all specimens the test again indicated that cutting velocity was the critical factor, although between 1500 and 3000 fpm range, the cut surfaces were not bad except for the chip fragments adhering to them. The B-120 was again the exception since it showed signs of plastic flow. The results are summarized in Table III.

TABLE III

SERIES A-III. CONSTANT ENERGY LEVEL

Material Cut	Speed fpm	Crest Length of Specimen (in.)	Feed Per Tooth (in.)	Depth of Cut (in.)	Cutting Time Per Chip (sec)	Cutting Time Per Pass (sec)	No. Passes Per Specimen	No. Chips Per Specimen	Total Cutting Time Per Specimen (sec)	Total Metal Removal Per Specimen (in.^{3})	Surface Finish
A-110	1500	.1	.001	.012	.000333	.152200	5	460	1.230000	.004220	Very smooth
A-110	3000	.2	.0005	.012	.000333	.304400	4	920	1.527500	.005400	Blotched
B-120	1500	.1	.001	.012	.000333	.152200	5	460	1.230000	.004220	Welded fragments
B-120	3000	.2	.0005	.012	.000333	.304400	5	920	1.995000	.006950	Smeared by plastic flow
C-120	1500	.1	.001	.012	.000333	.152200	5	460	1.230000	.004220	Extremely good
C-120	3000	.2	.0005	.012	.000333	.304400	3	920	1.088500	.003780	Good surface but slightly blotched

Series A-IV

Objective:

To vary chip sizes, feed, and depth of cut, in an attempt to identify an optimum chip cross-sectional area for B-120 and C-120 alloys.

Test Conditions:

Specimen:

1. B-120 and C-120 alloys.
2. .200 stand-out specimen (see Fig. 4a).
3. Specimen width: .456 in.
4. Specimen rotated (see Fig. 4c).

Tool and Holder:

1. Kendex SN 4 KSFL 85A tool holder.
2. Vascoloy 2A5 tungsten carbide insert.
3. Zero radius insert with tool holder set at angle to allow 4° clearance between workpiece and tool bit (see Fig. 6).

Cutting Conditions:

1. Velocity: 3000 fpm.
2. Feed/tooth: .002, .004, .006, .008, and .012.
3. Cutting depth: .012

Observation:

The B-120 specimens showed a decrease in chip burning as the cuts got thicker. The chips came off the tool at higher velocity as the feed was increased. The .002- by .012-in. cut left a good underlaying surface but it was flecked with droplets of molten metal caused by heat and a thin chip. The .004- by .012-in. cut left a fairly satisfactory surface. Plastic flow was beginning to be in evidence as all four edges of the specimens had a burred projection.

The .008- by .012-in. cut definitely had some degree of plastic flow as indicated by the amount of projecting burr in all four sides of the cut face. The surface was very cleanly cut. The .012- by .012-in. cut still showed evidence of plastic flow at the edges but due to the size of the chip, it carried most of the burr along with the chip. Again the surface was quite clean but there was some evidence of molten metal.

The C-120 specimens were well cut but each one had a small amount of adhesion of drops of molten metal. The .006- by .012-in. cut machined well and had a generally clean surface. There was end to end chip welding, resulting in unusually long chips. This behavior has always been more frequent with the C-120 alloy. The .008- by .012-in. specimen showed a little burr projecting over the edges but it was not as pronounced as with the B-120 specimens. The .012- by .012-in. cut left a clean surface also.

All specimens were cut with 5 passes and the .012- by .012-in. cross-sectional area chip appears to be within a satisfactory range. No actual tool failure occurred during the test. A greater depth of cut did not appear detrimental to the surface finish, nor to shorten tool life appreciably. The results are summarized in Table IV.

TABLE IV

SERIES A-IV. VARIABLE CHIP SIZE

Material Cut	Speed fpm	Crest Length of Specimen (in.)	Feed Per Tooth (in.)	Depth of Cut (in.)	Cutting Time Per Chip (sec)	Cutting Time Per Pass (sec)	No. Passes Per Specimen	No. Chips Per Specimen	Total Cutting Time Per Specimen (sec)	Total Metal Removal Per Specimen (in.^{3})	Surface Finish
B-120	3000	.200	.002	.012	.000333	.007650	5	230	.522000	.0015300	Some flecking by molten metal
B-120	3000	.200	.004	.012	.000333	.003825	5	115	.251000	.0015300	Fairly satisfactory
B-120	3000	.200	.008	.012	.000333	.001912	5	57	.124000	.0015300	Fairly clean with large burred edges
B-120	3000	.200	.012	.012	.000333	.001275	5	38	.082600	.0015300	Clean
C-120	3000	.200	.006	.012	.000333	.002550	5	77	.167500	.0015300	Very small amount of flecking - good
C-120	3000	.200	.008	.012	.000333	.001912	5	57	.124000	.0015300	Similar to above
C-120	3000	.200	.012	.012	.000333	.001275	5	38	.082600	.0015300	Similar to above

Series A-V

Objective:

It was assumed that a square cross-sectional chip is best, so this series explored larger chips than the previous tests.

Test Conditions:

Specimen:

1. B-120 alloy.
2. .200-in. crest length stand-out profile (see Fig. 4a).
3. Specimen width: .456 in.
4. Specimen rotated (see Fig. 4c).

Tool and Holder:

1. Kendex SN 4 KSFL 85A tool holder.
2. Vascoloy 2A5 tungsten carbide insert.
   Carboloy 883 tungsten carbide insert.
3. Zero nose radius.
4. Tool holder set so as to allow a 4° clearance between workpiece and back edge of tool insert.

Cutting Conditions:

Velocity, fpm	Feed/Tooth, in.	Depth of Cut, in.
3000	.016	.016
3000	.020	.020
6000	.008	.008

Observations:

The .016- by .016-in. cut at 3000 fpm was satisfactory. Many discontinuous chips were thrown out by the tool at fairly high velocity. Some of the chips scratched the cut surface as they came away. A heavy burr was left at the exit edge. There was a smaller burr at the entry. These burrs indicate some plastic flow because of rubbing by the tool flank.

The .020- by .020-in. cut at 3000 fpm was also quite satisfying. The same behavior was observed as with the .016- by .016-in. cut. The burrs at the leading and exit edges were torn off by the larger chip size. The plastic flow was not evident on the cut face on either of the specimens.

A cut of .008 by .008 in. was made at 12,000 fpm. The cut surface appeared to be satisfactory but it was splotched with bits of molten metal. The tool also did not hold up well at this speed. While none failed completely during the tests, it appeared that failure would have occurred with another pass or two.

From this series and the previous series, it does appear that a square chip cross section approaches an optimum. The .020- by .020-in. chip was good for a metal-removing operation, but the feed rate naturally would yield a higher rms value for the surface finish. The results are tabulated in Table V.

TABLE V

SERIES A-V. EVALUATION OF SQUARE CUT

Material Cut	Speed fpm	Crest Length of Specimen (in.)	Feed Per Tooth (in.)	Depth of Cut (in.)	Cutting Time Per Chip (sec)	Cutting Time Per Pass (sec)	No. Passes Per Specimen	No. Chips Per Pass	Total Cutting Time Per Specimen (sec)	Total Metal Removal Per Specimen ($in.^3$)	Surface Finish
B-120	3000	.200	.008	.008	.000333	.001912	4	57	.088800	.003320	Good undersurface splotched with molten metal
B-120	3000	.200	.016	.016	.000333	.000933	4	28	.049400	.008400	Good surface but scratched by chip
B-120	3000	.200	.020	.020	.000333	.000765	4	23	.043000	.009850	Similar to above

SERIES B

EVALUATION OF TOOL MATERIALS

Objective:

To evaluate different cutting-tool materials.

As a next step, it was deemed advisable to study the behavior of several different cutting-tool materials for machining titanium at high cutting speeds. Ten materials were tested; four were ceramic inserts and five were tungsten carbide inserts. Along with these, a high-speed steel tool bit was tried.

Materials Tested:

Ceramic Inserts:

Carboloy 030
Vascoloy VR-97
Kentanium K 151A
Japanese NKT

Tungsten Carbide Inserts:

Carboloy 350, 370, 883, and 999
Vascoloy 2A5

High-Speed Tool Material:

Circle "C"

Test Conditions:

Specimen:

1. A-110 alloy.
2. 1.600-in. CL stand-out profile (see Fig. 4).
3. Specimen rotated (see Fig. 6).

Cutting Tools and Holders:

1. Materials listed previously.
2. Kendex SN 4 KSFL 85A.
3. Tool points had zero radius.
4. Holder set at angle to allow 4° clearance between back of tool and specimen (see Fig. 6).
5. The high-speed tool bit was similarly mounted.

Cutting Conditions:
Velocities: 1500 fpm - 1000 rpm
2250 fpm - 1500 rpm
3000 fpm - 2000 rpm
Feed/tooth: .008 in.
Depth of cut: .008 in.

Procedure:

The 1.600-in. specimen and a counterbalancing dummy were locked into the rotating chuck. The tool was first set with a 15° clearance between the workpiece and the specimen but chips were caught in the clearance gap, welding to the surfaces. Therefore, a 4° clearance was selected which proved to be satisfactory. The cross-feed was adjusted for the .008-in.-per-tooth feed rate for each of the various spindle speeds that were used. The goal for each tool material was set at five cutting passes. Visual inspection of the tool and specimen was sufficient at this stage to determine the pass on which tool failure occurred.

Results:

The ceramics were not satisfactory at any velocity. There was excessive chip burning, apparently due to the generated heat going entirely to the chip. The failures were induced by thermal stresses and impact.

The high-speed steel tool was even less satisfactory; it did not cut over 25% of the pass across the specimen. Of the tungsten carbides, the Carboloy 350, 883, and 999 grades along with the Vascoloy 2A5 grade were satisfactory. The most satisfactory were the Carboloy 883 and 999 grades; the 883 was considered a trifle better, but not conclusively.

Observations:

The ceramic inserts were tried first. None of the tools stood up over 2 passes, and most of them failed on the first pass. A Vascoloy VR-97 grade insert was modified by grinding a 45° by .020-in. bevel all around the top edges to reduce the impact shock and change the cutting entrance angle. This tool failed on the first pass. An insert of a Japanese ceramic, NKT, was tried, and it failed in a similar pattern.

A Kenametal Kentanium tool, a titanium carbide material, was tried with very poor results. All cuts made with the ceramics caused a lot of chip burning since the heat was driven to the chip by the insulating qualities of the ceramic cutting tools.

A 1-in.^{2} circle "C" high-speed steel tool bit was ground to the same tool geometry as were the inserts. Its failure was the quickest of any; it succeeded only in cutting the two foremost corners before complete failure.

The tungsten carbide inserts proved to be the best tested. The softer grade, Carboloy 350, stood the test for all three cutting velocities. The next harder grade, Carboloy 370, did not stand up at any of the speeds. The hardest grades, Carboloy 883 and 999, both stood up very well. The Vascoloy 2A5 broke down repidly at a speed of 3000 fpm.

With the specimen crest length of 1.600 in., the completion of five passes was good performance. The ACT/chip for this length of specimen and at the velocities of 1500, 2250, and 3000 fpm were as follows:

1500 fpm (1000 rpm) - 5350 μsec
2250 fpm (1500 rpm) - 3570 μsec
3000 fpm (2000 rpm) - 2675 μsec.

After examining the surface finishes, the cutting tools, and the chips, it was determined that the Carboloy 883 grade was slightly better than the 999 grade, but both grades were considered as the most satisfactory of those materials tested.

The results are plotted in Figs. 7, 8, and 9 for cutting speeds of 1500 fpm, 2250 fpm, and 3000 fpm, respectively.

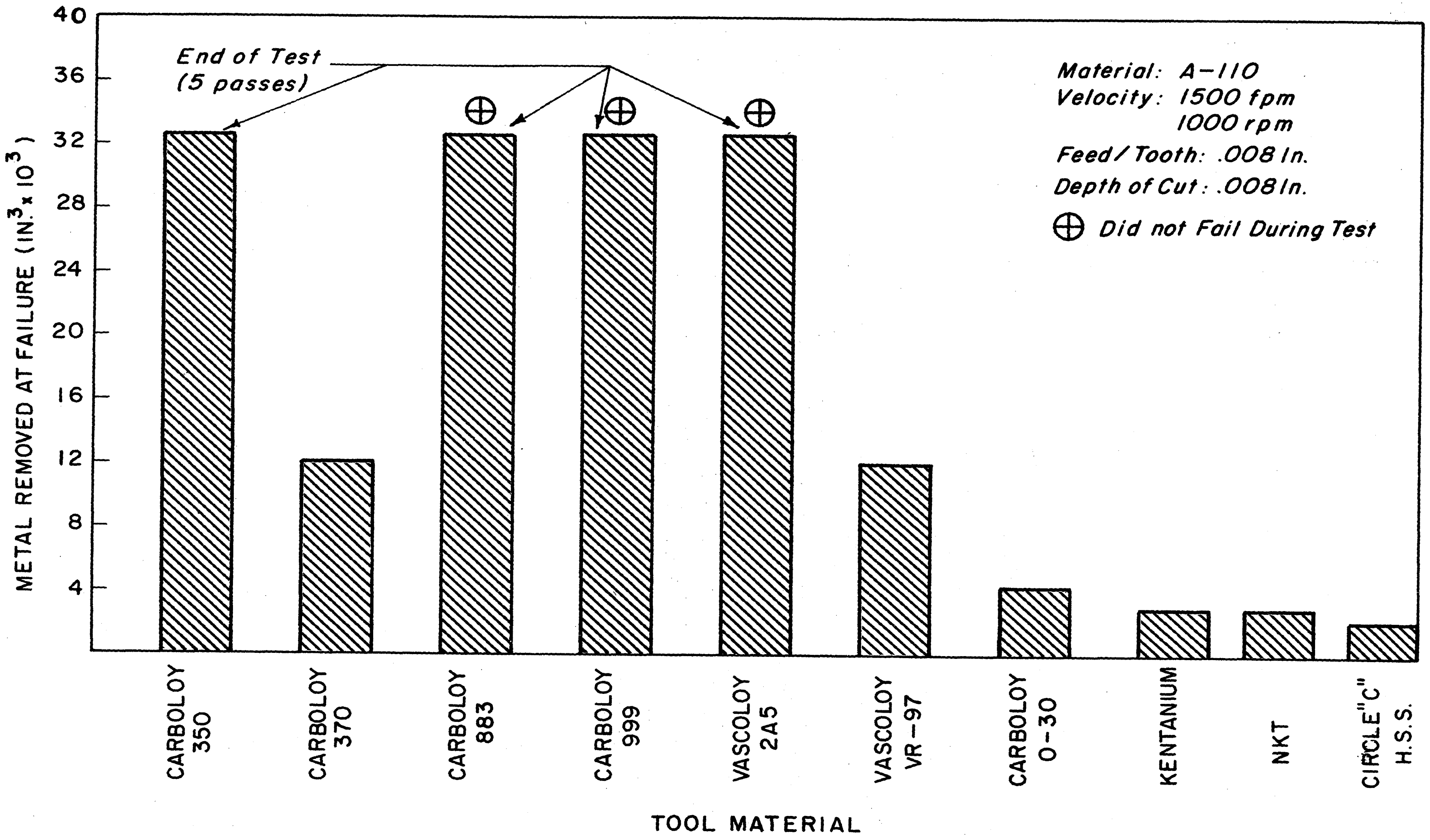

Fig. 7. Metal removed at failure vs. tool material: 1000 rpm.

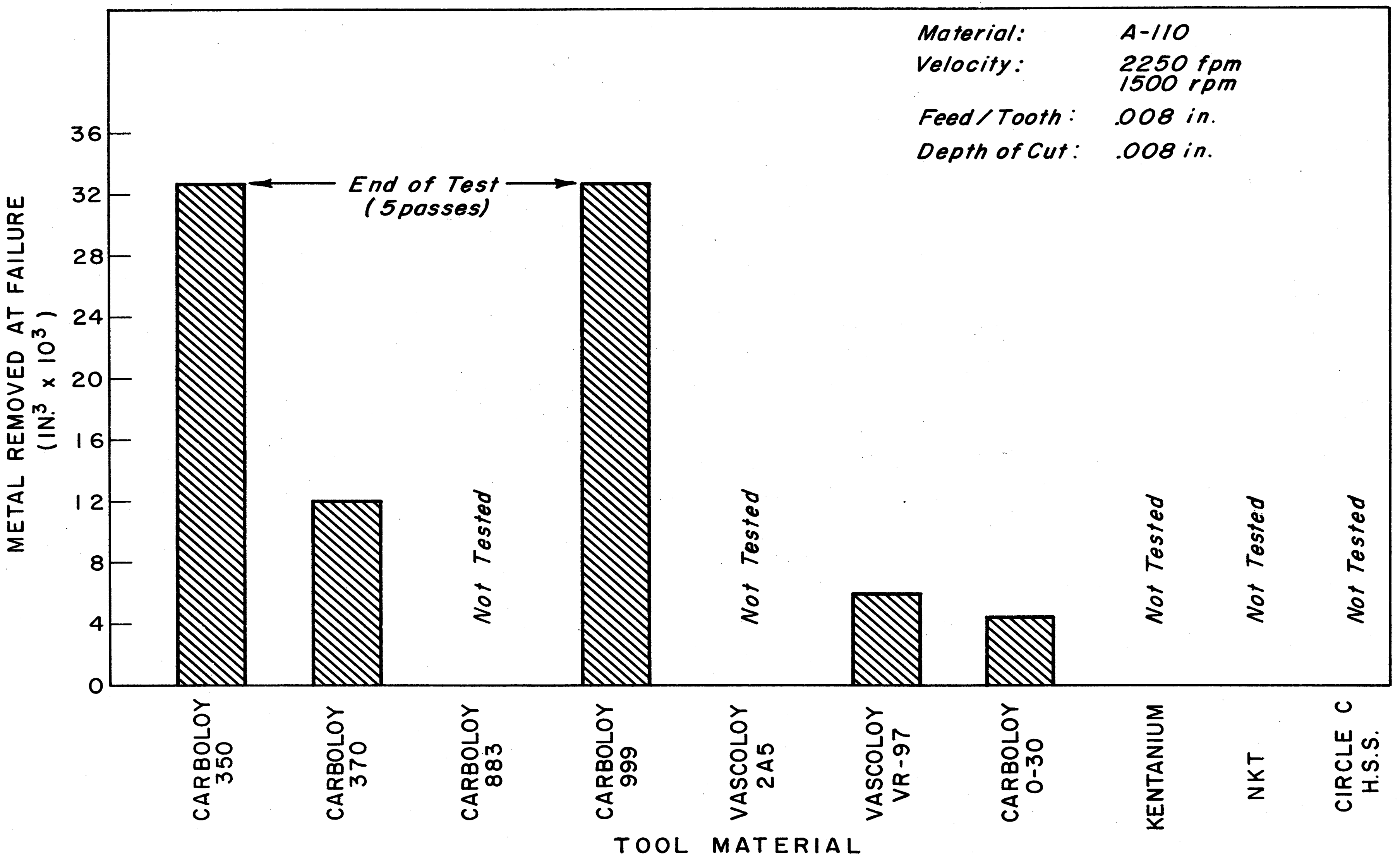

Fig. 8. Metal removed at failure vs. tool material: 1500 rpm.

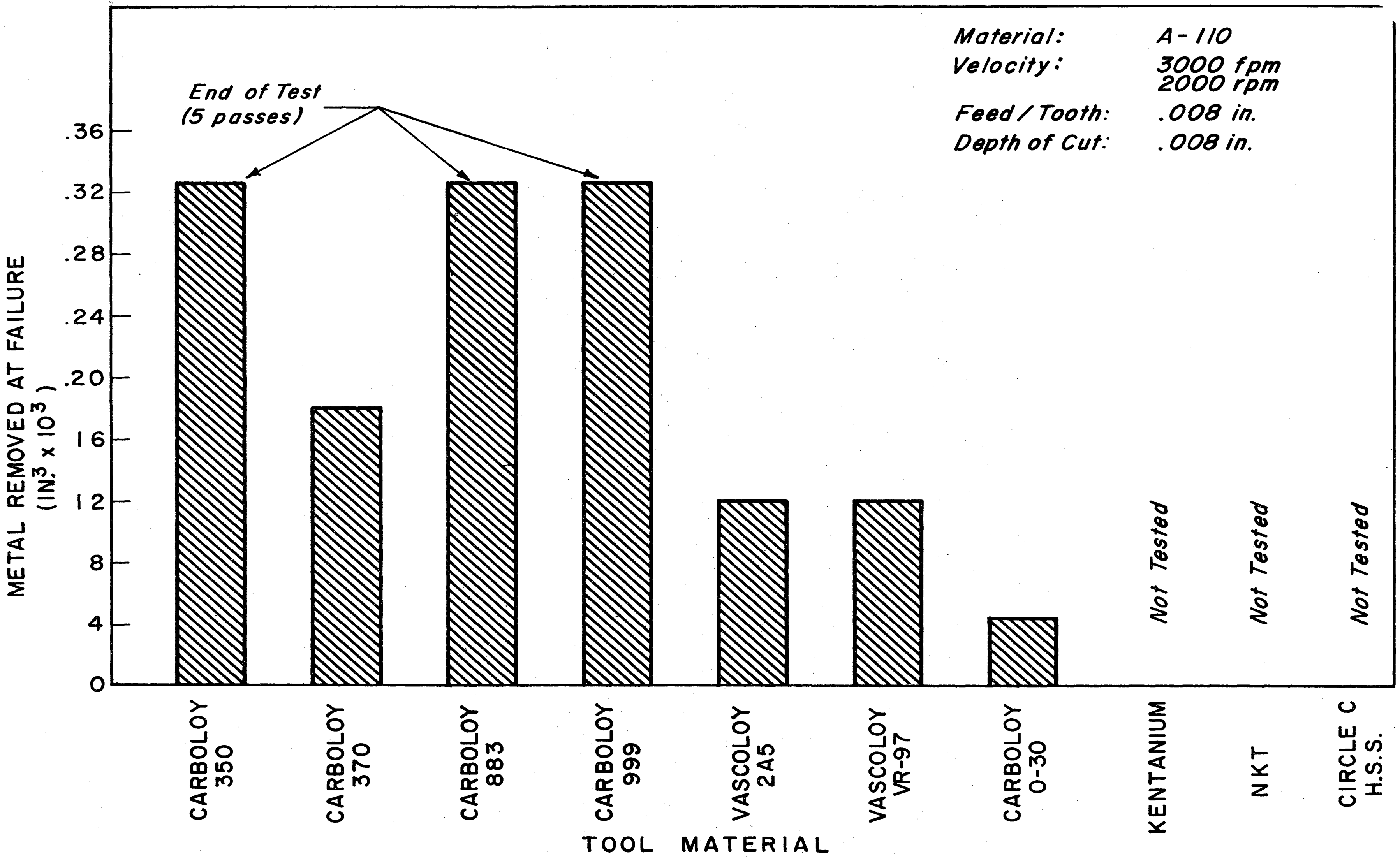

Fig. 9. Metal removed at failure vs. tool material: 2000 rpm.

SERIES C

COMPARISON OF TITANIUM WITH OTHER METALS

I. Preliminary

Objective:

To observe the cutting actions of various metals whose properties are known and to observe the action in cutting A-110 alloy along with them in a visual comparison.

As a further exploratory step into the cutting properties of titanium and into the tool wear rate, A-110 alloy and five other materials were machined in a comparable situation. The other materials were:

1. Stainless steel - T 316 grade.
2. Stainless steel - T 304 grade.
3. Commercially pure copper.
4. Inconel.
5. AISI - 1018 steel.

Test Conditions:

Specimen

Materials	Size	Position
(as listed)	.456 x 1.990 x (1-1/2 to 2-1/4) in.	Rotated

Tool

Tool Material	Tool Geometry	Position
Carboloy 883	Zero Radius	4° back clearance
Carboloy 999	Zero Radius	4° back clearance

Tool Holder

Tool Holder No.	Position
Kendex SN 4 KSFL 85A	Negative 20° off perpendicular to specimen face (see Fig. 6).

Cutting Conditions

Velocity, fpm	Feed/Tooth, in.	Cutting Depth, in.
1500 (1000 rpm)	.008	.008
2250 (1500 rpm)	.008	.008
3000 (2000 rpm)	.008	.008

Procedure:

1. The specimens were cut for five passes and the chips were caught. Observations were made after each pass as to chip appearance, cutting condition, specimen appearance, and tool point conditions.

2. The specimen was rectangular in shape with no stand-out profile. The cut was made along the 1.990 length with the feed traversing across the specimen in the .456 direction.

3. Some runs were duplicated in comparing carboloy inserts of grades 883 and 999. There appeared to be some slightly better performance through using the 883 grade inserts, so they were used for the balance of the testing.

Observations:

Several observations were made such as color of chip, general chip length, general configuration of the chip, whether the chip was red hot while cutting, whether the tool and specimen made a pounding sound as they impacted together, the burring conditions, the specimen finish, and where tool wear occurred.

Since the test was primarily exploratory in nature, very little could actually be concluded from it except that the tool failed only while cutting A-110 titanium. Much of the other observations are known characteristics of these materials. It should be noted that the cutting time per chip was relatively long. It varied from 3.4 to 6.8 milliseconds, which is from 10 to 15 times as long as subsequent studies indicated that it should be.

II. Tool Life and Chip Formation

Objective:

To detect the first sign of tool failure as indicated by the surface finish of the specimen and to determine the metal removed up to this end point.

Following the C-I test, a comparison was desired of the first point of detectable tool failure between titanium A-110 and six other materials. Consecutive passes were made until a distinguishing mark appeared on the specimen surface. On some of the materials, such as the 70-30 brass, the tests were stopped when it became evident that a large number of passes would be required to produce such a condition.

Test Conditions:

Specimen

Materials	Size	Position
A-110 titanium	.456 x 1.990 x (1-1/2 to 2-1/4)	Rotating
T-316 stainless steel		
T-304 stainless steel	(see Fig. 10)	(see Fig. 6)
AISI 1018 steel		
Inconel		
Armco Ingot iron		
70-30 brass		

Tool

Tool Material	Tool Geometry	Position
Carboloy 883	Zero radius	4° back clearance

Tool Holder

Tool Holder No.	Position
Kendex SN 4 KSFL 85A	Negative 20° off perpendicular to specimen face (see Fig. 6)

Cutting Conditions

Velocity, fpm	Feed/Tooth, in.	Cutting Depth, in.
1500 (1000 rpm)	.012	.020
2250 (1500 rpm)		
3000 (2000 rpm)		

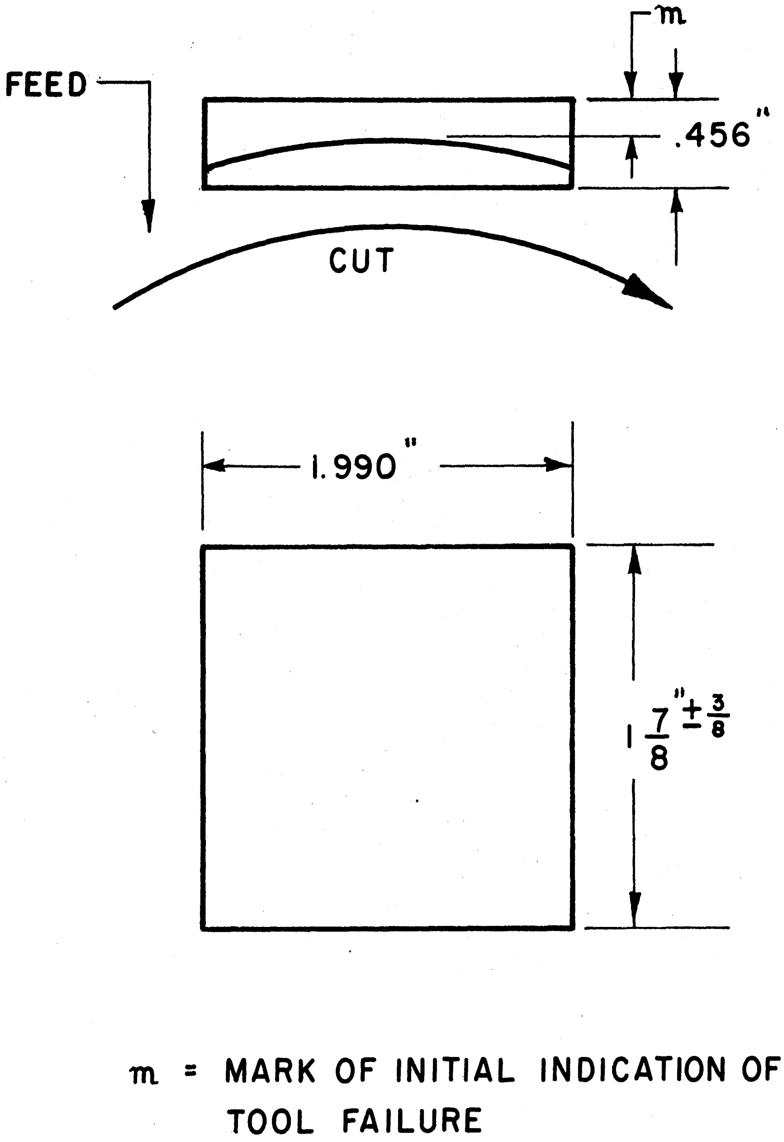

Fig. 10. Specimen for Series C, I and II.

Observations:

Consecutive passes were made across the specimen until a mark or step appeared upon the surface that indicated some form of tool failure was just beginning to take place. The distance across the .456 dimension prior to the mark was scaled. The volume cut then was the volume per pass times the number of passes taken plus the volume of the section cut prior to the mark.

If 10 passes were taken or if the examination of the tool insert indicated that virtually no wear had occurred, the test was discontinued because too many passes would be required.

The comparative chip length and chip colors were noted for temperature indications. The specimens were also checked for hardness. The results show that the only comparable materials were the T-316 and T-304 stainless steels and A-110 titanium. The A-110 had the shortest tool life. The results are summarized in Table VI.

TABLE VI

CUTTING TIMES AND VOLUMES TO FIRST VISIBLE SIGN OF TOOL WEAR ON VARIOUS MATERIALS
(Series C-II)

Material	Speed fpm	Cutting Time Per Chip (μsec)	Cutting Time Per Pass (sec)	Total Tool Contact Time Prior to Point Failure (sec)	Volume of Material Removed (in.^{3})	Depth of Cut	Feed Per Revolution	Relative Chip Length	Chip Color	BHN
1018	2250	4,580	.174040	1.218*	.127*	.012	.012	Short	Black	179
1018	3000	3,440	.130720	.366	.031	.012	.012	Short	Black	179
Inconel	2250	4,580	.174040	.653*	.091*	.012	.012	Long	Bright	163
Inconel	3000	3,440	.130720	.312	.043	.020	.012	Medium	Bright	163
Stainless										
T-304	1500	6,880	.261440	.134	.010	.020	.012	Short	Tan	149
T-304	2250	4,580	.174040	.113	.010	.020	.012	Short	Bright	149
T-304	3000	3,440	.130720	.058	.006	.020	.012	Short	Bright	149
T-316	1500	6,880	.261440	.134	.026	.020	.012	Very short	Light tan	143
T-316	2250	4,580	.174040	.063	.005	.020	.012	Very short	Bright	143
T-316	3000	3,440	.130720	.094	.012	.020	.012	Very short	Tan	143
Titanium										
A-110	1500	6,880	.261440	.080	.004	.020	.012	Long Welded	Dull	332
A-110	2250	4,580	.174040	.030	.002	.020	.012	Long Welded	Dull	332
A-110	3000	3,440	.130720	.003	.001	.020	.012	Particles		332
Armco Ingot Iron	3000	3,440	.130720	1.307*	.182*	.020	.012	Short	No change	131
30-70 Brass	3000	3,440	.130720	1.307*	.182*	.020	.012	Particles	No change	116

*No failure

SERIES D

TOOL WEAR

Objective:

To determine the effects of cutting velocity upon tool wear.

From the previous series of tests, it was well demonstrated that velocity was the major factor in tool wear. By varying the cutting velocity and measuring the land wear after each cut with the toolmaker's microscope, a definite wear pattern could be determined. Based on the results of Series B, Carboloy 883 tungsten carbide was chosen for the tool material. Similarly, the .008- by .008-in. chip size was chosen from the results of Series A-V. A-110 was chosen as the material for the work specimen.

At this stage, it was also decided to rotate the tool and hold the work specimen stationary. (See Fig. 11.) The specimen had a rectangular cross section of .456 by 1.990 in. The feed was in the 2-in. direction with the cut taken across the .456-in. dimension. (See Fig. 12b).

A Kendex SN 4 KSDR 85A tool holder was modified to be held in the rotating chuck for this test. (See Fig. 12a.)

Test Conditions:

Specimen

Material	Size	Position
A-110	.456 x 2.000 in.	Stationary

Tool

Tool Material	Tool Geometry	Position
Carboloy 883	(1) Zero radius (2) .030 radius	45° to center of rotation

Tool Holder

Tool Holder No.	Position
Kendex SN 4 KSDR 85A (Modified)	Clamped into rotating chuck

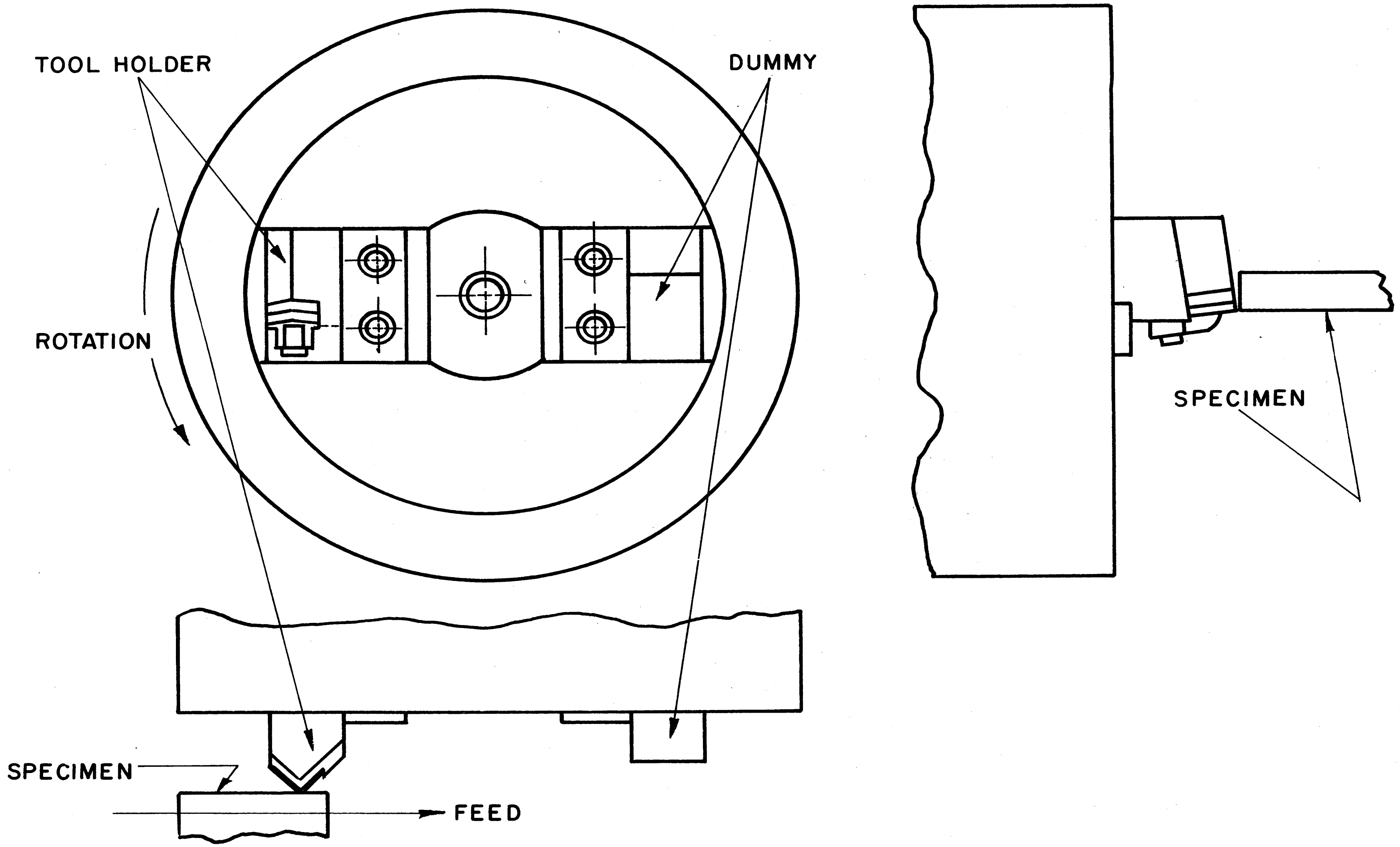

Fig. 11. Rotating tool holder and stationary specimen.

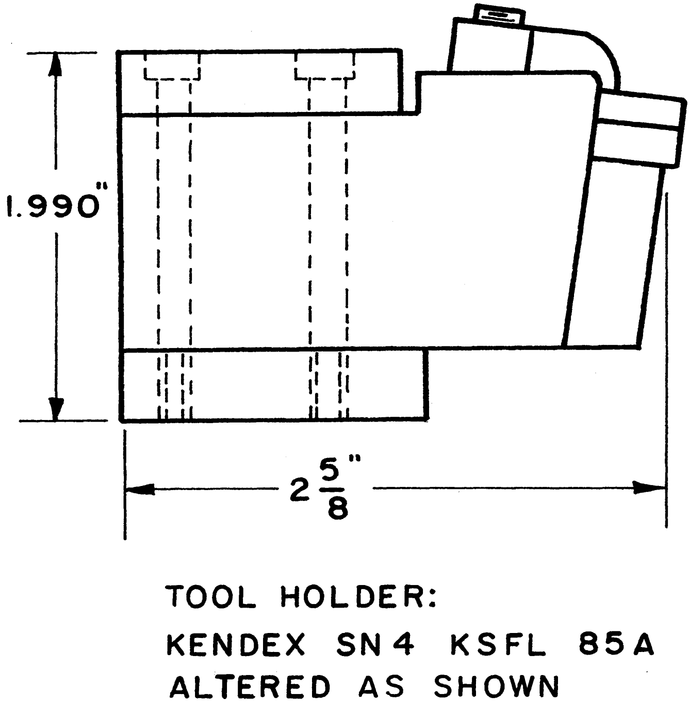

Fig. 12a. Modified tool holder for rotating chuck.

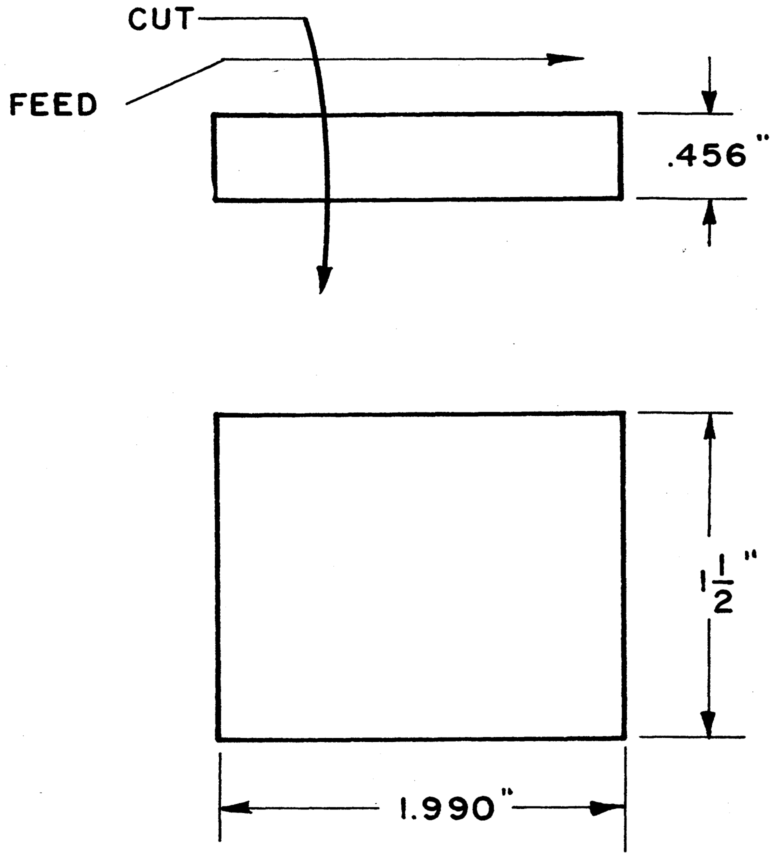

Fig. 12b. Specimen for Series D.

Cutting Conditions

Velocity, fpm	Feed/Tooth, in.	Depth of Cut, in.
2000 (1000 rpm)	.008	.008
2250 (1500 rpm)	.008	.008
3000 (2000 rpm)	.008	.008

Observations:

It was soon apparent that the zero-radius tool inserts were not going to stand the test. Three attempts were made and each time the tip chipped out on the first pass across the specimen. At this point, the .030-radius tool inserts were used.

This tool made 23 passes at 1500 fpm velocity (1000 rpm) before the end point was reached. In doing this, it made approximately 6000 chips.

At 2250 fpm (1500 rpm) the tool averaged 14 passes and 4400 chips before the end point. Three tests were run to establish this average.

The 3000 fpm (2000 rpm) test averaged only 5 passes or 1300 chips to the end point. Again, three tests were run to prove the repeatability of the data.

The results are summarized in Table VII and have been discussed along with plots of the data in the main body of the report.

TABLE VII

SUMMARY OF TOOL-WEAR RESULTS

Speed fpm	Chip Size	Approx. No. of Impacts to End Point*	Average No. of Cuts Taken to End Point*	Volume Per Cut (in.^{3})	Total Volume Cut to End Point* (in.^{3})	Cutting Time Per Pass (sec)	Total Cutting Time to End Point* (sec)	Average Flank Wear Rate (in./sec)
1500	.008 x .008	6,000	22	.007328	.161000	.408830	8.994260	.0033
2250	.008 x .008	4,400	14	.007328	.103000	.272590	3.81630	.0079
3000	.008 x .008	1,300	5	.007328	.036640	.204415	1.022075	.0293

Tools:

Tip: Carboloy 883 SQT 162 U2

Holder: Kendex SN 4 KSDR 85A

Specimen: Stationary

Tool: Rotated

Feed: .008 in./rev.

Depth: .008

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*End point was .030-in. flank wear on the tool.

SERIES E

VIBRATIONS

Objective:

To investigate vibrations and their effects in the machining of the three titanium alloys, A-110, B-120, and C-120 and to make a limited comparison with some selected ferrous and nonferrous metals.

Three distinct sets of experiments were run. One was to make a comparison between titanium and other metals, another was to investigate whether the material or the physical set-up determined the pattern of frequencies, and the last (Series E, F, and G) was a rather complex sequence of tests wherein temperature, vibration, and cutting force were studied concurrently.

The first set of experiments compared seven different metals. A stationary work specimen and a rotating tool were used. Vibrations in the stationary workpiece (Fig. 13) were recorded for both the vertical and horizontal positions of the accelerometer as shown in Fig. 14.

The second set used a similar set-up except that the overhang and the specimen length were varied so as to determine whether the physical dimensions of the work specimen and its mounting had any influence on the observed frequencies. Only A-110 alloy was used for this study.

Description of the Measuring Device:

A Kistler Model 802 accelerometer and a Model 565 amplifier were used in conjunction with a Tecktronic Model Dual-Beam Oscilloscope.

The 802 accelerometer is a compact, 3/8-in.-diameter, 3/4-in. long, spring-loaded quartz transducer. The transducer was attached at the point of interest by a threaded stud that is an integral part of the body.

Work Specimens:

The stationary type used for this Series is illustrated in Fig. 13. This type had a 2-1/2° angle machined along the top surface to allow it to be securely locked into position in the tool-holder block by a complimentary self-locking wedge. One specimen was made from each of the following materials.

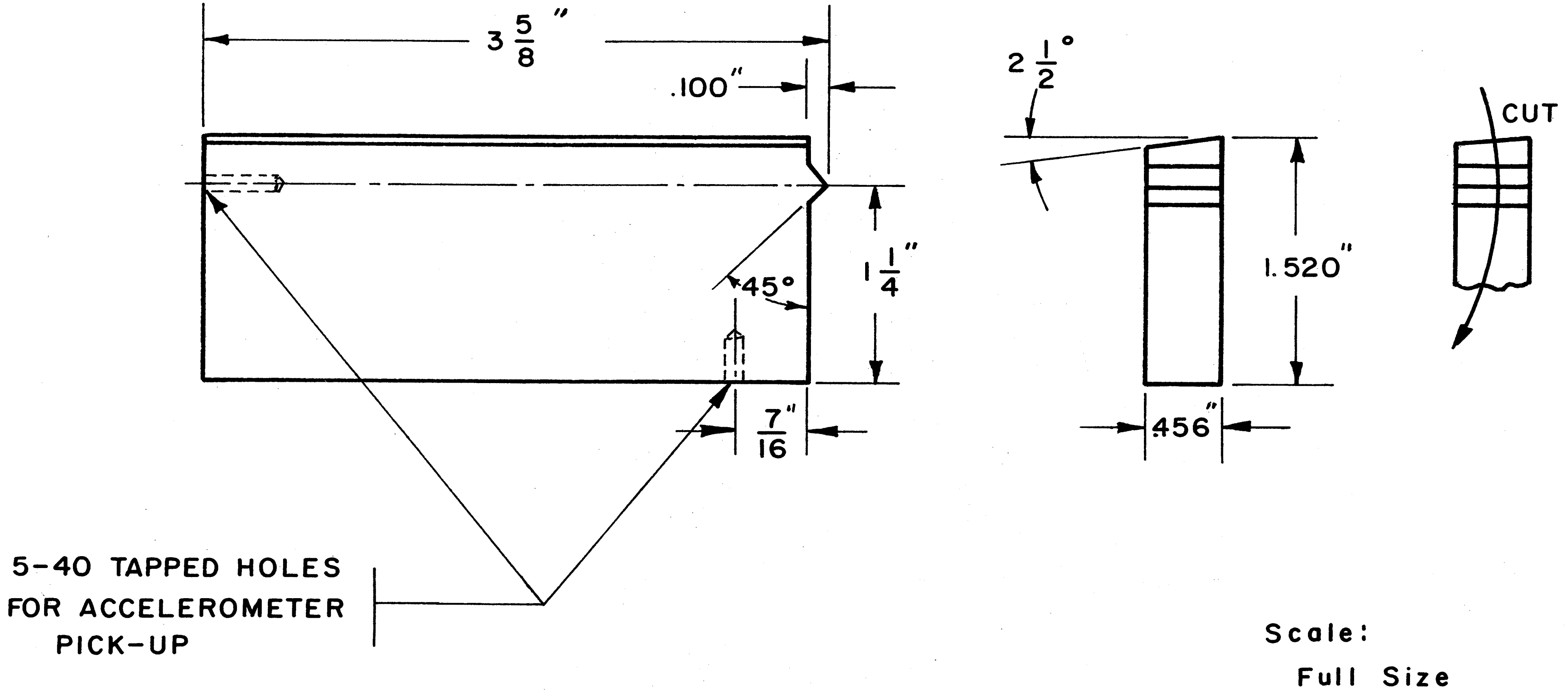


Fig. 13. Specimen for vibration study.

(1) A-110 titanium
(2) B-120 titanium
(3) C-120 titanium
(4) Armco ingot iron
(5) 70-30 brass
(6) Copper
(7) Nivco-10 Steel (an experimental high-damping steel)

Each of these specimens had a stand-out profile machined on one end at a position corresponding to the centerline height of the spindle.

Cutting Tools:

Holder - Kendex, SN 4 KSDR 85A
Insert - Carboloy 883, style SQT 162 U2 (1/2 x 1/2 x 1/8)

Cutting Conditions:

Velocity, fpm	Feed/Tooth, in.	Depth of Cut, in.
1500	.008	.008
3000	.008	.008
4500	.008	.008

Test Procedure:

Oscillograph traces were photographed for single cuts with the accelerometer mounted in both the horizontal and vertical positions shown in Fig. 14. This was repeated for each of the seven work materials at each of the three cutting speeds.

Results:

The results of this series of tests are discussed in the main body of the report.

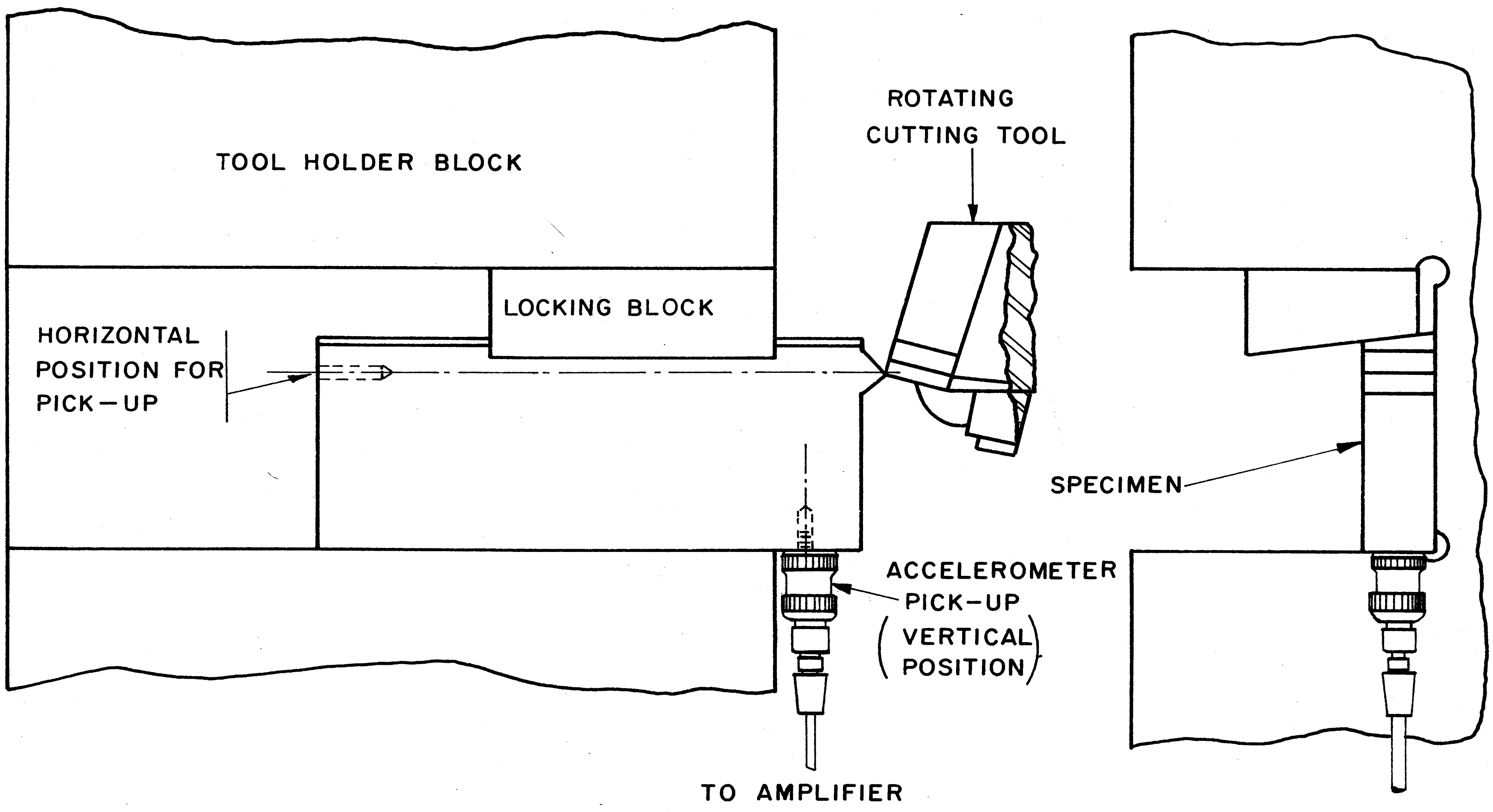


Fig. 14. Position of specimen and cutting tool for vibration study.

SERIES F

CUTTING TEMPERATURES

Objective:

The purpose of this series was to determine the relative cutting temperatures while machining A-110, B-120, and C-120 at different combinations of speed and size of cut. A contact thermocouple was embedded in a hole in the underside of the carbide tool insert.

Test Conditions:

Specimen:

1. A-110, B-120, and C-120.
2. Stand-out profile with zero crest length (see Fig. 17).
3. Specimen width: .456 in.
4. Specimen was rotated (see Fig. 1).

Tool:

1. Tool holder No. SN 4 KSDR 85A.
2. Carboloy 883 tungsten carbide insert, style SQT 162 U2 and with four .028-in.-diameter holes ultrasonically drilled in each corner to within .010 in. of the tool surface. (See Figs. 15 and 16.)

Cutting Conditions:

1. Velocity varied:
    1500 fpm at 1000 rpm
    3000 fpm at 2000 rpm
    6000 fpm at 4000 rpm
2. Feed rate varied:
    .002 in./tooth
    .004 in./tooth
    .008 in./tooth
3. Cutting depth constant at .008 in.

Description of Thermocouple Arrangement:

The thermocouple used in this series was a Baldwin-Lima-Hamilton, Chromel P-Alumel, micro-miniature thermocouple, type TCA-FS-50. The probe length was approximately 1/2 in. long with a diameter of .015 in. The probe comes with

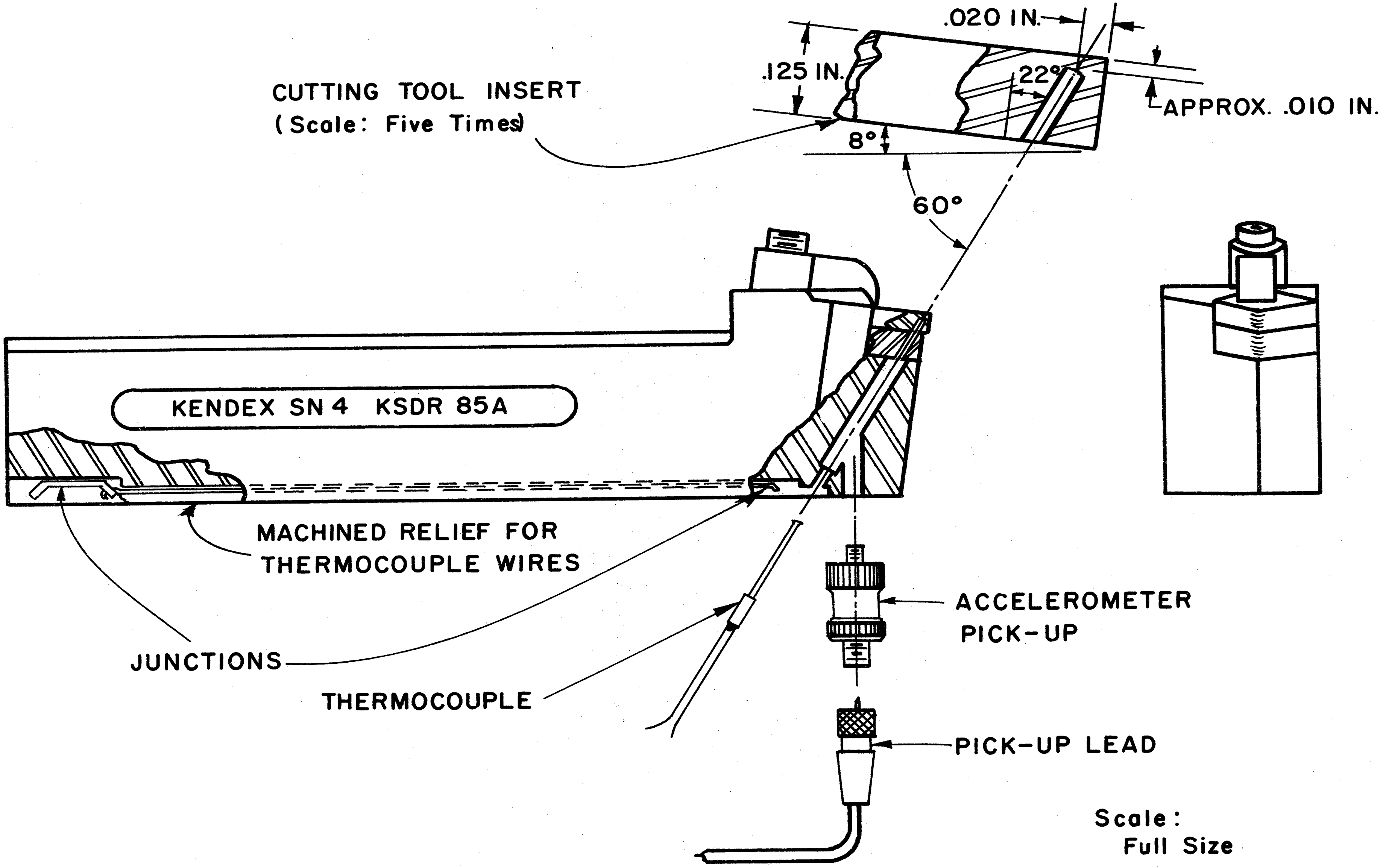


Fig. 15. Modified tool holder for temperature and vibration measurements.

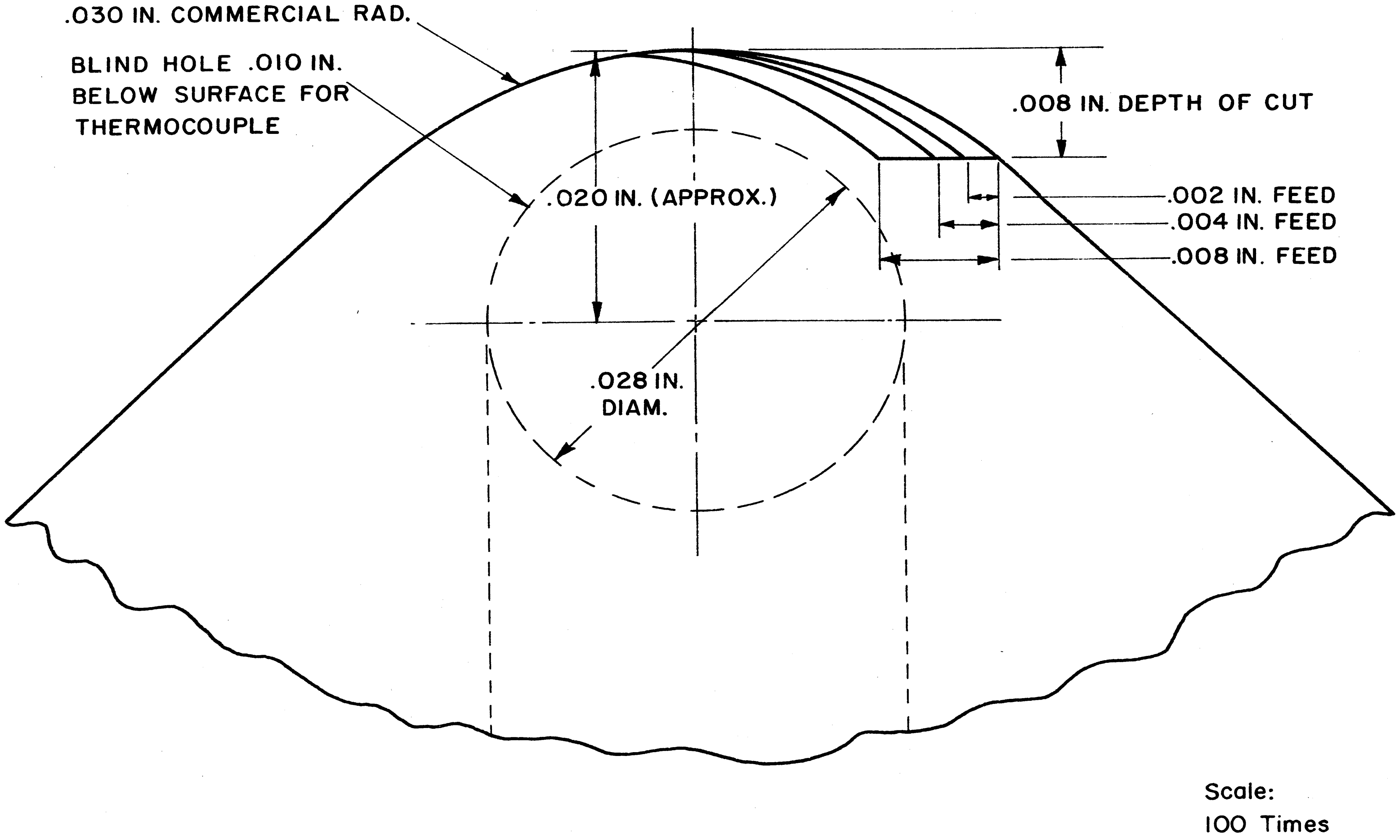
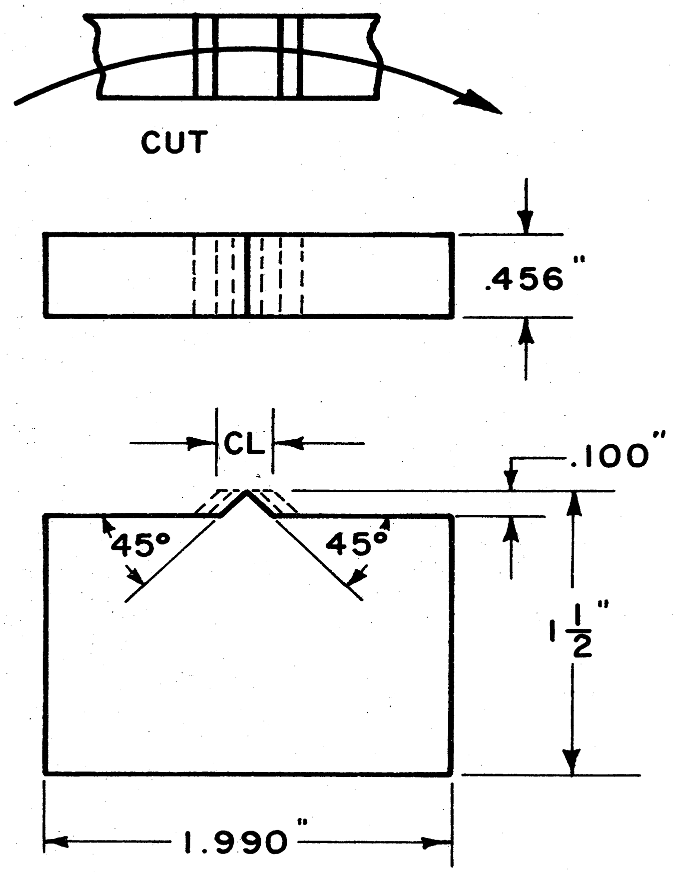


Fig. 16. Location of interfaces of the tool, work material, and the thermocouple.



CL = CREST LENGTH
.00, .100, & .200 IN.

Scale:
Full Size

Fig. 17. Specimen for temperature study.

the tip containing the couple flattened into a wedge with a width of .028 in.; this gives a small contact area between the tip of the probe and the rounded bottom of the hole in the tool insert. Contact was assured, however, by spring-loading the thermocouple probe.

Holes were drilled through the tool holder and tool pad to acommodate the thermocouple probe. The probe tip extended above the pad surface so that, when the carbide insert was mounted in position, the tip made good contact with the bottom of the hole. The point of final contact was then approximately .010 in. from the tool surface. Figure 15 shows details of the arrangement.

Recording and Calibration:

Basically, the procedure involved recording the thermocouple output and then converting the observed pen deflection into temperature units. The small voltage generated in the thermocouple during cutting was fed into a Sanborn low level preamplifier, Model 150-1500. The amplified signal was then fed into a Sanborn recorder, Model 60-1300, which provided the permanent record on recording paper.

A cold-junction reference thermocouple was placed in parallel with the recording couple so that, when both couples were at the same temperature, no signal would be received by the preamplifier. The reference junction was placed in ice water so that the generated signal would indicate the true temperature of the couple in the tool insert. The effect of room temperature, then, was to displace the stylus on the recorder a certain distance. This position was essentially the zero point and any additional deflection was proportional to the energy released during cutting.

Before each pass across a specimen, the calibration of the preamplifier and the recorder was checked so that a constant calibration factor was maintained in terms of millivolts per millimeter of pen deflection. When the calibration was adjusted, the recording tape was put in motion at a speed of 1 mm/sec; the lathe cross-feed was then engaged. The stylus deflection in millimeters was recorded and multiplied by the calibration factor to give the voltage generated by the thermocouple. This voltage reading was then converted to degrees Fahrenheit by use of the Chromel P-Alumel thermocouple tables.

The system response was similar to that of any simple, first-order system reacting to a step-function signal. This was assumed to be valid for all data reduction. The corresponding time constant was found to be 3.5 sec.

Results:

The converted step-function temperatures are plotted in Figs. 18 to 26 against the corresponding cutting times involved in removing single chips. Since the rate of metal removal increased on successive passes, the same results are plotted also against average rate of metal removal in Figs. 27 to 29. The significance of the temperature data is discussed in the main text.

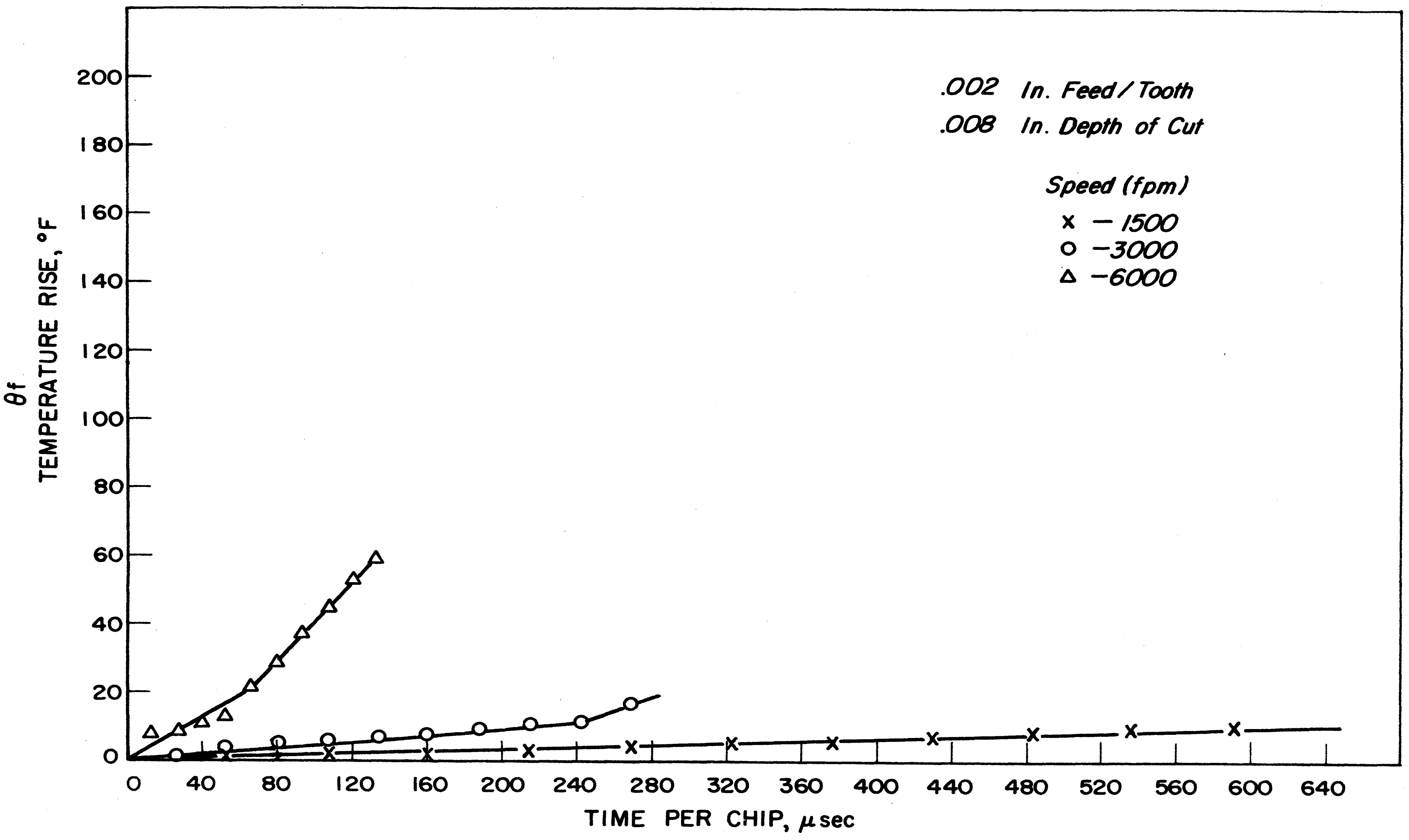


Fig. 18. Temperature rise vs. time per chip, .002 in./tooth: A-110.

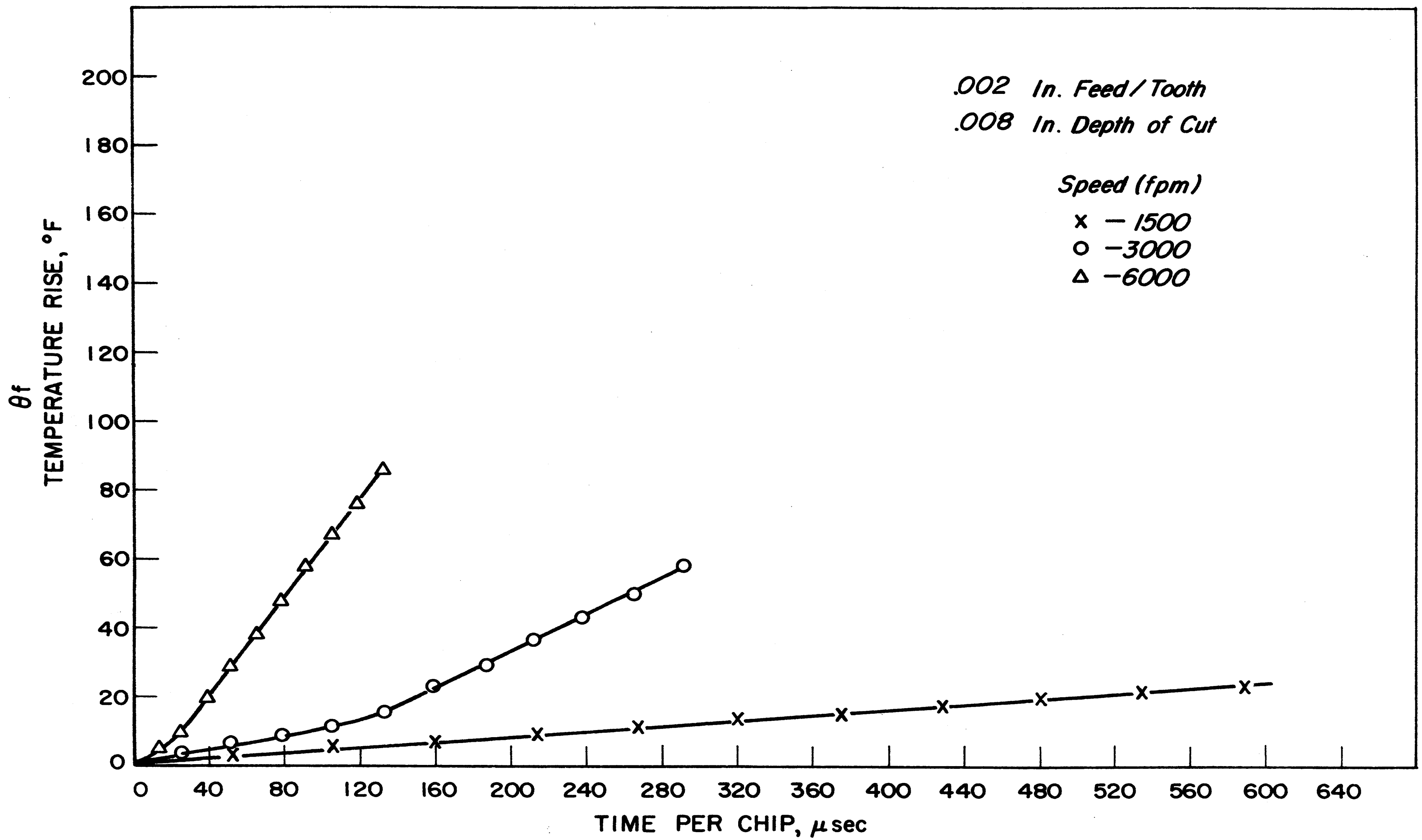


Fig. 19. Temperature rise vs. time per chip, .002 in./tooth feed: B-120.

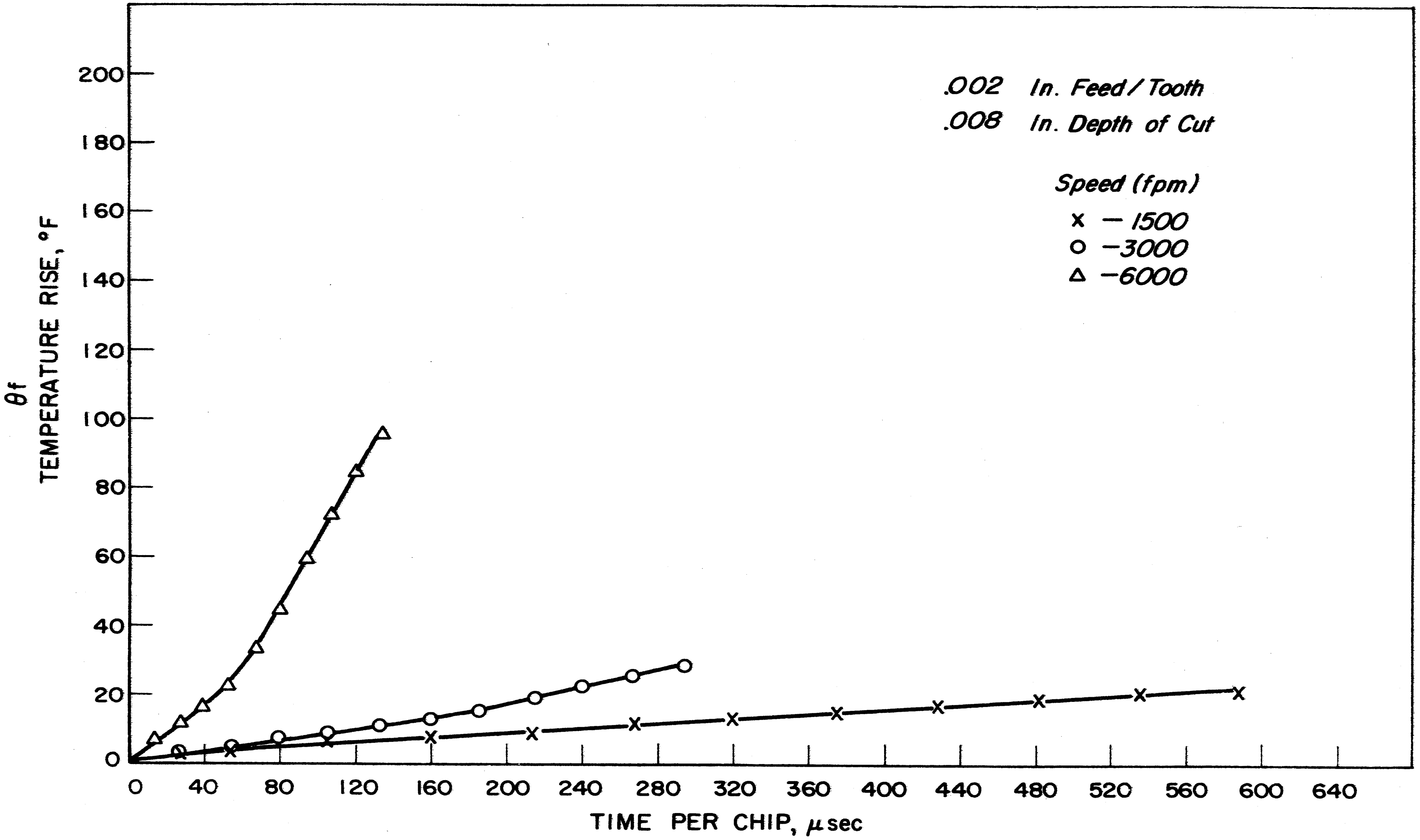


Fig. 20. Temperature rise vs. time per chip, .002 in./tooth: C-120.

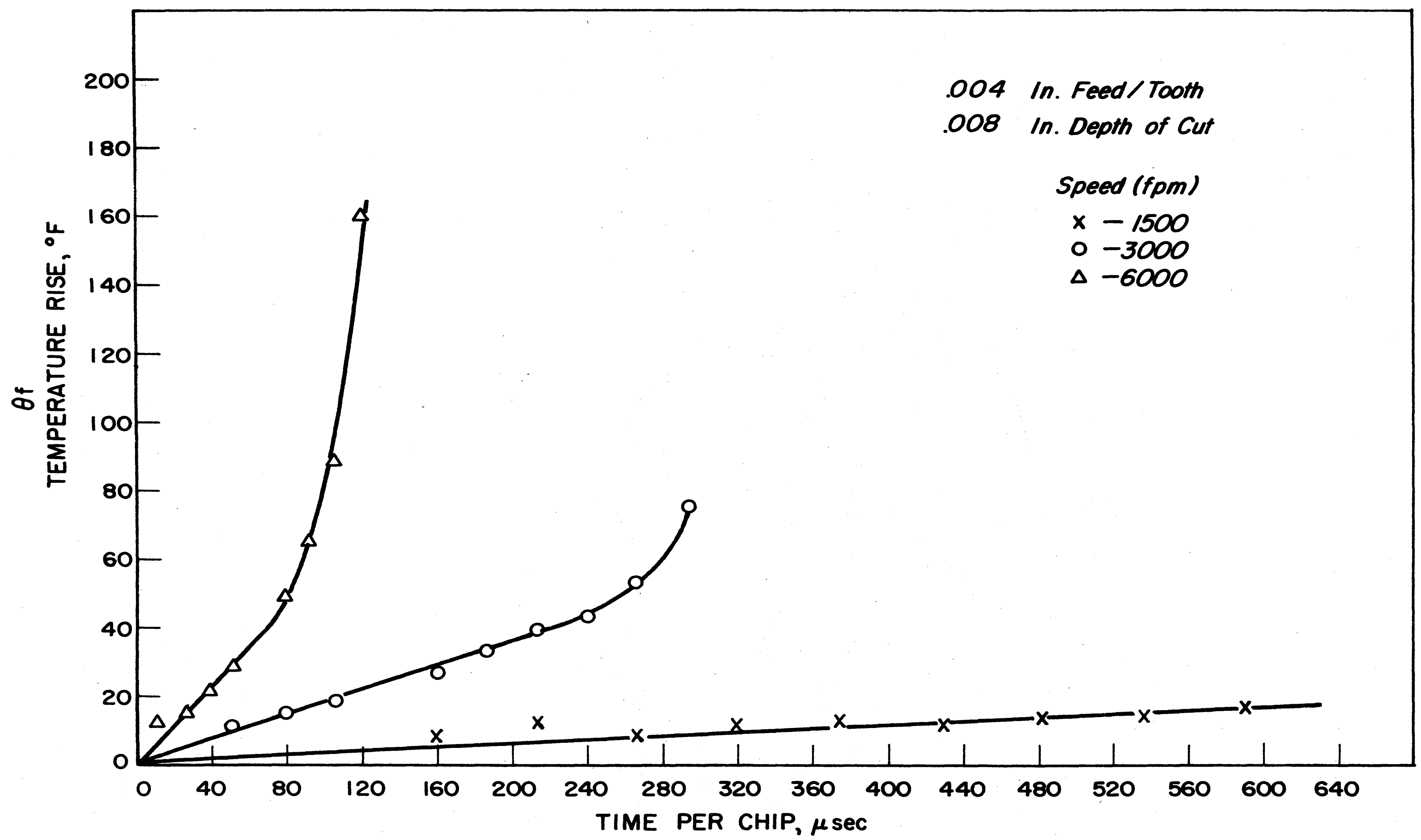


Fig. 21. Temperature rise vs. time per chip, .004 in./tooth: A-110.

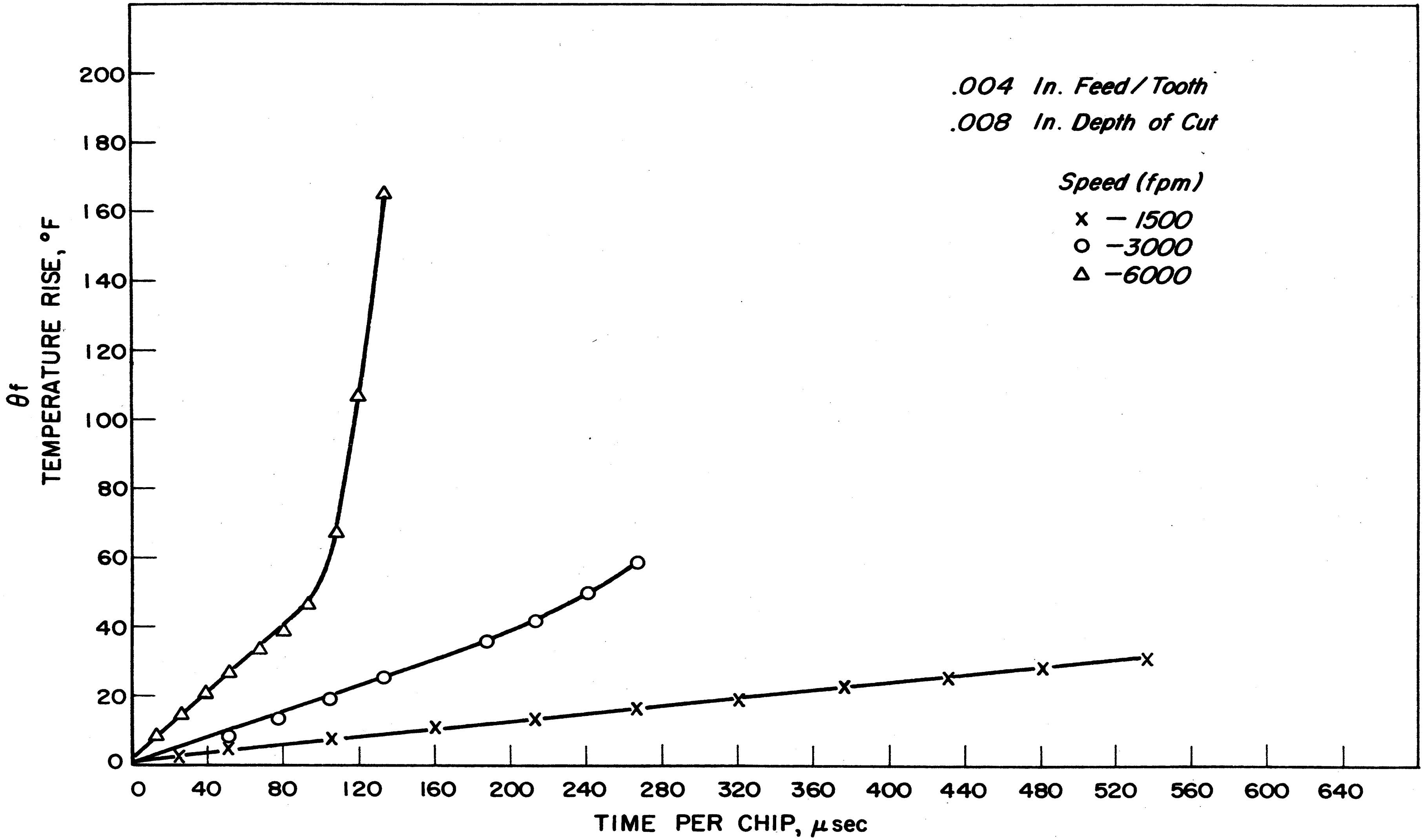


Fig. 22. Temperature rise vs. time per chip, .004 in./tooth feed: B-120.

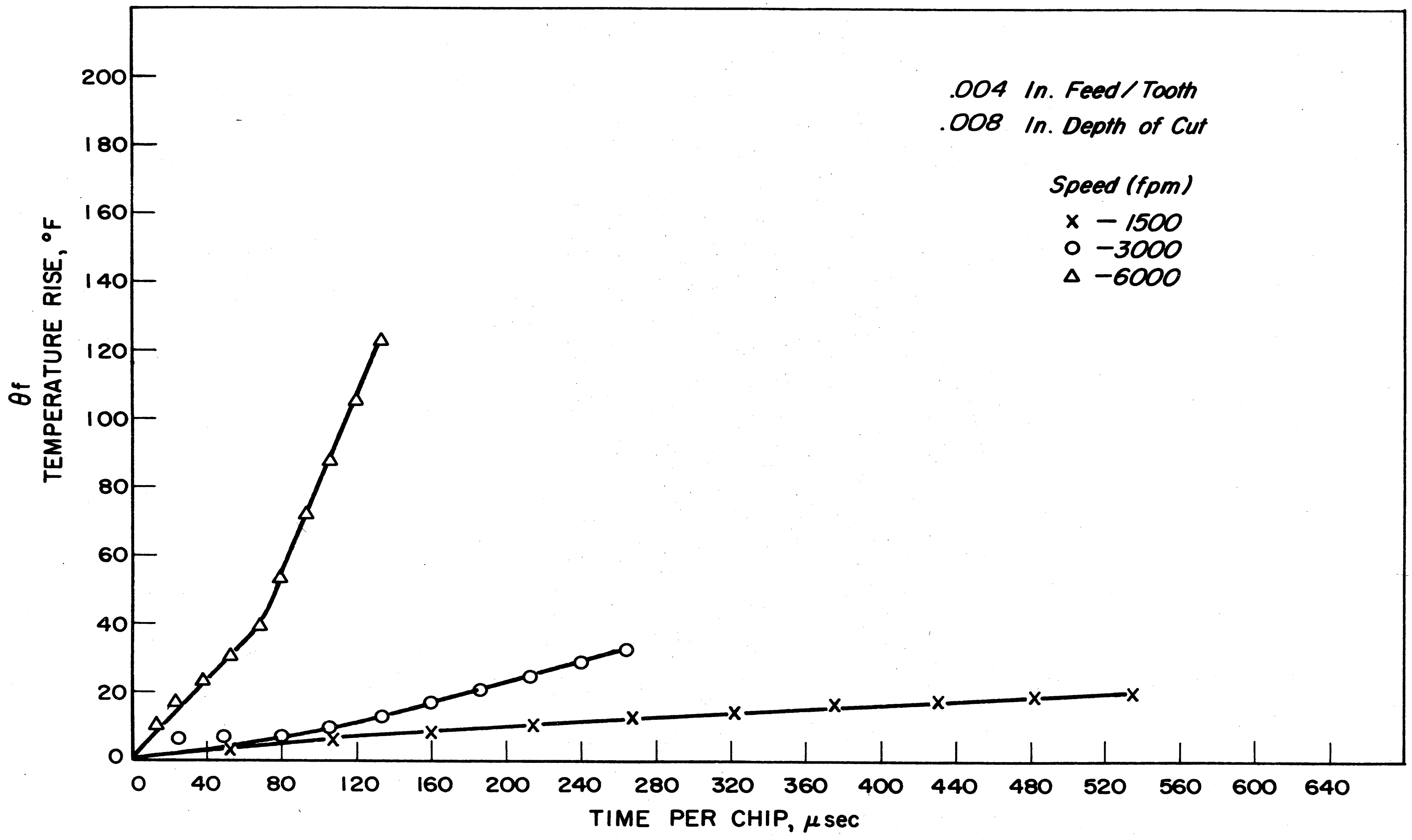


Fig. 23. Temperature rise vs. time per chip, .004 in./tooth feed: C-120.

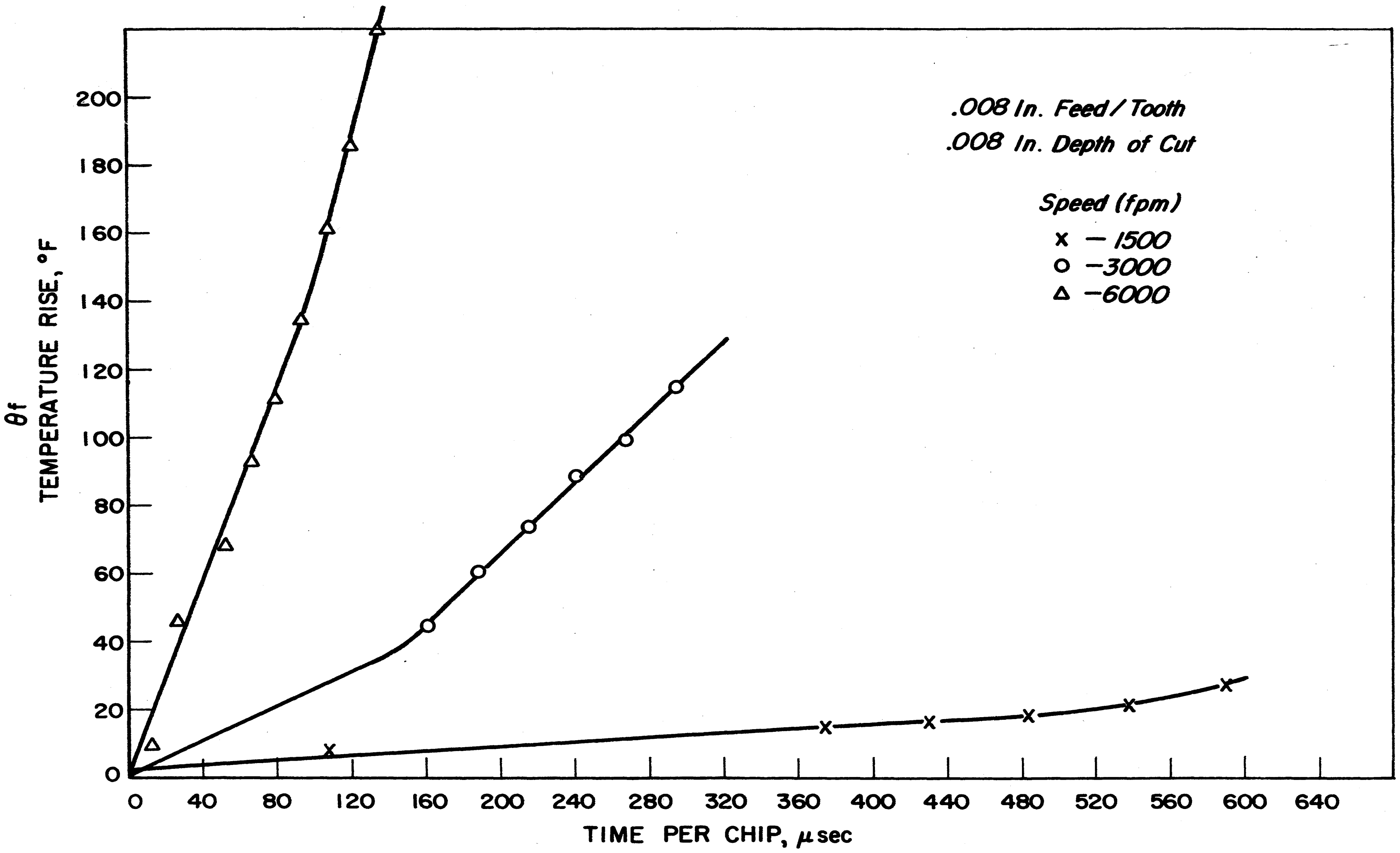


Fig. 24. Temperature rise vs. time per chip, .008 in./tooth: A-110.

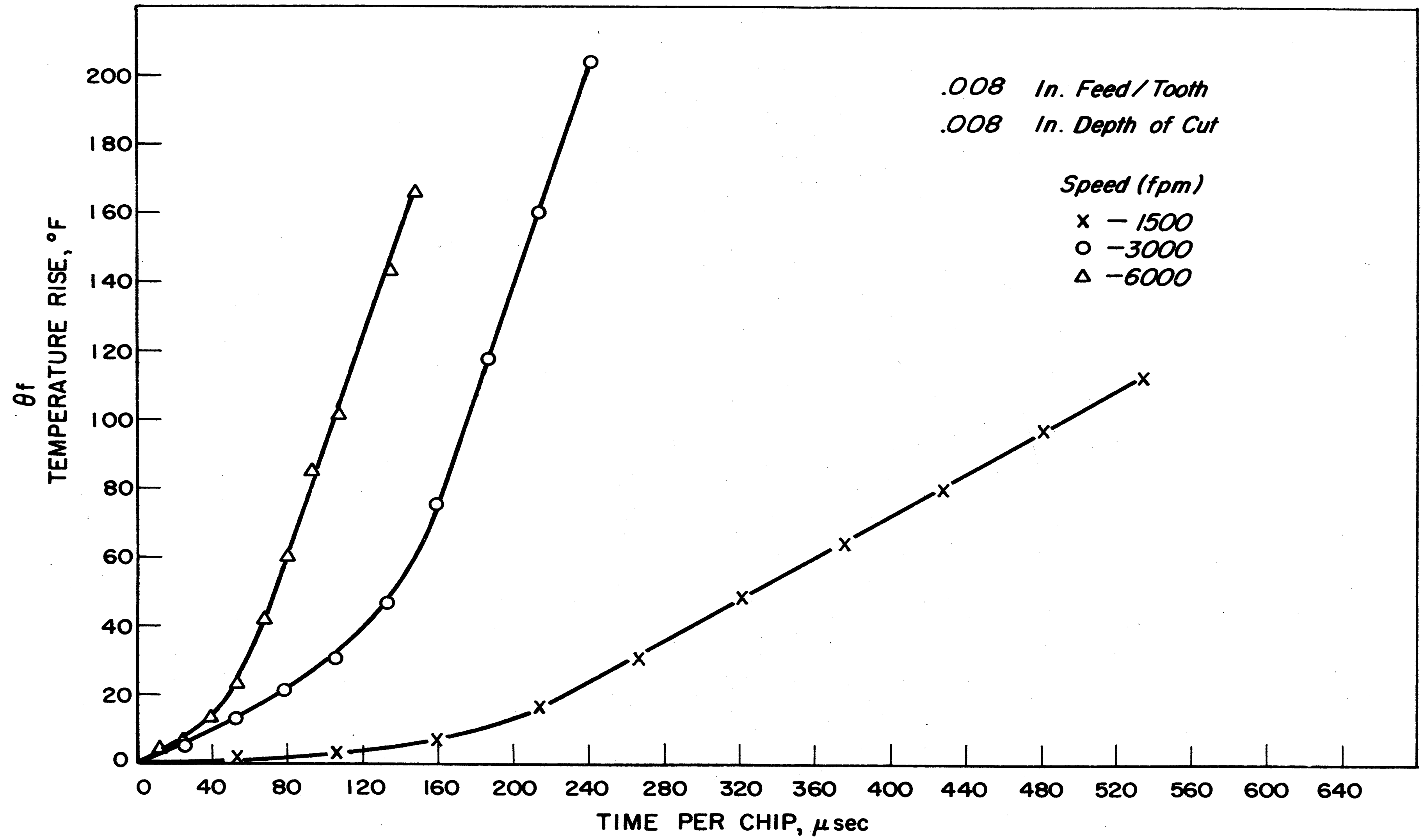


Fig. 25. Temperature rise vs. time per chip, .008 in./tooth feed: B-120.

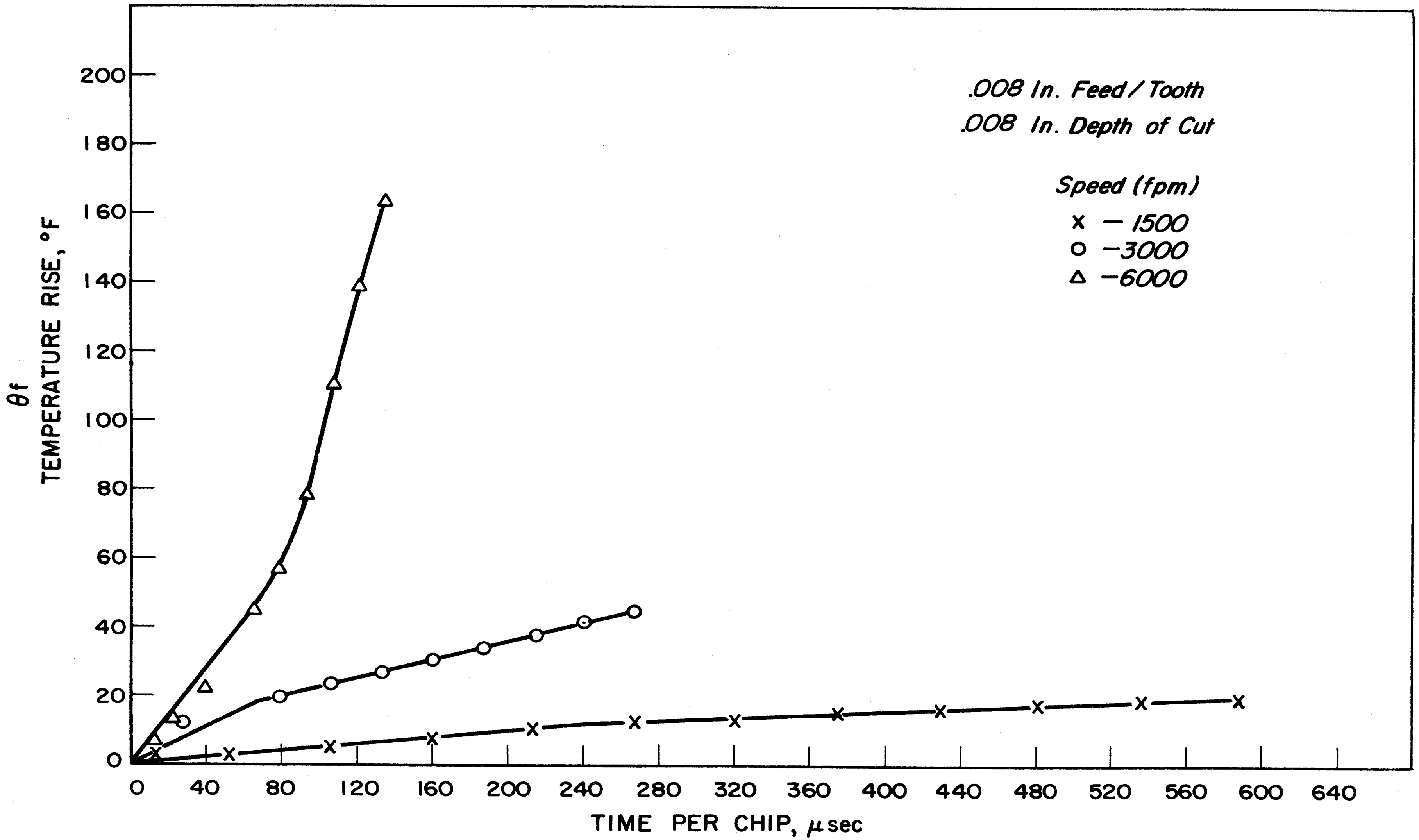


Fig. 26. Temperature rise vs. time per chip, .008 in./tooth feed: C-120.

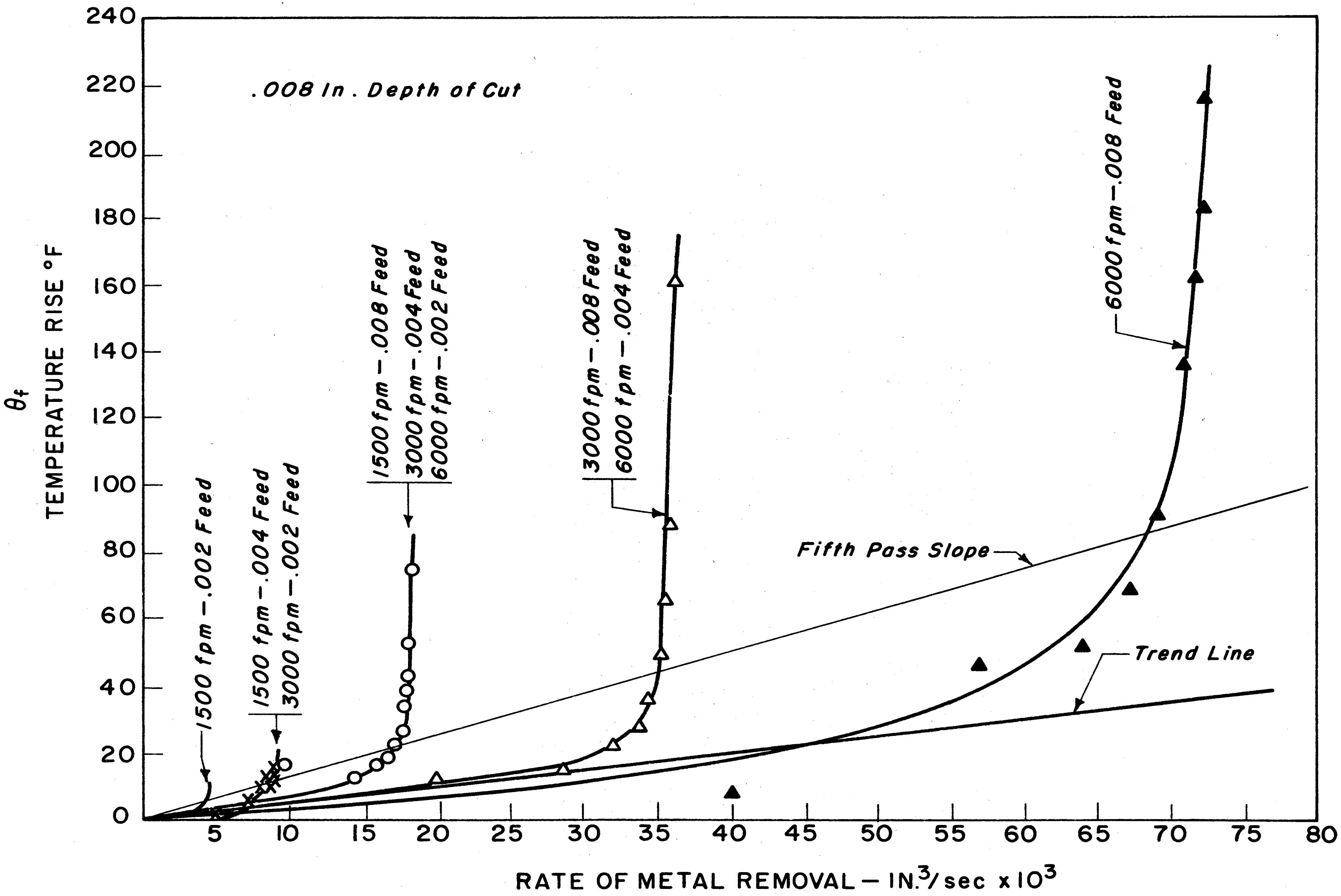


Fig. 27. Temperature rise vs. average rate of metal removal: A-110.

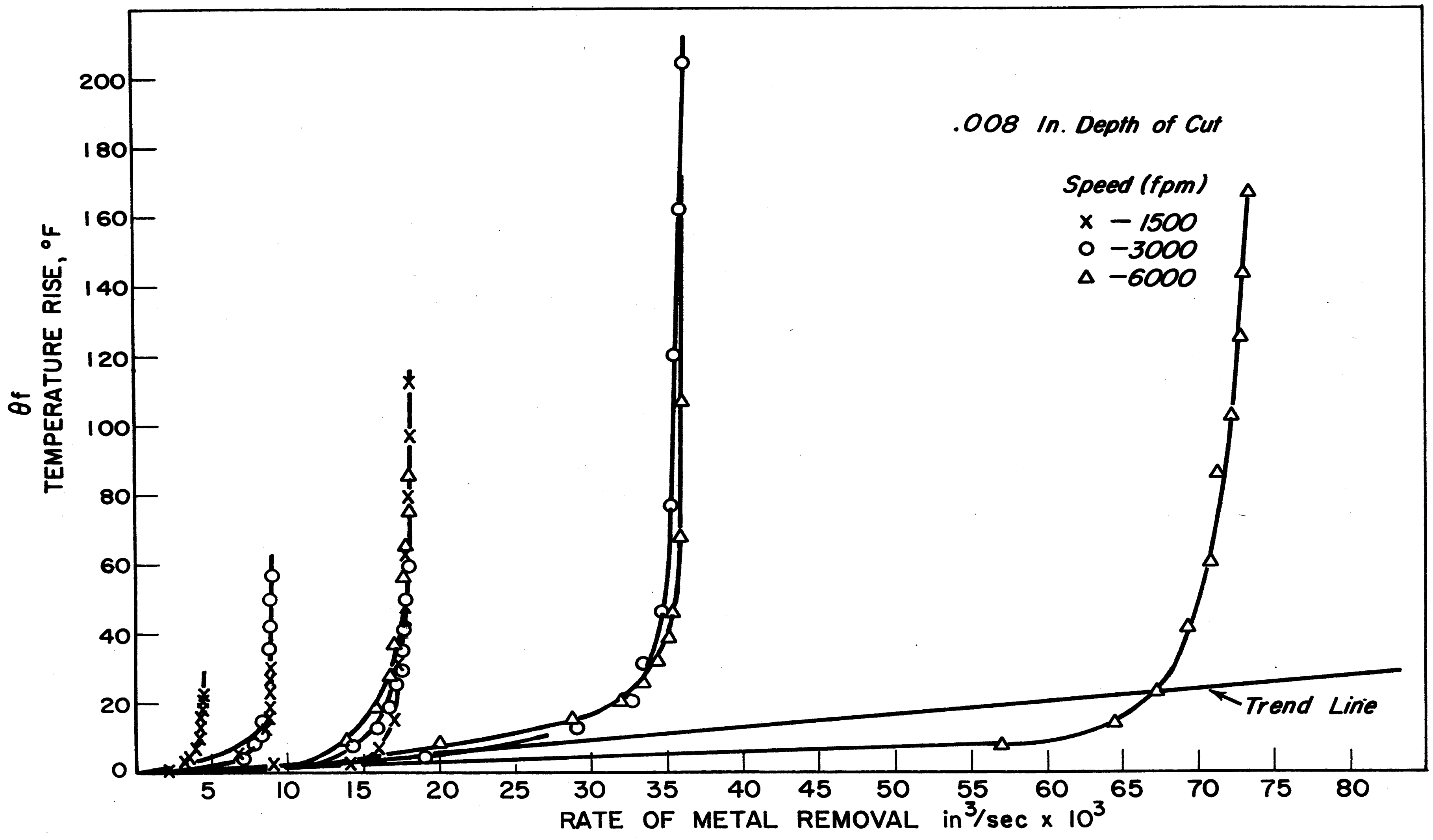


Fig. 28. Temperature rise vs. average rate of metal removal: B-120.

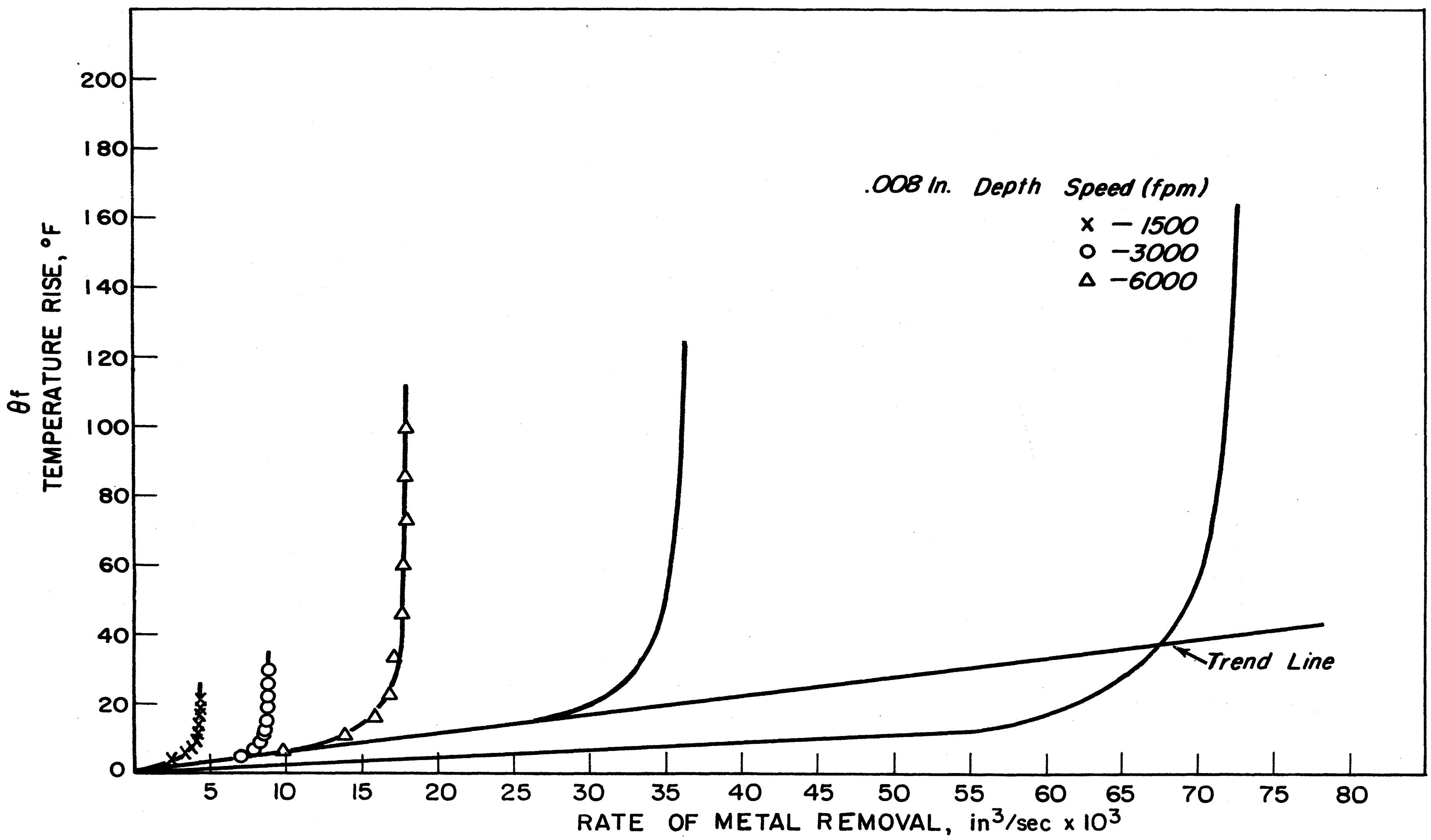


Fig. 29. Temperature rise vs. average rate of metal removal: C-120.

SERIES G

CUTTING FORCES

Description of the Measuring Device:

A Kistler Model 910 and an electrostatic charge amplifier Model 566 were used to measure the rapidly varying forces.

The load cell was very compact and was positional between a supporting block and the bottom of the tool holder. The cell has a resolution of 0.01 lb and a maximum load capacity of 5000 lb. The maximum deflection at full load is less than 0.001 in. It has 0.1% linearity with signal rise time of 5 µsec.

The Kistler 566 Electrostatic Charge Amplifier changed the electrostatic charge of the quartz transducer to a voltage signal compatible with the input requirements of the Tektronix Model Oscilloscope. Both load-cell and accelerometer signals for single cuts were photographed along with a 10-kc time reference. A Polaroid camera was used for this purpose.

Test Conditions:

Specimen

Material	Size	Crest Lengths	Position
B-120 C-120	.456 x 2 x 1-1/2 in.	0.0 in. with sharp point	Rotated with chuck

Tool Holder

Holder No.	Position
Kendex SN 4 KSFL 85A	Locked stationary in tool holder block

Tool

Tool Material	Tool Geometry	Position
Carboloy	.030 radius at corners	40° to the specimen

Cutting Conditions

Velocity, fpm	Feed/Tooth, in.	Depth of Cut, in.
1500 (1000 rpm)	.002, .004, and	.008
3000 (2000 rpm)	.008 for each	.008
6000 (4000 rpm)	velocity.	.008

Procedure:

The load cell was positional between the bottom of the tool holder and a supporting block (see Fig. 30). The cell was then calibrated by hanging dead weight on the tip of the tool. The results were linear as shown in Fig. 31. The conversion factor was 11 pounds of force per centimeter of oscilloscope deflection with the gain settings indicated.

Ten to twelve passes were made across each specimen, during which time three photographs were taken per specimen. These pictures contained an identification label, a trace of known frequency from the signal generator, traces of both the vibrations and the force transducers at 2X sweep magnification, and another set of traces at 10x sweep magnifications.

Results:

The results are presented and discussed in the main body of this report.

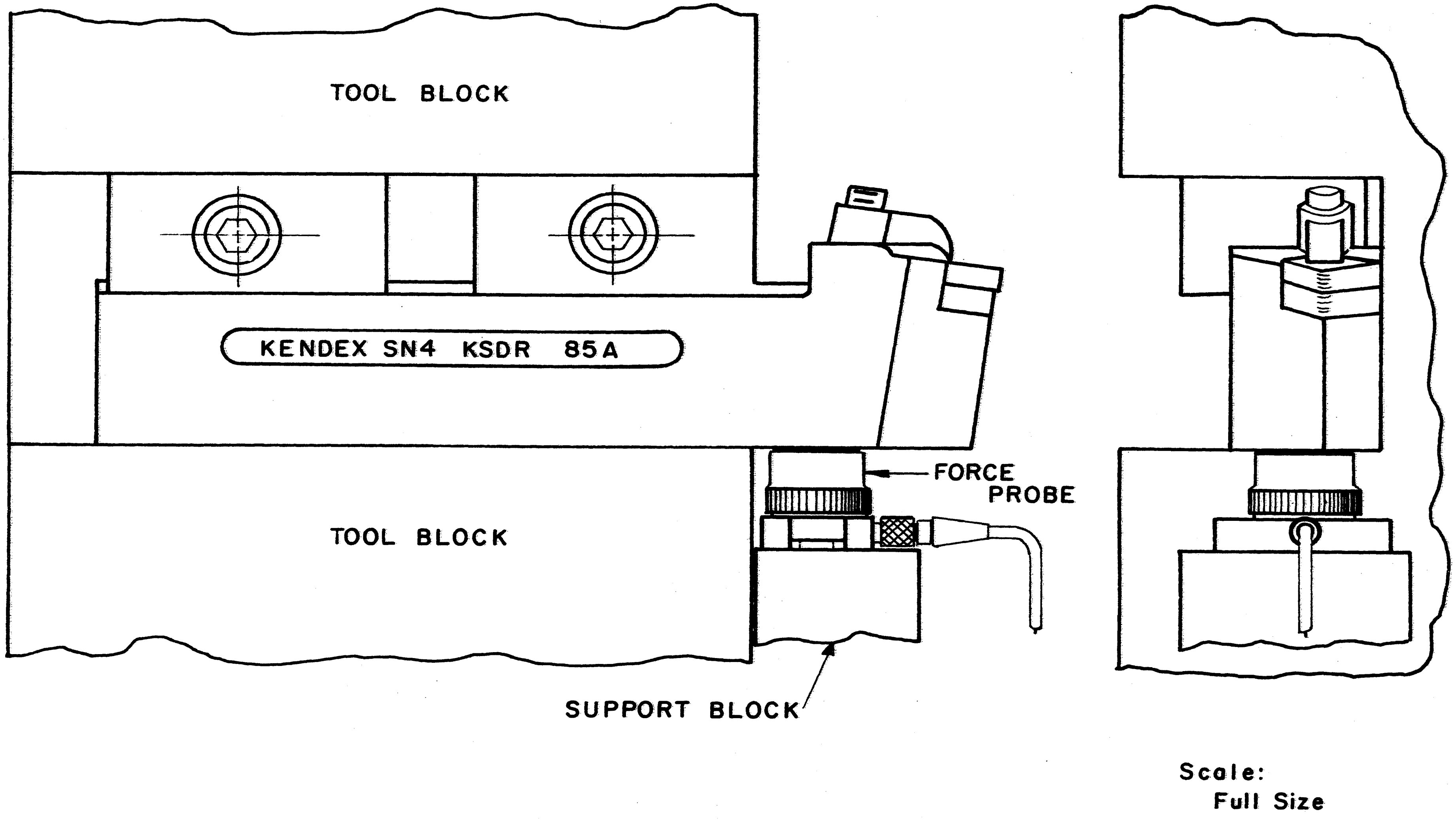


Fig. 30. Tool holder and force probe.

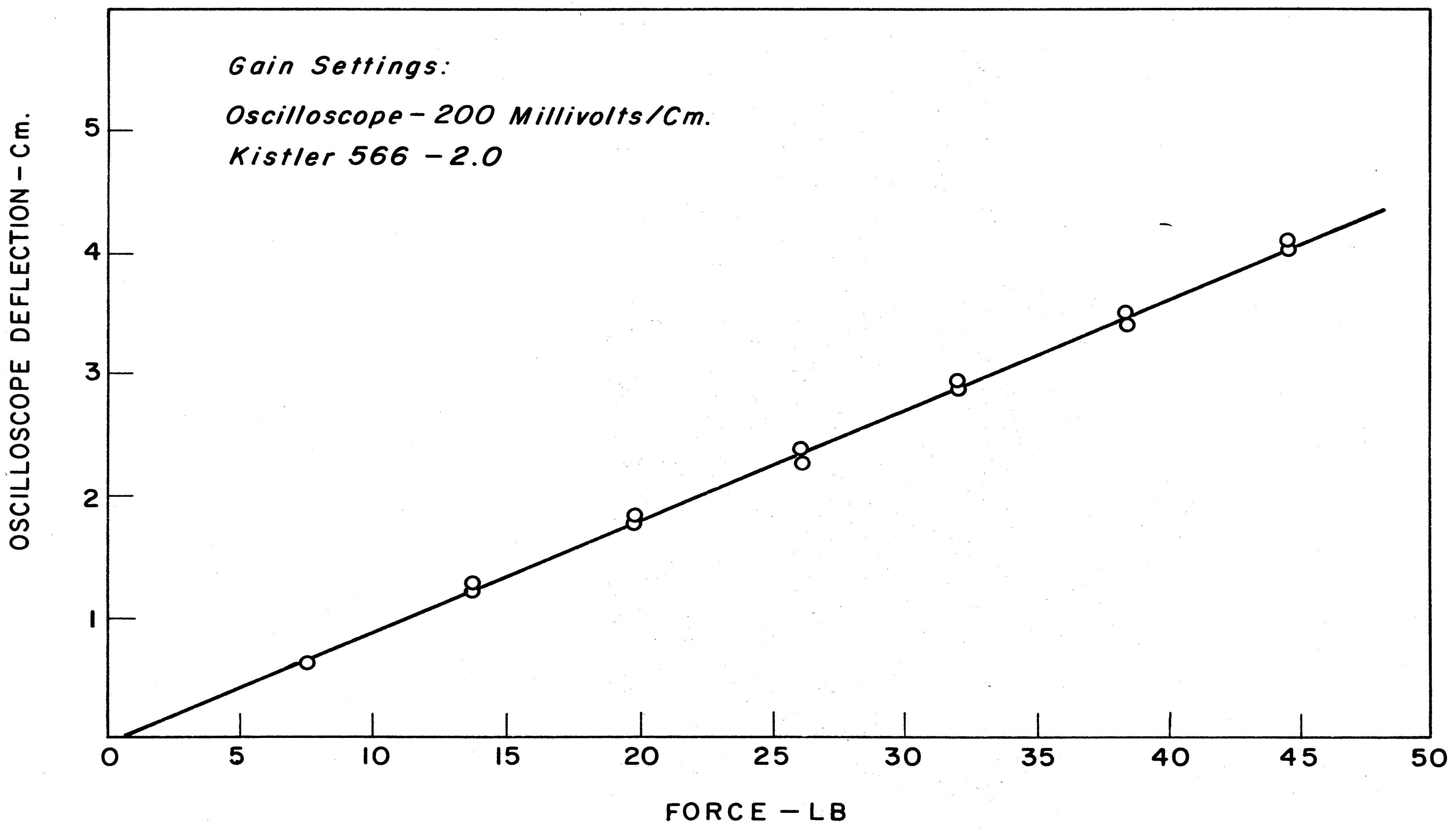


Fig. 31. Calibration curve - force transducer.

SERIES H

MICROMILL STUDIES

Objective:

The objective of this study was to try out the principles or conclusions derived from the earlier tests. In brief, these indicated that it is better to cut metal at low speed and large size of cut than at high speeds and correspondingly smaller cuts. Superimposed over the whole problem is the fact that tool wear in interrupted cuts can be minimized by reducing the time that a cutting tool is exposed to cutting temperature. This must be achieved through an appropriate balance between high surface speeds and small depths of cut.

The net result is a process appropriately called micromilling. It lies between grinding and orthodox milling in terms of operational characteristics. It is similar to grinding in that surface speeds and feed rates are high and depths of cut are low. It is similar to orthodox milling in cutting action and type of cutting tool.

Experimental Conditions:

Three somewhat different cutters of this type were investigated in this study. One was a special design as shown in Fig. 32. Two were standard catalog items as produced by the Severance Tool Co. of Saginaw, Michigan. One standard cutter with a high helix angle is illustrated in Fig. 33.

The cutting conditions and general observations are summarized in Tables VIII to X inclusive for the respective tungsten carbide cutters. Ranges of speeds, feed, and depth of cut were explored without any resharpening of the cutters because of lack of facilities. Consequently, no reliable information could be obtained on rate of tool wear. Instead, observations were made of indications of adverse conditions such as high temperature, smearing of tools or work surface, and unfavorable chip formation.

Results:

Several conclusions were made possible by these tests. The most important is that relatively high cutting speeds can be accompanied by very high feed rates even when cutting titanium alloys. The feed rate was extended to the maximum capacity of the experimental machine, 230 in. per minute.

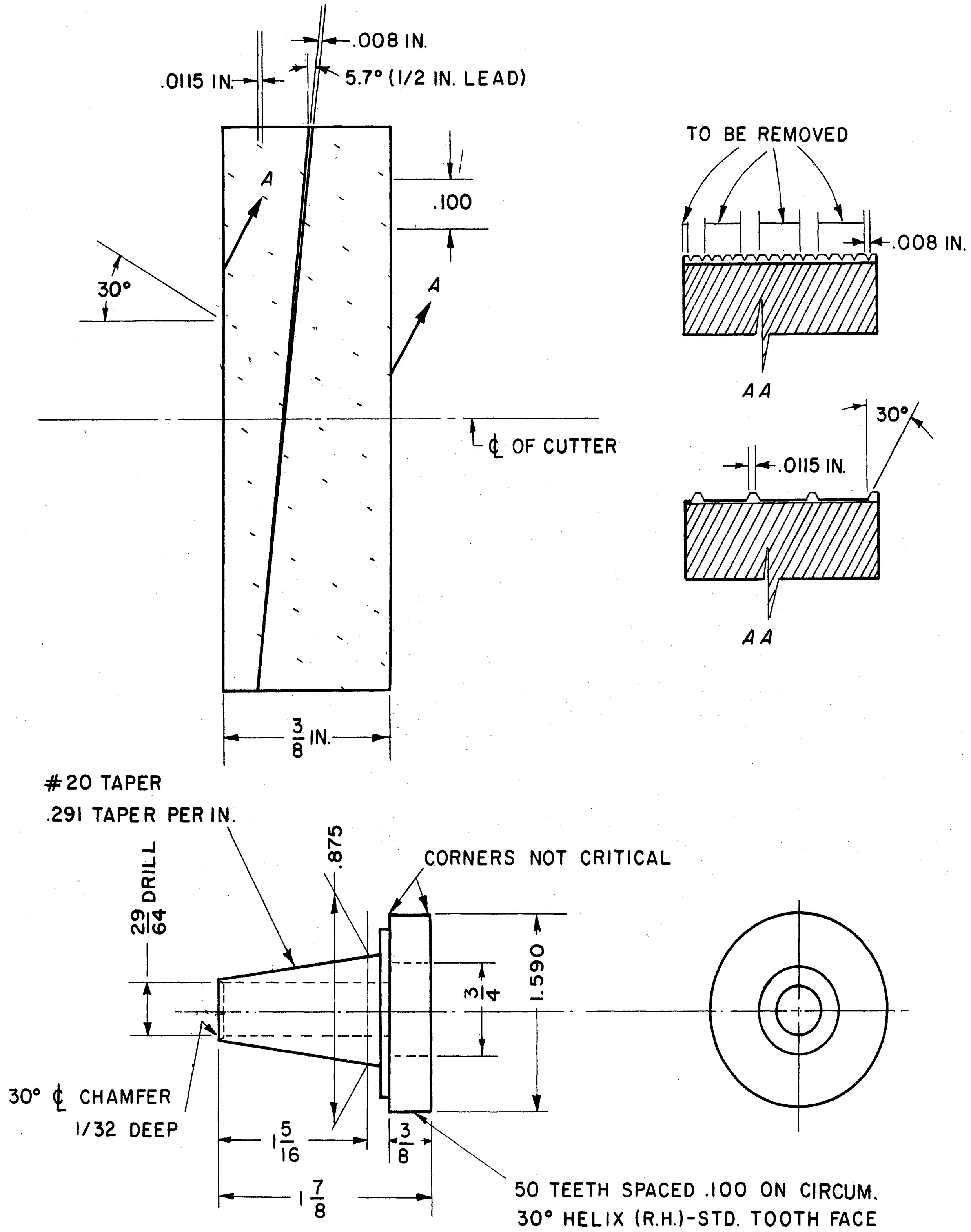
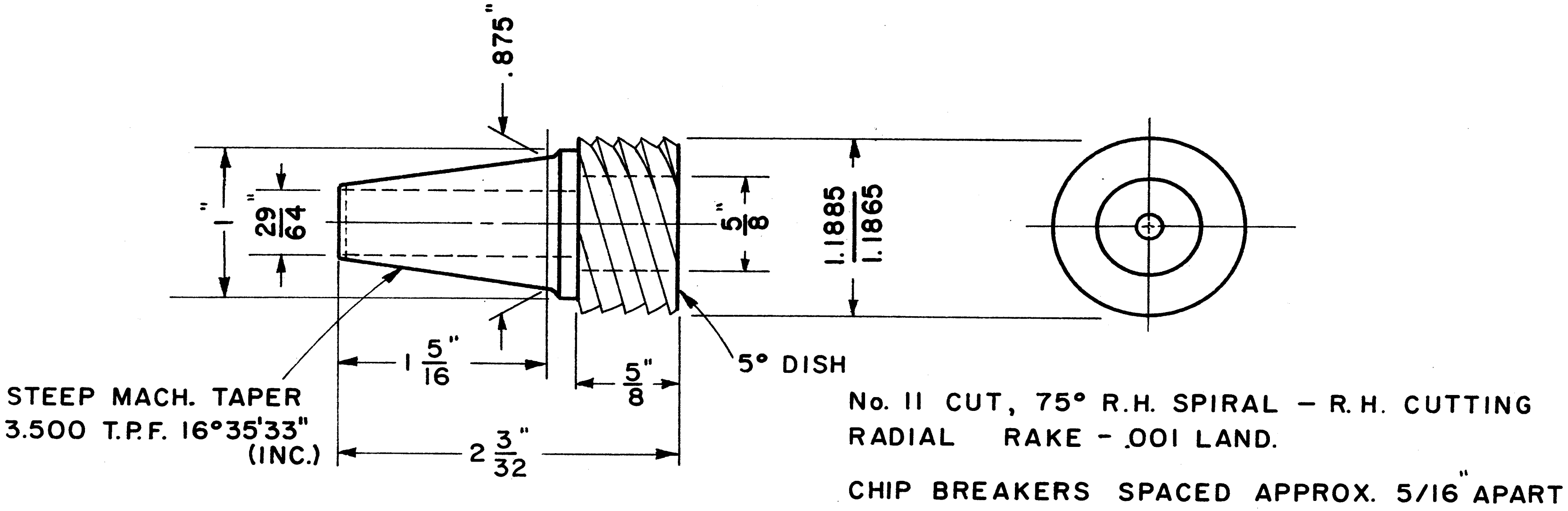


Fig. 32. Special micromill.



No. 11 CUT, 75° R.H. SPIRAL – R.H. CUTTING
RADIAL RAKE - .001 LAND.

CHIP BREAKERS SPACED APPROX. 5/16" APART

Fig. 33. Profile cutter.

TABLE VIII

SPECIAL MICROMILL-MC-929-W
(1.590 in. Diam; 50 Flutes; 5 Teeth)
(Slab-Milling Only)

Specimen Material	Pass No.	Speed rpm	Speed fpm	Feed ipm	Depth in.	Cutting Time μsec	Chip Thickness	Observations
A-110	1	2000	840	230	.012	815	.0042	No evidence of heat Good surface finish
	2	2000	840	230	.012	815	.0042	No evidence of heat Good surface finish
	3	4000	1680	230	.012	408	.0021	Very low red around cutter—finish good no heat
	4	4000	1680	230	.012	408	.0021	White sparks Good finish
C-120	1	2000	840	230	.012	815	.0042	Good finish No discoloration
	2	2000	840	230	.012	815	.0042	Good finish No discoloration
	3	2000	840	230	.012	815	.0042	Good finish No discoloration

TABLE IX

HIGH HELIX, 7 TOOTH, MICROMILL-PC-61-814-W
(1.18-in. Diam)

Operation	Specimen Material	Pass No.	Speed		Feed	Depth	Cutting Time	Chip Thickness	Observations
			rpm	fpm	ipm	in.	µsec		
Slab-milling	C-120	1	4000	1240	115	.012	550	.0017	Dull red cutter Chips & finish OK
Slab-milling		2	2000	620	32	.012	1100	.0034	No discoloration
Slab & end-mill		3 Forward & return	2000	620	230	.012	1100	.0034	No discoloration
End-mill	C-120	1	2000	620	230	.010	920		Finish rough No smear
End-mill	A-110	1	2000	620	115	.010	920		Broken teeth
Slab-milling	C-120	1	2000	620	230	.012	1100	.0034	Good finish
		2	2000	620	230	.012	1100	.0034	Good finish
		3	2000	620	230	.012	1100	.0034	Good finish
		4	2000	620	230	.030	2700	.0053	Dull red around cutter Chips & finish—good
		5	2000	620	115	.030	2700	.0027	Dull red around cutter Chips & finish—good

TABLE X

SLAB-MILLING WITH STANDARD MICROMILL-MC-928-W
(20 Teeth; 1.590-in. Diam)

Specimen Material	Pass No.	Speed		Feed	Depth	Cutting Time	Chip Thickness	Observations
		rpm	fpm	ipm	in.	µsec		
70-30 Brass	1	2000	840	230	.030	1300	.0016	Clean surface
	2	4000	1680	230	.030	650	.0008	Clean surface
	3	8000	3360	230	.030	325	.0004	Clean surface
Aluminum	1	2000	840	230	.030	1300	.0016	Clean surface
	2	4000	1680	230	.030	650	.0008	Some smear
	3	8000	3360	230	.030	325	.0004	Heavy smear
A-110	1	2000	840	230	.030	1300	.0016	
	2	4000	1680	230	.030	650	.0008	Some sparking
	3	8000	3360	230	.030	325	.0004	Dull red around entire cutter circumference during cut
A-110	1	2000	840	230	.012	815	.0010	Dull red around cutter Some smear
	2	2000	840	230	.012	815	.0010	
	3	2000	840	230	.012	815	.0010	Dull red around cutter Good finish
	4	2000	840	230	.012	815	.0010	Dull red around cutter

Almost as important is the conclusion that it is better to cut at greater chip thickness and lower speed for the same maximum feed rate. This was predicted by the temperature data shown in Figs. B, C, and D in the main body of the report.

Chip disposal also appeared as a very important problem, particularly when cutting titanium, which produces unusually long chips which in turn weld and cling to the cutter teeth despite high centrifugal forces. If there is insufficient space to accommodate the chips, they will jam up in the flutes and produce excessive overheating from the resultant rubbing with the machined surface. Tool failure can be almost instantaneous when this occurs.

The chip-disposal problem can be eased through proper cutter design and selection of appropriate cutting conditions. It is significant that chip disposal is better with thick chips than with thin ones. In other words, the problem is aggravated by light feed rates. The length of the chip also is critical. For this reason, it is necessary to limit the number of teeth in a cutter and to design the teeth to provide for chip flow along the flute as well as across it. It is possible to alleviate the chip problem further through the use of cutting fluids, dry lubricants, or even with ultrasonic vibrations.