THE UNIVERSITY OF MICHIGAN
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Department of Mechanical Engineering

Final Report for Phase II

METAL CUTTING WITH SUPERIMPOSED ULTRASONIC VIBRATIONS

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ABSTRACT

The purpose of this investigation was to follow up some earlier studies of the superposition of ultrasonic vibrations on metal cutting with the further objective of evaluating its usefulness for turning. The results show that substantial improvement in chip formation, surface finish, cutting forces, and tendency to chatter can be achieved at low cutting speeds where these properties normally are not satisfactory without superimposed vibration.

Most of the experiments in this study were carried out with orthogonal cuts but the results are applicable to conventional turning. The advantages to be gained by vibrating are obtained most readily and most extensively only when the superimposed motion is in the direction of cutting velocity. Vibration perpendicular to the work surface may improve the chip formation but larger amplitudes cause the cutting forces to increase and surface finish to deteriorate.

When vibrating the tool in the direction of cutting velocity, it was found necessary to vibrate at amplitudes sufficient to cause a gap between the chip and tool during much of each cycle. Consequently the benefits of ultrasonic vibration are limited to the lower levels of cutting speeds. The apparent power component of cutting force was reduced from 70 to 90% for a group of common metals ranging from brass and aluminum through copper to stainless steel. Similarly the forces for tungsten, molybdenum, Rene 41, and hardened 4340 steel were reduced from 50 to 74%. The influence of size of cut and cutting speed are analyzed for cutting free cutting grades of brass and aluminum.

INTRODUCTION

This study was essentially an extension of earlier investigations both here and abroad which showed that superposition of ultrasonic vibrations on metal cutting could exert substantial influences on forces, finish, and chip formation. In 1963 Skelton and Tobias[1] summarized the results obtained by four different groups of Soviet investigators.[2-5] One group[3] reported that tool life of high speed steel was decreased with relatively large amplitudes of vibration at 22 kcs but that the tool life increased by as much as four to five times as that without vibration as the amplitude was decreased; vibration was in the radial direction in a turning operation on a creep-resisting alloy. This same group reported a consistent decrease, however, when using carbide tools.

Another group[4] reported substantial decreases in cutting forces and increase in cutting temperature and concluded that it was best to vibrate in the tangential or cutting direction. The amount of reduction in cutting force appeared to diminish toward zero as the cutting speed approached about 220 fpm. Further, all three components of cutting force both with and without vibration seemed to vary somewhat erratically as the cutting speed was changed.

As a consequence of these and similar results, it was decided to restudy the question of direction of vibration and to try to obtain more fundamental information on the nature of the influence of these vibrations particularly as it might relate to the amplitude. The decision was made to study these factors in orthogonal cutting and then to spot check them in turning.

Early attempts at controlling amplitude simply through control of input power were unsuccessful because of unpredictable changes in resonant frequencies arising out of both temperature change within the transducer and unpredictable changes in coupling between the cutting tool and the workpiece. Later attempts to monitor continuously the amplitude of vibration in the direction of attempted motion were highly successful. Consistent relationships were developed between amplitude on the one hand and the influence of cutting speed and feet rate on the other. Although this method of continuous monitoring of amplitude did bring about a substantial improvement in observations and measurements, it was not completely successful since it did not completely describe the real motion of the tool in three-dimensional space as will be explained later.

Results obtained early in this investigation confirm the conclusions of the Soviet group[4] to the effect that vibration in the tangential direction gives the best overall results. Vibration in either the feeding direction or radial direction in turning can produce substantial deterioration in surface finish and more than 100% increase in cutting forces at relatively large amplitudes even though there may be some modest improvement in surface finish, in chip formation and a small reduction in cutting forces at somewhat lower amplitudes.

Ultrasonic vibration in the tangential direction has succeeded in reducing the power component of cutting force by as much as 90% and the feeding component by nearly 100%, although the latter was at such a low level as to make it difficult if not impossible to measure accurately. These of course are the forces as measured by a dynamometer which cannot sense the real instantaneous forces because of the very substantial mass attenuation of the dynamometer itself. However, it does mean that the magnitudes of the forces which are imposed on the machine tool system are indeed substantially reduced.

It was observed further that the low frequency oscillatory component of the cutting force is substantially reduced by the ultrasonic vibration. It was found also that the reduction of the oscillatory component was accompanied by a much lower tendency toward chatter. Consequently, one of the more significantly potential benefits of superimposed ultrasonic vibration is the feasibility of at least inhibiting and perhaps even eliminating chatter.

Both chip formation and surface finish can be improved substantially by ultrasonic vibration in the tangential direction. These improvements are most pronounced at the lowest cutting speeds, but both tend to diminish and eventually to disappear as the cutting speed is increased toward a relatively high but critical level.

One appropriate application of superimposed ultrasonic vibrations on metal cutting might be either plunge forming or cut off of a soft ductile metal like copper or low carbon steel wherein the cutting speed must be relatively low. At low cutting speeds the chip formation and surface finish generally are unsatisfactory and there is a strong tendency toward chatter. In an application of this type more uniform chip formation and the lower cutting forces would be conducive to better size control as would the improved surface finish. For such applications to be realized within the production shop, however, it appears necessary to design better vibration transducers and to provide closed-loop control for both frequency and aplitude of vibration.

Another possible application would be for finishing tools on numerically controlled machine tools when chatter influences the critical parameters of size control and surface finish.

THE EXPERIMENTAL SET-UP AND TEST PROCEDURE

All of the mechanical and electrical equipment used in these studies is illustrated in Fig. 1. A large (No. 5) horizontal spindle, knee and column-type milling machine was equipped with a three component force dynamometer mounted on the table. A combination magnetostrictive transducer and ultrasonic transformer or horn which served also as the cutting tool is mounted on top of the dynamometer. The transducer shown opposite the end of the horizontal spindle was driven by a "Cavitron" generator rated at 300 watts of output power. The generator is shown at the lower left in the figure with the frequency counter setting on top of it.

Average values of the three components of cutting force were continuously recorded on three of the four available channels of the carrier-amplifier recorder shown at the right in Fig. 1. The dynamometer was equipped with semiconductor strain gages and gave an overall sensitivity somewhat better than 1/4 lb/mm of pen deflection on the strip chart.

A non-contacting, inductive type pick-up system was used for continuous monitoring of the motion of the cutting edge in a direction essentially parallel to the axis of the transducer. This motion along with the exciting frequency was monitored continuously on the dual-beam oscilloscope shown in front of the milling machine. The amplitude of the motion of the cutting edge also was continuously recorded in the fourth channel of the four-channel recorder.

Figure 2 is a close-up picture showing the cutting edge in position ready for cutting on the end of a tubular-shaped specimen mounted in a collet. In contrast to Fig. 1 the magnetistrictive transducer and the cutting edge have been rotated down into a horizontal position where they were used to provide ultrasonic vibration in the feeding direction. Feeding was provided by motion of the saddle parallel to the axis of rotation of the work specimen.

The fixture in which the cutting tool-transducer combination was mounted made possible the use of this combination for vibrating in both the horizontal and vertical directions. When the assembly was rotated into the vertical direction, that surface of the tool which is rake face as shown in Fig. 2 then became the relief flank and vice versa.

In addition the assembly shown in Fig. 2 also can be pivoted about a vertical axis to provide vibration in a radial direction for a turning cut and then rotated into a vertical position for vibration in a tangential direction during a turning cut. Adjustment of the milling machine table so as to translate the center line of the rotating workpiece to one side of the cutting tool also made it possible to vibrate in the feeding direction on a turning cut.

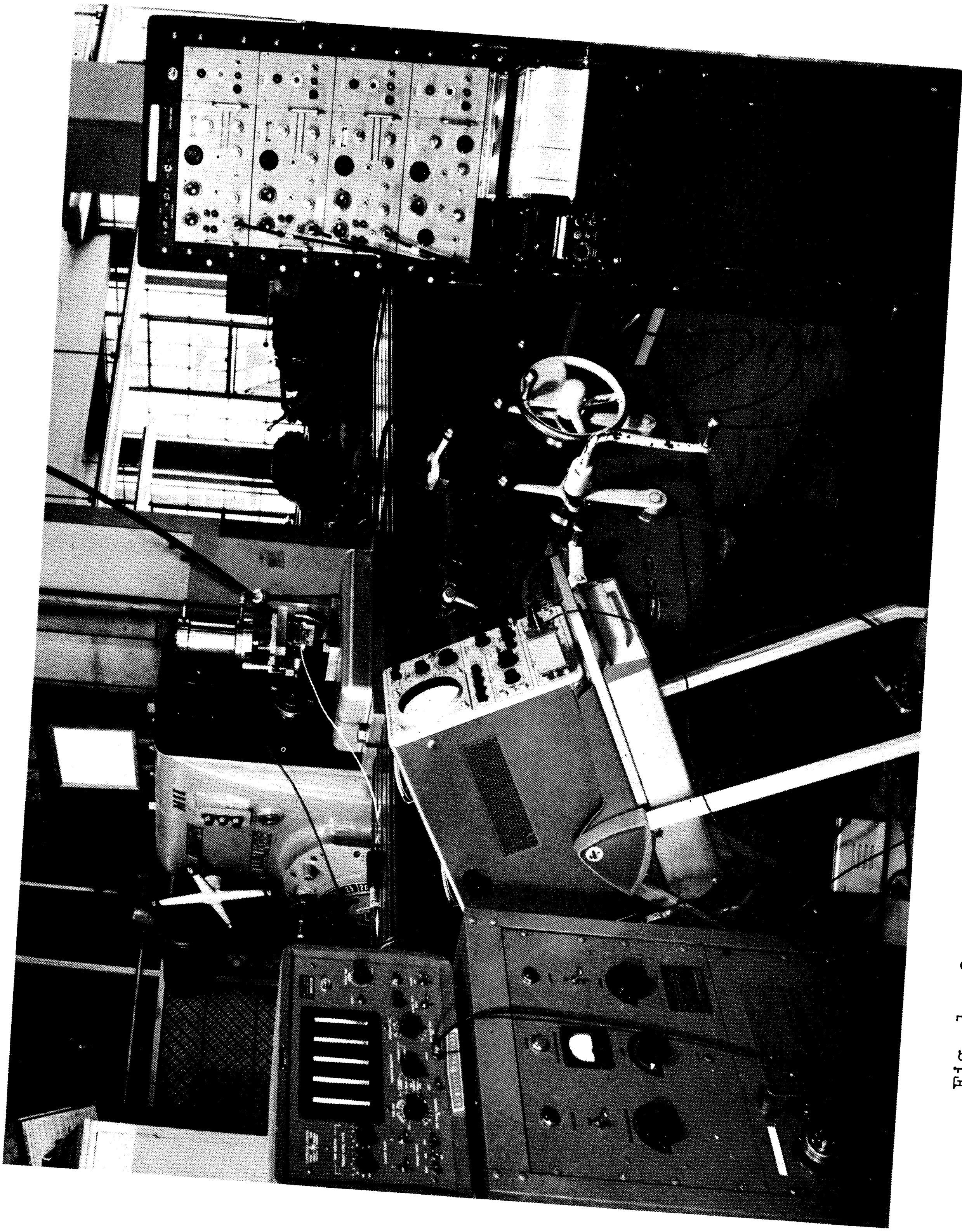


Fig. 1. Overall view of machine and instrumentation arrangements.

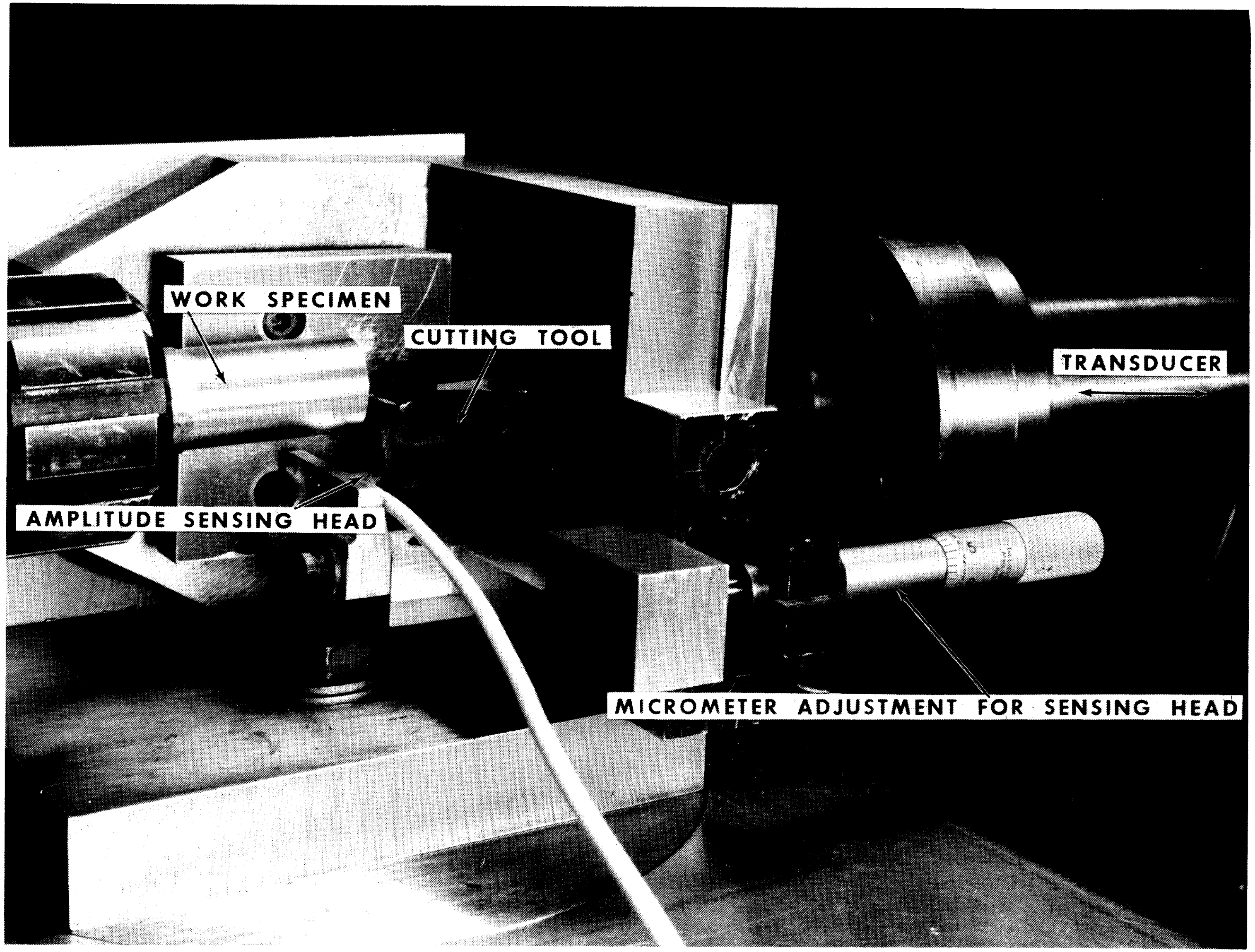


Fig. 2. Close-up view of specimen with tool positoned for vibrating horizontally in feeding mode.

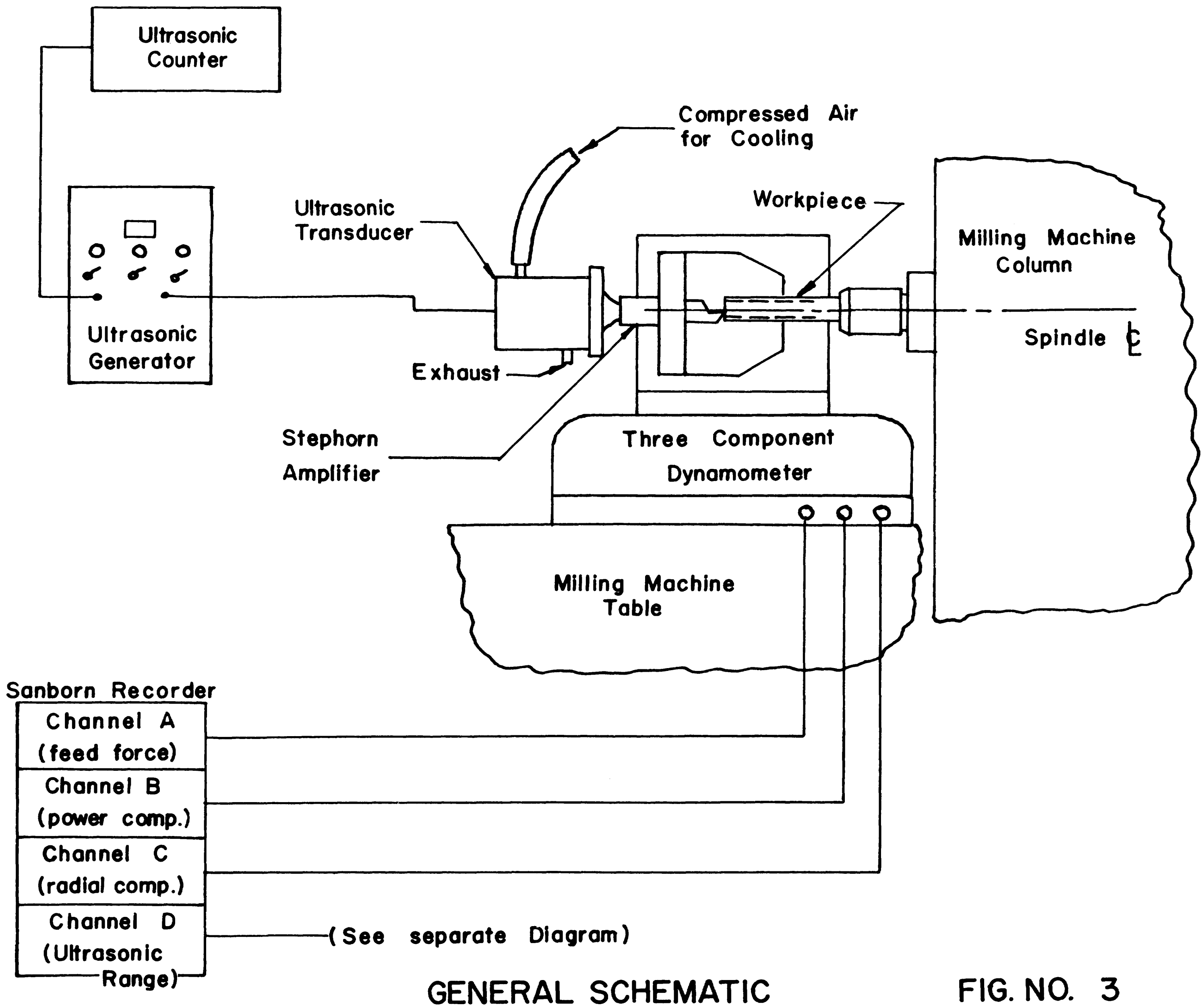
Figure 2 also illustrates details of the vibration-amplitude monitoring system. The light colored cable near the lower center in Fig. 2 connects to a non-contacting spiral inductive coil opposite the flank of the cutting tool. This coil in turn is mounted on a hinged lever system in contact with the spool of a conventional micrometer so as to permit direct calibration in place on the dynamometer assembly. An optical microscope equipped with a Filar eye-piece was used to calibrate this system at the ultrasonic frequencies. It was found that the electrical attenuation at these frequencies was of the order of 50%. The electrical gain of the oscilloscope could readily be set so that 1 cm of deflection on the oscilloscope tube represented 0.0001 in. of vibration range. Similarly the electrical sensitivity of the fourth channel of the strip recorder was adjusted so that 5 mm of pen deflection also represented 0.0001 in. of vibration range. Schematics of the mechanical equipment and the associated electrical instrumentation are illustrated in Figs. 3, 4, and 5.

CHARACTERISTICS OF THE ULTRASONIC SYSTEM

The magnetostrictive transducer and the associated combination horn and cutting tool constructed to go with it had not previously been used for superimposing ultrasonic vibrations on metal cutting. Consequently little was known at the outset as to the power and force capability of this unit except for prior knowledge that the generator had a rated output of 300 watts and that magnetostrictive transducers generally are assumed to be no more than 50% efficient in the conversion of electrical to mechanical energy. The data shown plotted in Figs. 6 and 7 are typical of some of the earlier evidence obtained on the nature of these characteristic limitations.

Figure 6 is a double-logarithmic plot of the percent power reduction versus the sustained level of power component of cutting force in the presence of ultrasonic vibrations. These data obtained for brass and aluminum for ranges of size of cut and cutting speed show that the ability of this particular transducer and power generator to achieve substantial reductions in spindle power begins to fall of substantially at sustained forces beyond the range of 30 to 40 pounds. This information was obtained for orthogonal cuts with vibration in the tangential direction and for a width of cut of 1/8 in. Based on this type of information subsequent cuts on higher strength materials were made on specimens with a smaller wall thickness.

Figure 7 gives a somewhat more accurate indication of the power limitations of the transducer, generator combination. This double logarithmic plot shows that the vibration amplitude as indicated by arbitrary units of oscilloscope amplitude drops off slowly but continuously as the sustained power component of cutting force is increased at full power output of the generator. As might be expected the maximum amplitude of the vibration drops off gradually with increased average cutting force which probably reflects a corresponding increase in the frictional energy which must be supplied by the



GENERAL SCHEMATIC

FIG. NO. 3

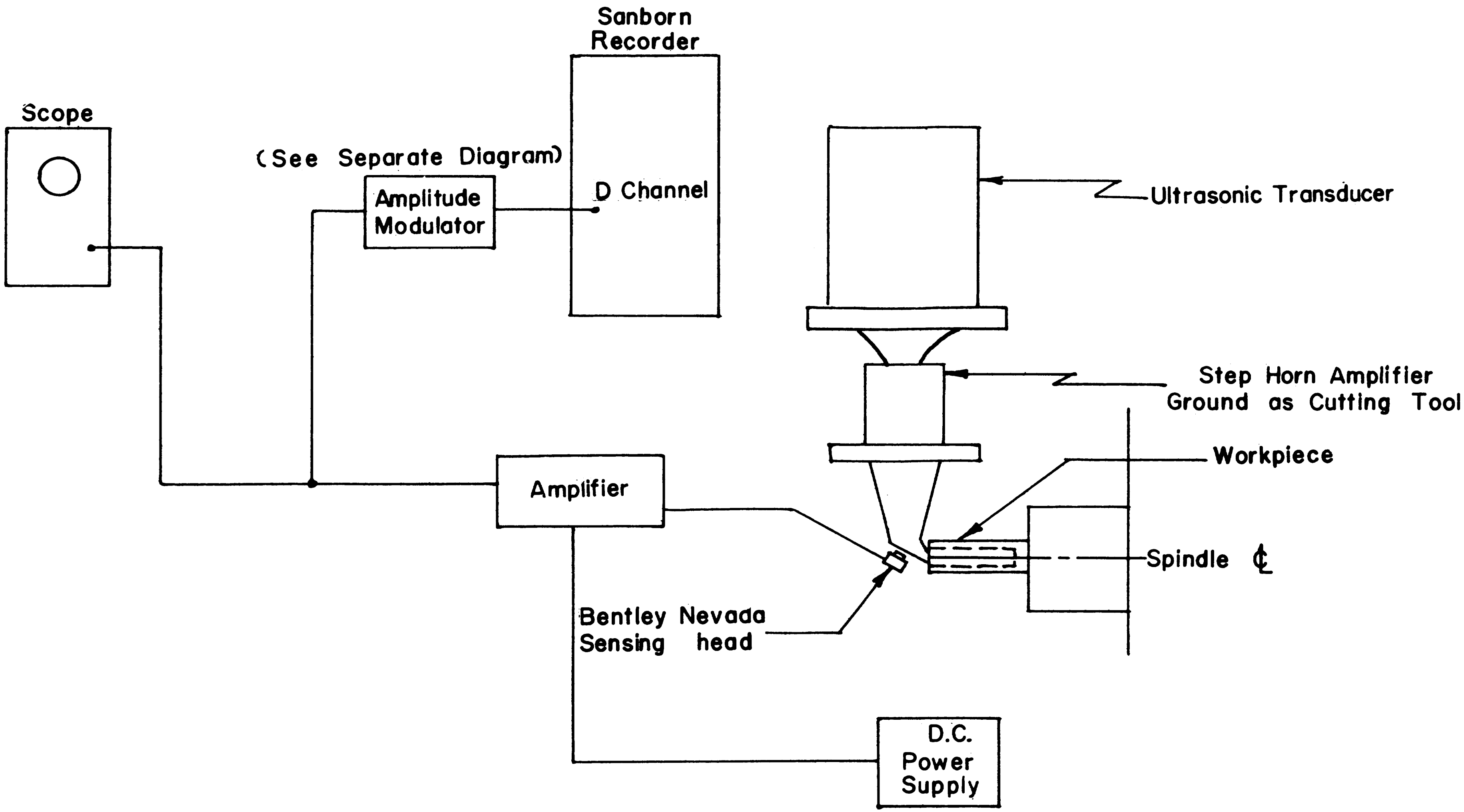
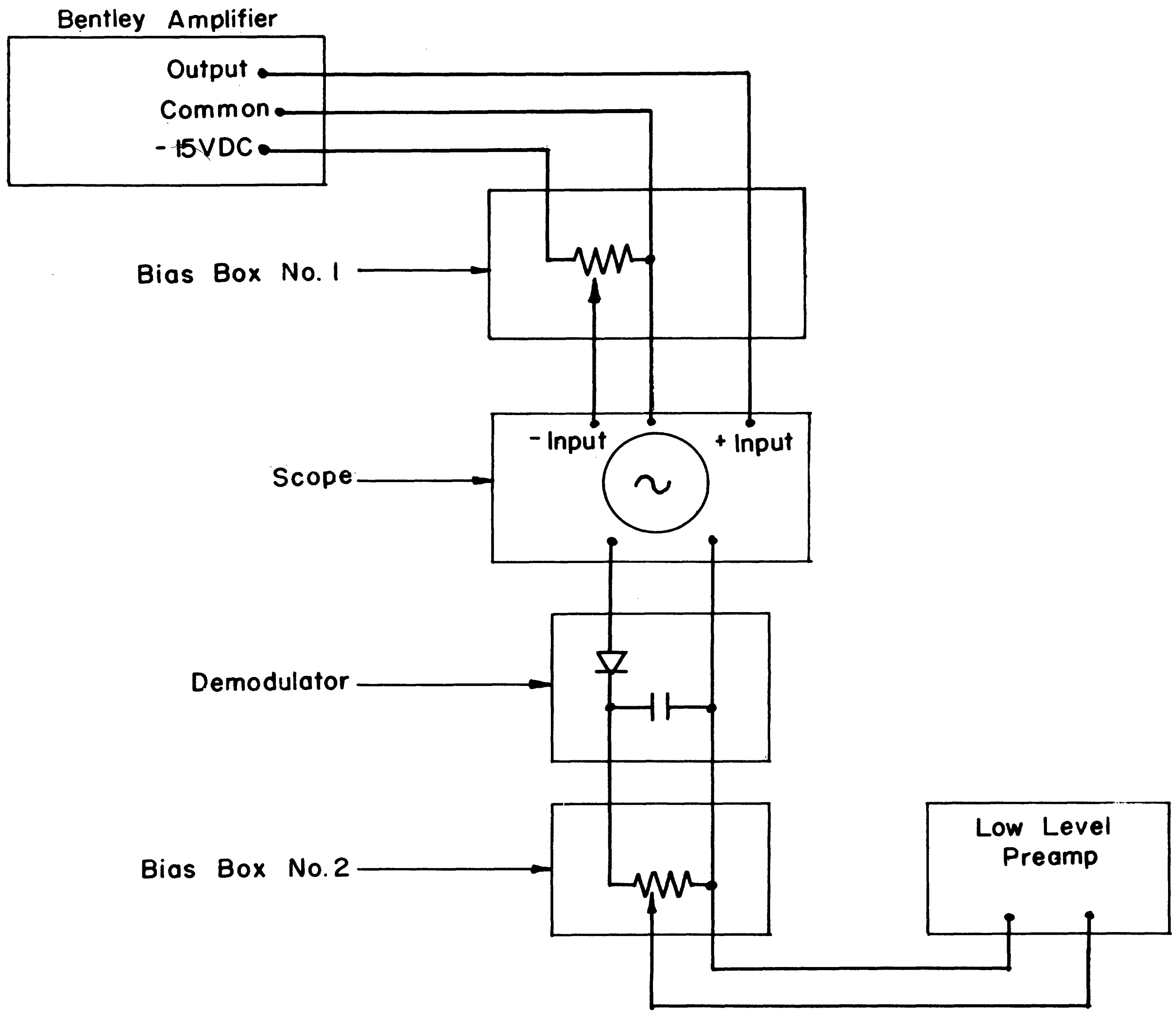


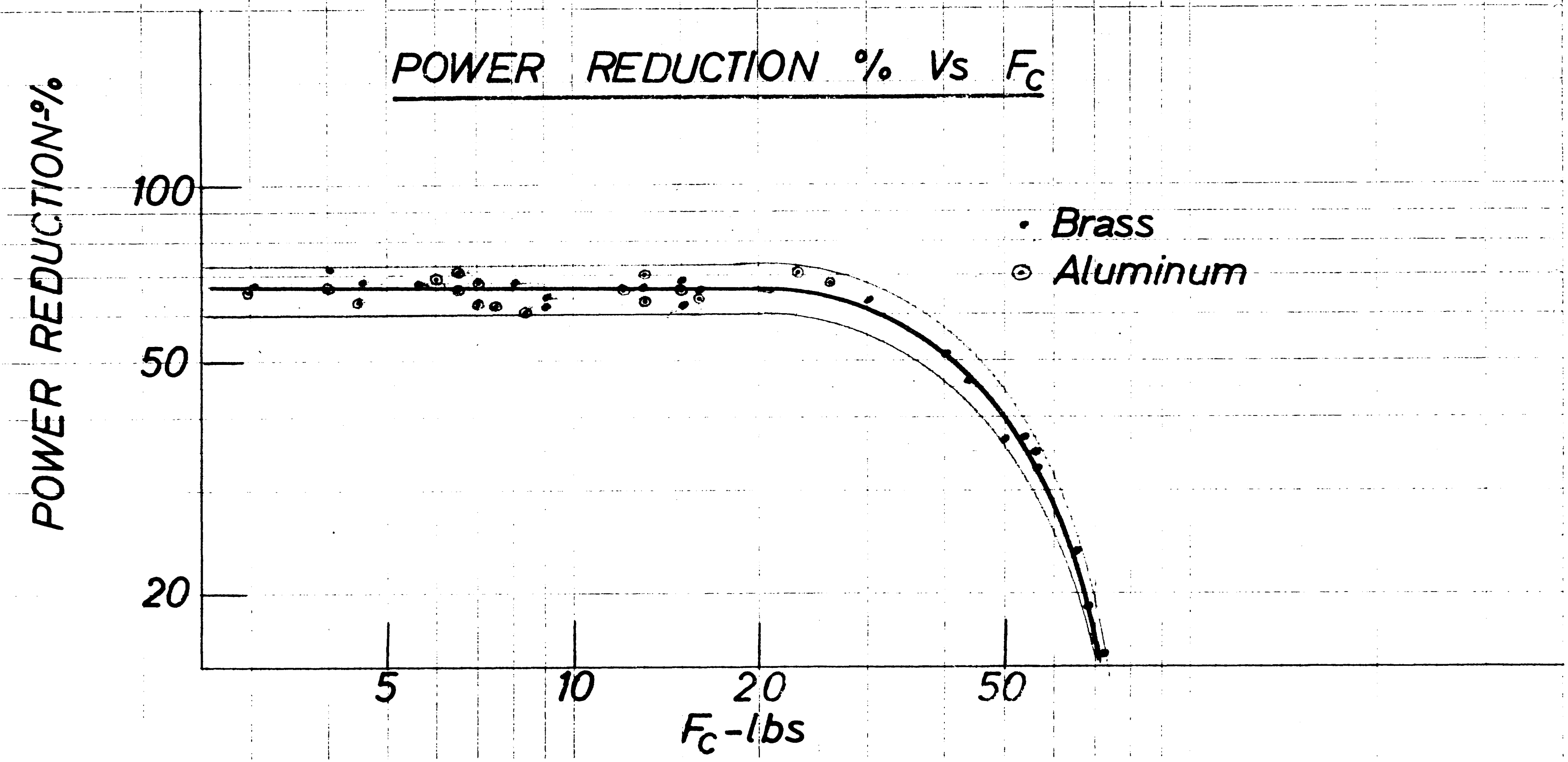
DIAGRAM OF VIBRATION MONITORING SYSTEM FIG. NO. 4

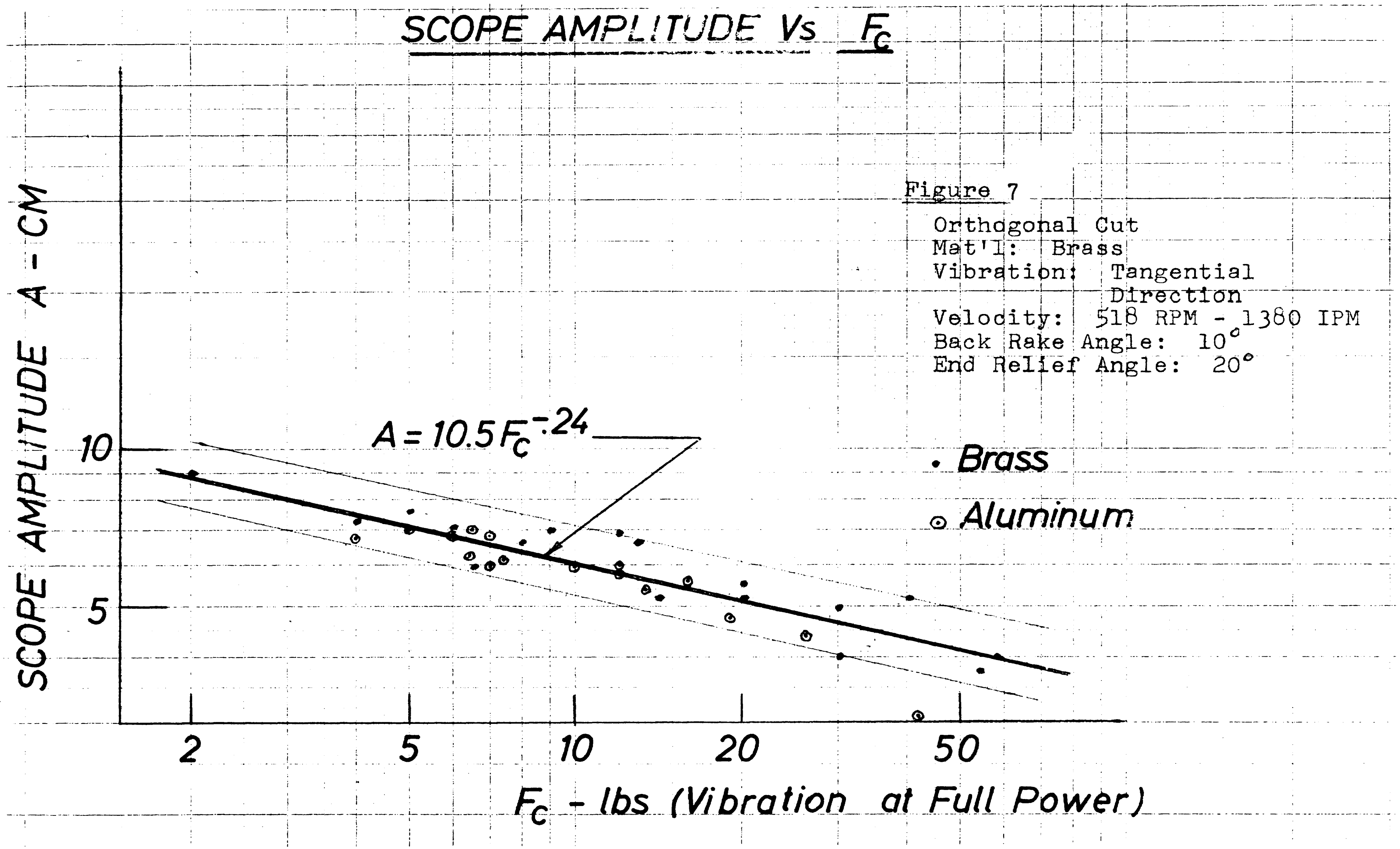


WIRING DIAGRAM FOR AMPLITUDE MONITORING FIG. NO 5

Figure 6

Orthogonal Cut
Mat'l: Brass
Vibration: Tangential Direction
Back Rake Angle: 10°
End Relief Angle: 20°





SCOPE AMPLITUDE Vs F_c
Figure 7
Orthogonal Cut
Mat'l: Brass
Vibration: Tangential Direction
Velocity: 518 RPM - 1380 IPM
Back Rake Angle: 10°
End Relief Angle: 20°
$A = 10.5 F_c^{-.24}$
• Brass
⊙ Aluminum
10
5
SCOPE AMPLITUDE A - CM
2
5
10
20
50
F_c - lbs (Vibration at Full Power)

transducer. This type of limitation was observed throughout all subsequent tests.

One of the more significant characteristics of the ultrasonic vibration of the cutting tool is illustrated schematically in Fig. 8. The conditions illustrated here are somewhat exaggerated so as to emphasize the fact that the real motions in any practical ultrasonic system seldom consist of motion in only one of the three Cartesian coordinate directions. Serious attempts may be made to confine the motion to but one Cartesian direction; however, lack of symmetry does give rise to at least small components of motion in the two other directions. Even small components in these other directions can exert substantial influence on the nature of the results as will be emphasized in this report.

Figure 8 illustrates the motion of the cutting edge as an elliptical path with the larger vertical motion being led by the smaller lateral motion by 90°. Just the opposite could have been true in which case the movement of the cutting edge about the elliptical path would be exactly opposite that shown by the arrow on the ellipse in the figure. If the two motions are exactly in phase, then the major axis of the ellipse would be inclined upward toward the right; whereas if they were 180° out of phase the same axis would be inclined upward toward the left. Obviously the nature of such behavior can have a profound influence on both the cutting forces and surface finish. Further, the existence of a component in a plane perpendicular to the figure also would have a substantial influence on the nature of the chip formation.

No attempt was made to measure these other components of motion during this particular study. However, it was evident that they did occur and in an unpredictable manner. This is believed to be due to oversimplification of the theory with regard to what happens at the stress node in an ultrasonic horn. All of the cutting forces were supported at this point, and it was evident that varying amounts of frictional energy were converted into heat. It was evident also that motion activity varied considerably from point to point around the horn at the stress node and point of support. Attention is called to evidence pointing toward these extraneous motions as the experimental results are presented and analyzed.

WORK SPECIMENS

All of the work specimens were in the form of 1 in. diam, round rods which were either cold rolled or cold drawn stock except for the high density tungsten which was recrystallized extrusion. These materials were held in a 1 in. diam collet with no more than 4 in. overhang in the extreme. Turning specimens consisted of solid bars on which a light clean-up cut had been made on the outside surface. Except for some of the higher strength materials all orthogonal cuts were made with tubular shaped specimens made from 1 in. diam bar stock.

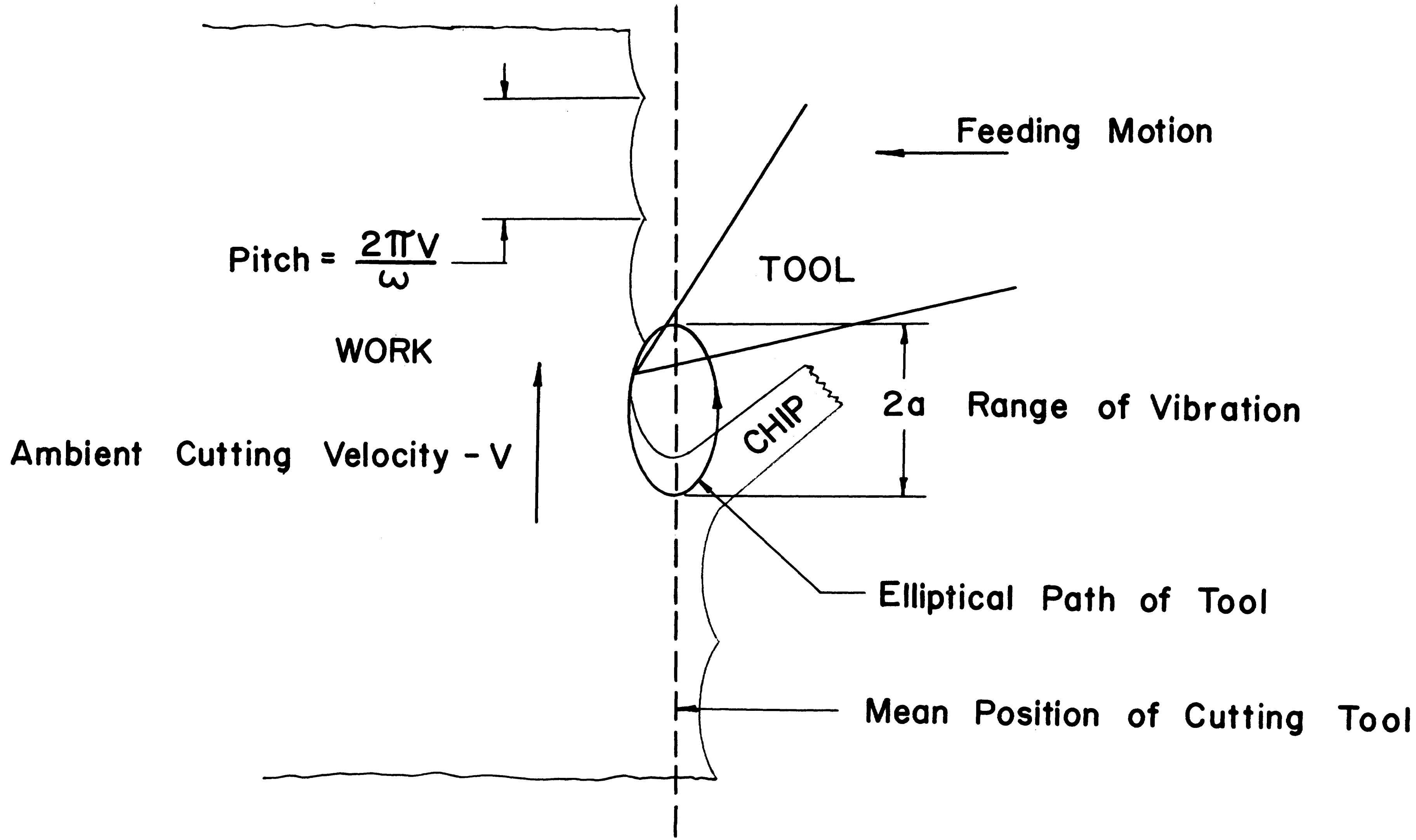


Fig. 8. Schematic motion of ultrasonically vibrated tool.

In the latter case the tubular shape was prepared by drilling and boring to a diameter of 0.750 in. for a depth up to 3.5 in. Some of the earlier specimens were used in this form while in later tests the outside diameter also was turned to 0.950 in. so as to leave a wall thickness of 0.100 in. In still other cuts the outside diameter was further reduced to produce a wall thickness of either 0.044 in. or 0.040 in. as will be noted in connection with the experimental data as presented.

TEST PROCEDURE

In the earlier stages the test procedure consisted of making a set-up and performing an initial cut without vibration at the specified feed and cutting speed. This was followed by cuts with and without vibration alternately at the programmed values of cutting speed and feet rate. Each cut was permitted to continue until the strip chart indicated that cutting forces had achieved equilibrium or until samples of the chips had been obtained where the latter required a greater length of time. Later it was discovered that the chip formation was sensitive as to whether or not the previous cut had been made with superimposed ultrasonic vibration. Consequently, tests late in the program were made wherein cuts without vibration were not interspersed with those with superimposed vibration.

At the outset of this investigation it was expected that standing waves in the workpiece might very well influence the nature of observed results. For this reason a series of tests were made with both brass and aluminum wherein the bored length of the specimen and the shank was varied both with and without vibration in an attempt to confirm or deny this possibility. No measurable evidence could be obtained on the existence of standing waves in terms of the measured cutting forces. Therefore, these precautions were abandoned in subsequent tests.

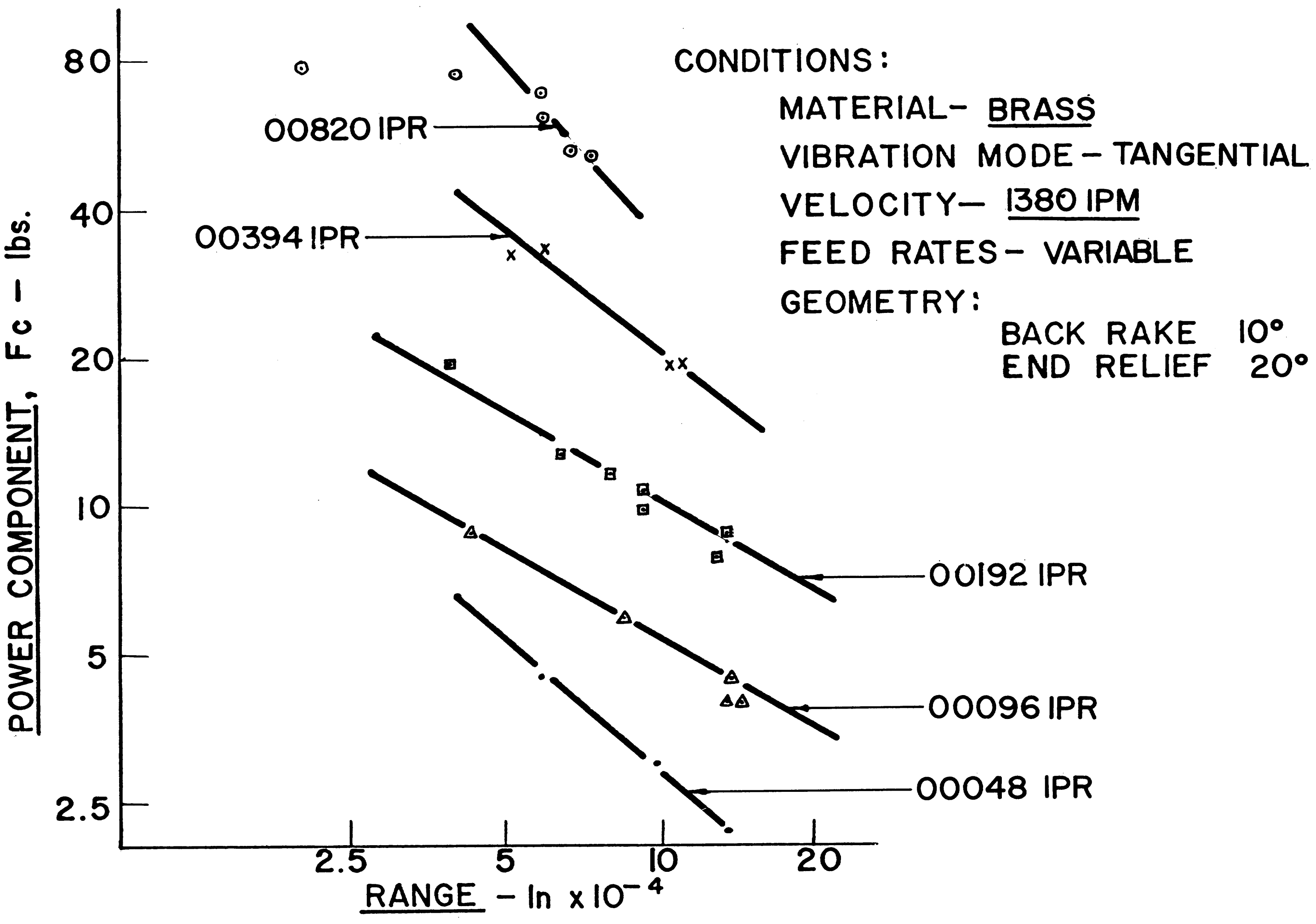
RESULTS OF EXPERIMENTS

It is believed that the more significant results obtained during this study came from the orthogonal cuts on brass and free cutting aluminum during that period of time in the later stages where continuous observations were made of the range of vibration amplitude. Consequently, these results are presented first and out of sequence. Corollary information on chip formation, surface finish and tool life will be presented but in much more simplified form because in general they tend to confirm the results presented in literature by other investigators. Typical cutting force data for brass and aluminum are presented in sequence in Figs. 9-14.

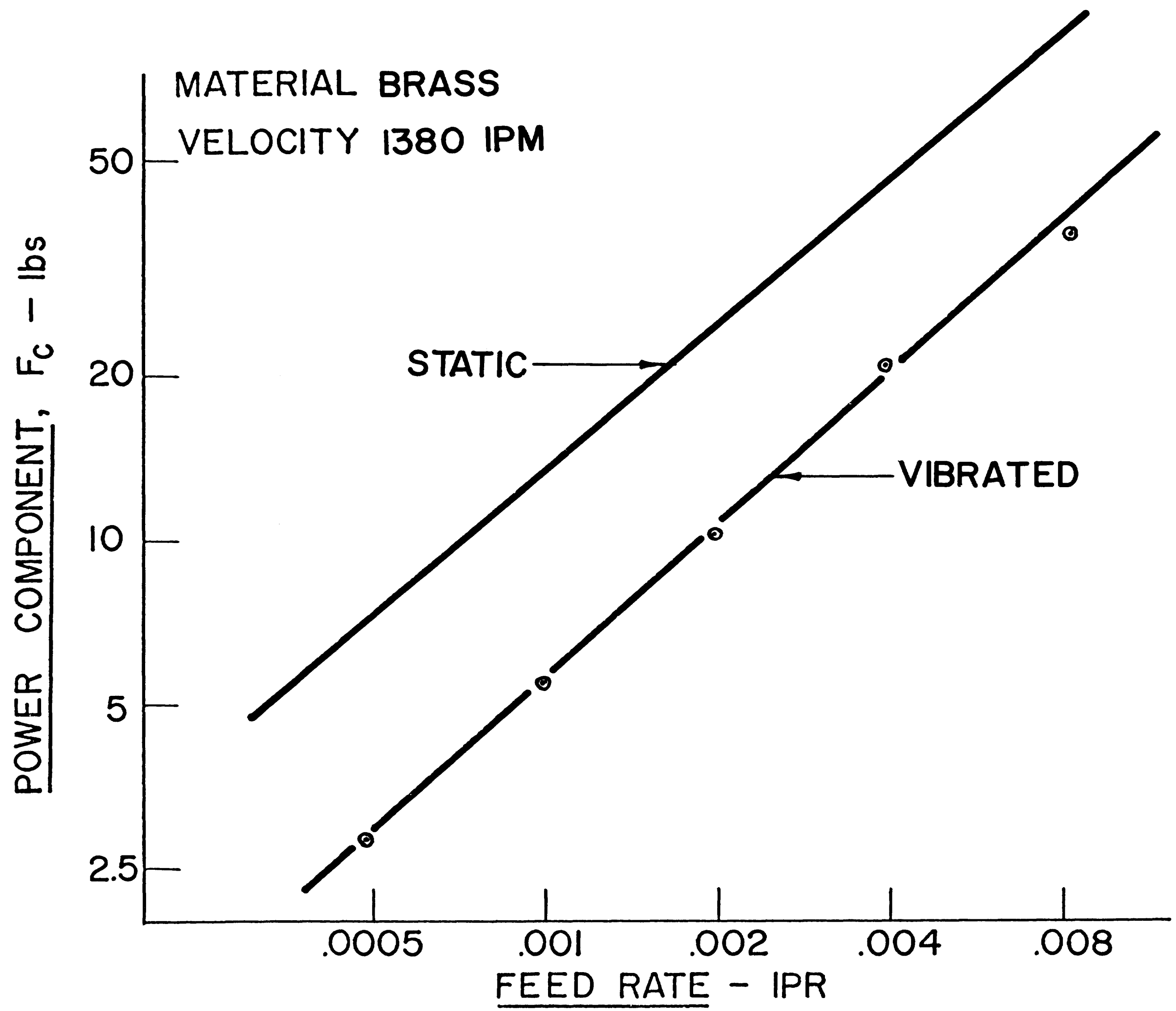
Initially 2011T3 aluminum was used as test material. Subsequently, check tests were made using 2024T4, and these data varied from 2 to 5% for similar tests with 2011T3.

Figure 9 is a typical presentation of what might be called original or raw data on the power component of cutting force versus the range of ultrasonic vibration. In a typical test the cut was permitted to continue until forces achieved apparent equilibrium as indicated on the strip chart. Initially the ultrasonic power was set at maximum level and after cutting began the frequency was adjusted so that maximum amplitude could be obtained as indicated on both the oscilloscope and the strip chart. Subsequently, the power output of the generator was decreased and permitted to persist for at least short periods of time before reducing the power to still lower levels. Various combinations of cutting speed or velocity and size of cut in terms of feed rate were carried out in a sequence which it was hoped would give a random reflection of the unpredictable tool motions in the other components. The slopes of the curves of power component of cutting force versus vibration range as shown in Fig. 9 appear to reflect this randomness. Each of the straight lines in Fig. 9, however, reflect single test sequences during which the ultrasonic power was varied. The decision was made to evaluate the power component at a vibration range of 0.001 in.

The results of such correlation are shown in Fig. 10 wherein the power component is shown plotted versus the corresponding feed rate in ipr. The corresponding line for the power component versus feed rate without vibration is also shown as a straight line labeled "static." Similar plots were made for each of the four different cutting speeds and ranges of feed rates. The corresponding equations are summarized in Tables I and II. The remainder of the original supporting data and corresponding plots of power component versus variable feed rate for both brass and aluminum are given in Figs. 22-35 in Appendix A.

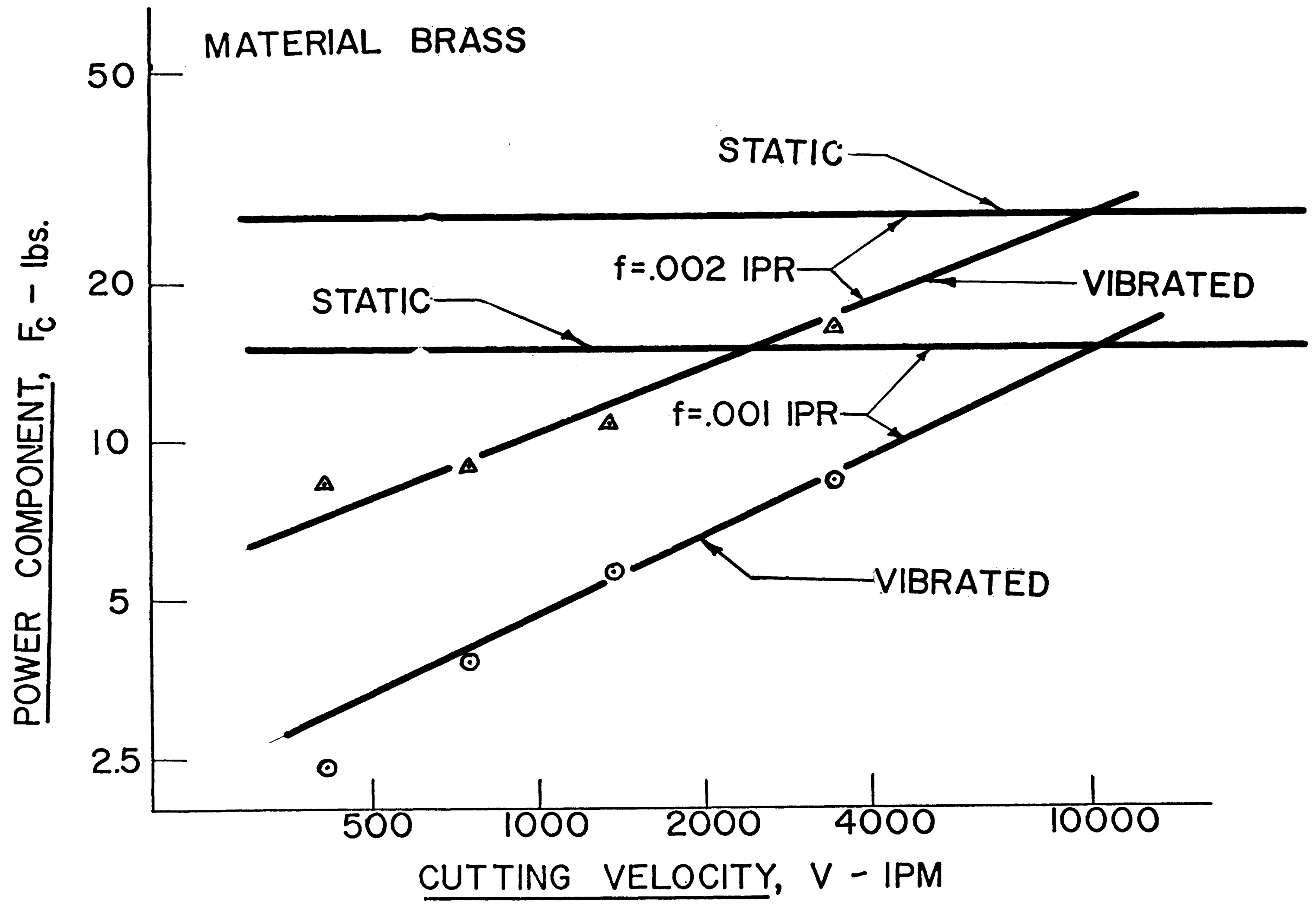


CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 9

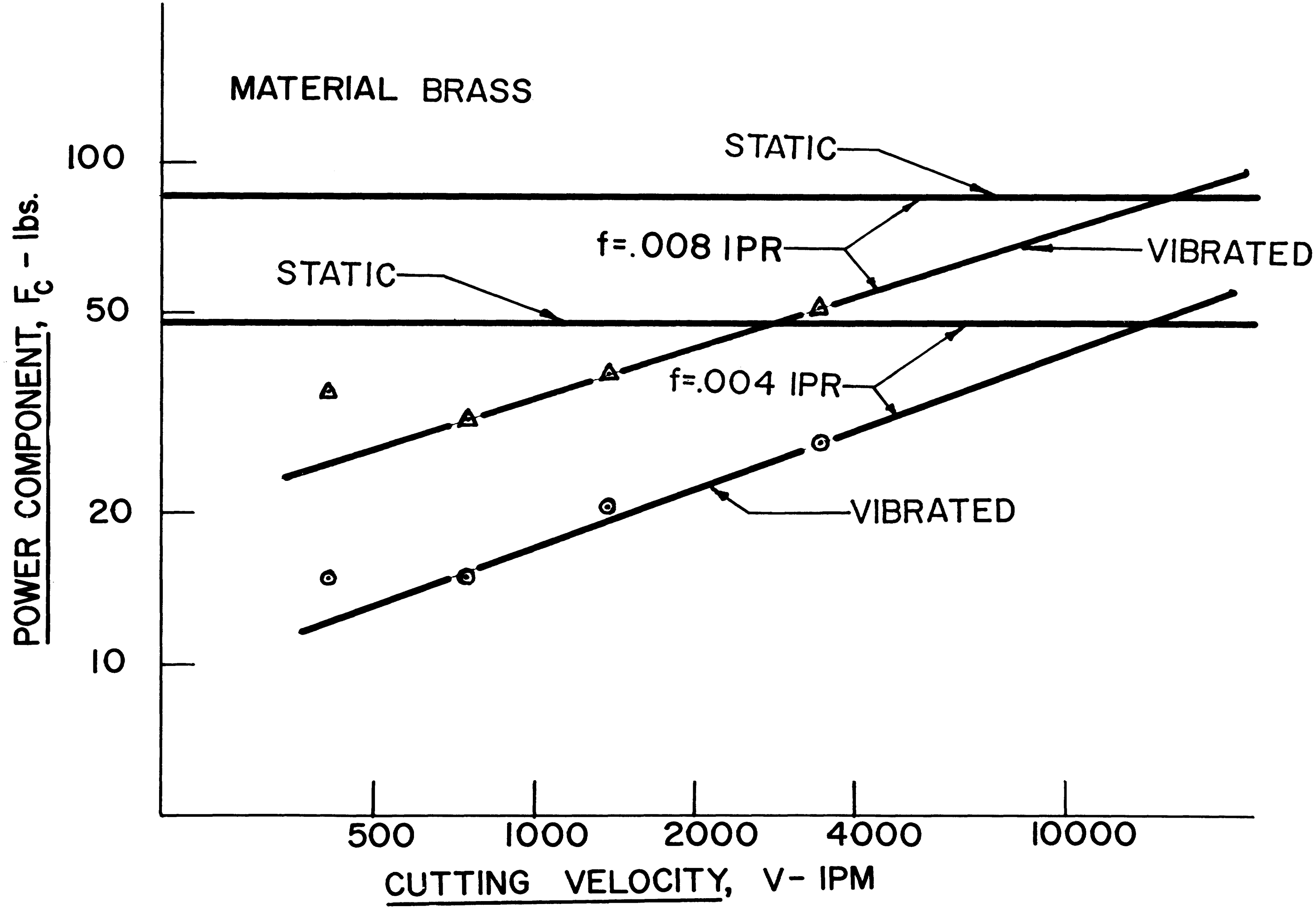


CUTTING FORCE VERSUS FEED RATE

FIG. NO. 10

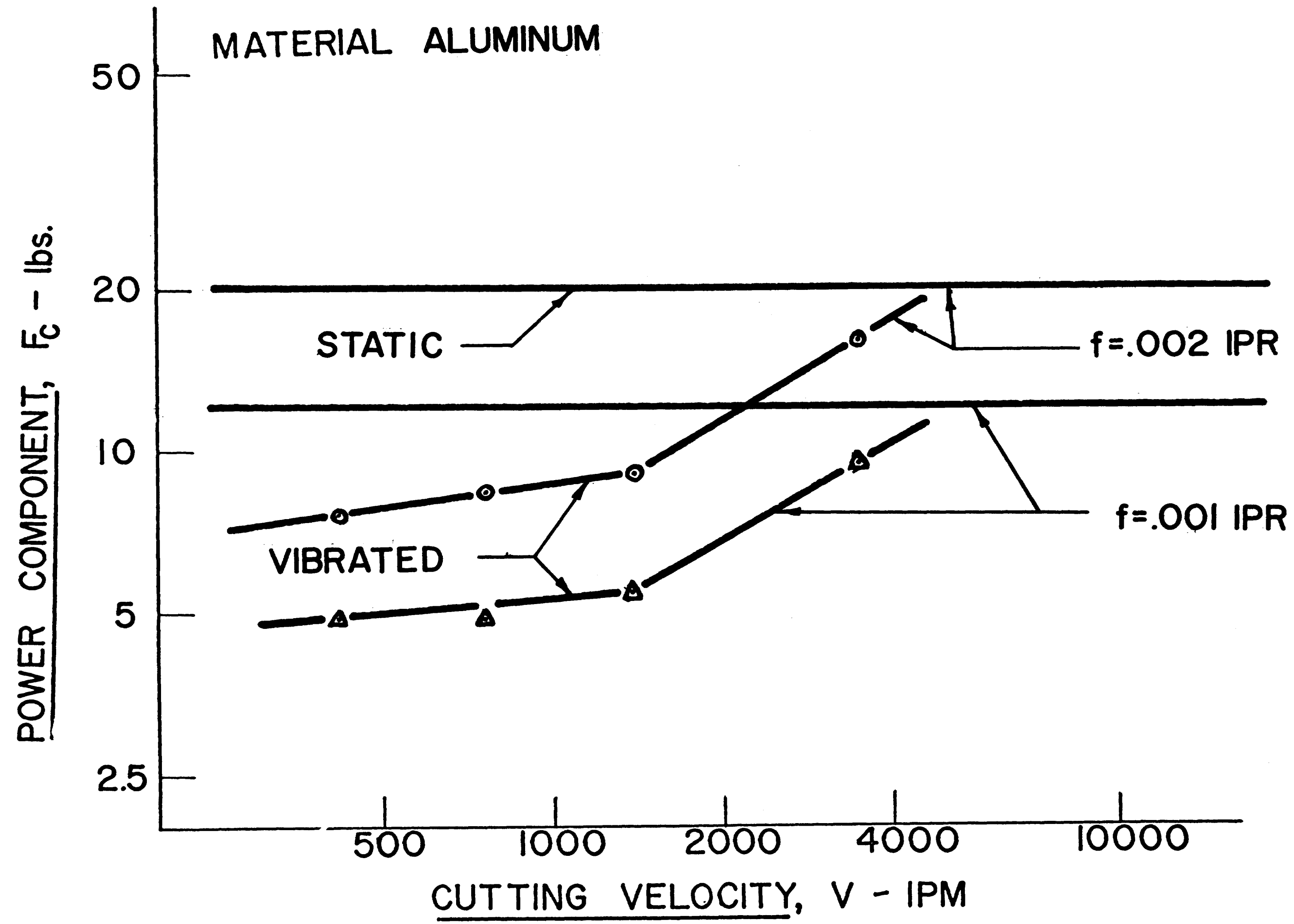


CUTTING FORCE VERSUS VELOCITY FIG. NO. 11



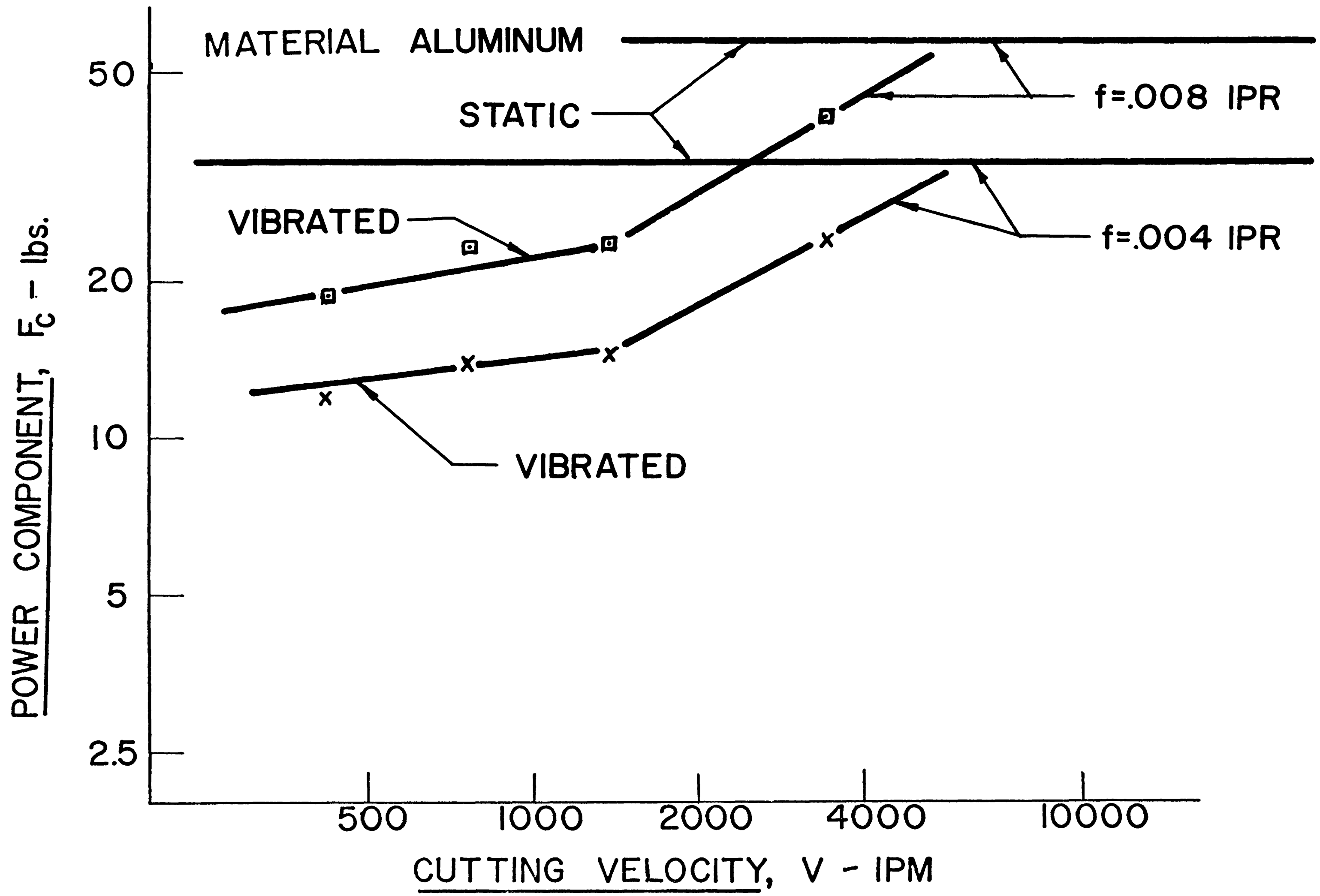
CUTTING FORCE VERSUS VELOCITY

FIG. NO. 12



CUTTING FORCE VERSUS VELOCITY

FIG. NO. 13



CUTTING FORCE VERSUS VELOCITY

FIG. NO. 14

TABLE I

SUMMARY OF FORCE EQUATIONS FOR BRASS

(Variable Feed)

Speed, ipm	Static	Vibrated
412	$F_c = 5530 f^{.86}$	$F_{cv} = 35,600 f^{1.39}$
752	$F_c = 5530 f^{.86}$	$F_{cv} = 3,800 f^{.996}$
1380	$F_c = 5530 f^{.86}$	$F_{cv} = 3,740 f^{.941}$
3450	$F_c = 5530 f^{.86}$	$F_{cv} = 3,460 f^{.87}$

TABLE II

SUMMARY OF FORCE EQUATIONS FOR ALUMINUM

(Variable Feed)

Speed, ipm	Static	Vibrated
412	$F_c = 2610 f^{.78}$	$F_{cv} = 302 f^{.60}$
752	$F_c = 2610 f^{.78}$	$F_{cv} = 700 f^{.73}$
1380	$F_c = 2610 f^{.78}$	$F_{cv} = 650 f^{.70}$
3450	$F_c = 2610 f^{.78}$	$F_{cv} = 1575 f^{.74}$

Plots of the power component of cutting force as a function of cutting velocity are shown in Figs. 11-14 for both the non-vibrated and vibrated conditions. It will be noted that the power component remains constant over a broad range of cutting speeds when there is no superimposed vibration. On the other hand, the force is much lower in the presence of vibration at lower cutting speeds but tends to diminish continuously as the cutting speed is increased. The rate of change appears to be continuous in the case of brass as shown in Figs. 11 and 12 but appears to be somewhat discontinuous with a rapid rise at somewhat higher speeds in the case of aluminum as shown in Figs. 13 and 14.

Equations for the power component of cutting force obtained as a function of variable speed for both brass and aluminum are summaried in Tables III and IV. The equations for aluminum include both the high speed and low speed sections wherein the rate of change relative to cutting speed differs substantially.

TABLE III

SUMMARY OF FORCE EQUATIONS FOR BRASS

(Variable Speed)

Feed, ipr	Static	Vibrated
.001	$F_c = 15.0\ V^{\circ}$	$F_{cv} = 0.149\ V^{.50}$
.002	$F_c = 27.0\ V^{\circ}$	$F_{cv} = 0.64\ V^{.40}$
.004	$F_c = 48.5\ V^{\circ}$	$F_{cv} = 1.16\ V^{.39}$
.008	$F_c = 86.0\ V^{\circ}$	$F_{cv} = 3.54\ V^{.33}$

TABLE IV

SUMMARY OF FORCE EQUATIONS FOR ALUMINUM

(Variable Speed)

Feed, ipr	Static	Vibrated	
		High Speeds	Low Speeds
.001	$F_c = 12.0\ V^{\circ}$	$F_{cv} = 0.071\ V^{.6}$	$F_c = 2.83\ V^{.091}$
.002	$F_c = 20.5\ V^{\circ}$	$F_{cv} = 0.107\ V^{.62}$	$F_c = 3.26\ V^{.141}$
.004	$F_c = 35.0\ V^{\circ}$	$F_{cv} = 0.286\ V^{.542}$	$F_c = 4.87\ V^{.157}$
.008	$F_c = 60.0\ V^{\circ}$	$F_{cv} = 0.291\ V^{.616}$	$F_c = 6.28\ V^{.186}$

The feeding component of force for the tests reported in Figs. 9-14 were somewhat more erratic and reflected the random nature of the test conditions in that they did not lend themselves to any correlation with cutting speed and feed rate as did the power component. However, this was due in part to the fact that the feeding forces were very much lower than the power component of force in this series of tests so that any dependency they might have had upon cutting speed and feed rate was greatly overshadowed by probable differences in cutting motion as suggested in Fig. 8.

Almost concurrently with the <u>variable amplitude</u> tests, carried out for brass and aluminum as shown in Figs. 10-14, a series of <u>maximum amplitude</u> tests were carried out for a range of materials with results as summarized in Table V. These tests were made at conditions which recognized the power limi-

TABLE V

SUMMARY OF CUTTING FORCES FOR CONSTANT SPEED
AND SIZE OF CUT AT MAXIMUM AMPLITUDE

(Vibration in Tangential Direction—Thin Wall)

Test Conditions

Orthogonal Cut
Wall Thickness: 0.040 in.
Speed: 155 rpm; 405 ipm
Feed: 5/16 ipm; 0.002015 ipr
Rake Angle: +10°
Relief Angle: +20°

Material	Tangential Force, lb		Feed Force, lb		Maximum Vibration Range, in. x 10^{-3}
	Without US	With US	Without US	With US	
Brass	11	2.5 (-77)	2	0+ (-100)	1.40
Brass*	11	3 (-73)	2	0+ (-100)	1.38
Magnesium	6	1.5 (-75)	2.5	0+ (-100)	1.44
Magnesium*	7	1.5 (-79)	3	0+ (-100)	1.42
Aluminum 2011	10	2.5 (-75)	5	1 (-80)	1.40
Aluminum 2011*	10.5	3 (-71)	3	1 (-66)	1.44
Copper	72	12 (-83)	40	6 (-85)	1.34
Copper*	80	8 (-90)	47	3 (-95)	1.32
Steel 1018	27	5 (-82)	14	3 (-78)	1.36
Steel 1018*	26	5 (-81)	14	2 (-85)	1.40
Steel 1042	32	7 (-78)	15	3.5 (-77)	1.34
Steel 1042*	25	6 (-76)	12.5	2.5 (-80)	1.40
Stainless Steel 18-8	46**	20**	30**	15**	0.39
Stainless Steel 18-8*	70	10 (-86)	50	6 (-88)	1.32

*Tests with carbide tool.
**Tool failure.
( ) Percent change resulting from vibration.

tations of the transducer and constituted a check on the conclusions that might be drawn from the variable amplitude check.

Substantial reductions were obtained in the level of all measurable cutting forces except for the case of a carbide cutting tool used in machining 18-8 stainless steel. In this case the tool failed shortly after the transducer was energized and even before full amplitude was achieved. Examination of the tool indicated that failure could have been the result of impact or fatigue. The steel cutting tool had been made from AISI 52100 steel and was hardened only on the end. It was used for all of the variable amplitude tests, for all of the earlier tests summarized in Tables VIII-XIV and for part of the tests in Table V. The grade 350 Carboloy tool consisted of two 1/16 in. thick tips brazed to the AISI 52100 tool. Consequently, one must accept also the possibility that the tool failure was induced by one or more thermal cracks. Subsequent to the tests reported in Table V, the entire horn of AISI 52100 failed because of numerous fatigue cracks which absorbed most of the ultrasonic energy and made it impossible to achieve adequate amplitude.

Table VI summarizes the results obtained from the last series of experiments which involved orthogonal cuts on high strength materials. A new horn

TABLE VI

SUMMARY OF CUTTING FORCES FOR HIGH STRENGTH MATERIALS

(Vibration in Tangential Direction—Thin Wall)

Test Conditions

Orthogonal Cut
Wall Thickness: 0.040 in.
Speed: 155 rpm; 202 ipm
Feed: 5/16 ipm; 0.002015 ipr
Rake Angle: +10°
Relief Angle: +20°

Material	Tangential Force, lb		Feed Force, lb		Maximum Vibration Range, in. x 10^{-3}
	Without US	With US	Without US	With US	
TZM	26	10 (-62)	15	5	.778
Rene 41	68	32 (-53)	46	26	.778
Steel 4340	38	10 (-74)	16	6	.585
Tungsten	50	25 (-50)	30	25	.455

( ) Percent change resulting from vibration.

was made from Type M-3 high speed steel and was full hardened by the National Twist Drill and Tool Company of Rochester, Michigan. The design was the same as the previous horn except for having a thicker flange at the supporting surface. Despite this, however, the maximum amplitude attainable with the new horn was appreciably less than two-thirds that of the old one. This re-emphasizes the need for better design of the supporting structure.

The properties of the high strength materials are given in Appendix B. Despite the lower vibration amplitude, substantial reductions in both force components were achieved with superimposed vibration. This may be attributed both to the expected results of vibrations and to the very low ambient cutting speed. It is believed to be significant that no tool failures occurred at any of the test conditions. Also it is feasible that substantially larger amplitudes and correspondingly greater force reductions could be achieved before adverse tool wear sets in.

Some of the results obtained early in the investigation before attempts were made to monitor the vibration amplitude are summarized in Tables VII-XIV. These are included in this report primarily to emphasize the broad range of results that can be obtained unless control is achieved over the complete motion of the cutting edge in such a way as to minimize or eliminate vibratory motion in other than the tangential direction. Some of these results also will emphasize the sensitivity of this behavior to the magnitude of the relief angle of the cutting tool.

Tables VII-X summarize cutting forces obtained from tests made over a substantial period of time during which the cutting tool was removed occasionally and resharpened after which it must be assumed that the clamping conditions at the point of support on the ultrasonic horn did not exactly duplicate those which persisted at the time the tool was removed for resharpening. An important consequence of this procedure, of course, would be that motion in directions other than that in which the tool was excited could be substantially different.

These tables show that it is possible for vibration to cause both components of force to go up or both or go down or for the power component to be decreased while the feeding component is increased. The measured forces indicate further that the several permutations of increases and decreases were sensitive both to size of cut and to cutting speed. Further, it is obvious that vibration in the feeding direction always resulted in increases in the feeding component of force.

Vibration was carried out at full power but at an unknown and unmeasured range which must be assumed to be somewhat variable, however, as a result of the uncontrolled support conditions. Variations in the support of clamping conditions could result in varying amounts of vibrational energy being converted to frictional heat at the clamping interfaces. It is believed to be significant also that all of these tests were carried out with a relatively

TABLE VII

SUMMARY OF CUTTING FORCES FOR ALUMINUM AT DIFFERENT LEVELS OF CUTTING SPEEDS

Test Conditions

Orthogonal Cut
Wall Thickiness: 0.125 in.
Rake and Relief Angles: 15°
Vibration Range: Unknown (full power)

Force Component, lb	Vibrated	Speed (rpm) and Feed (ipr)			
		155 .002	283 .00176	518 .00192	1300 .00193
		Tangential Mode			
Power	No	28	25	23.5	23.5
	Yes	8	10	10.5	19
Feed	No	15	11	7.0	11
	Yes	6	11	7.5	20
		Feeding Mode			
Power	No	28	21	26	23
	Yes	13.5	16.5	18.5	24
Feed	No	12	12	9	11
	Yes	14.5	17.5	16.5	22

TABLE VIII

SUMMARY OF CUTTING FORCES FOR BRASS AT DIFFERENT LEVELS OF CUTTING SPEEDS

Test Conditions

Orthogonal Cut
Wall Thickness: 0.125 in.
Rake and Relief Angles: 15°
Vibration Range: Unknown (full power)

Force Component, lb	Vibrated	Speed (rpm) and Feed (ipr)			
		155 .0020	283 .00176	518 .00192	1300 .00193
		Tangential Mode			
Power	No	33	30	27.5	29
	Yes	9-6	10	13	28-14
Feed	No	15	15	3	12
	Yes	19	20	6	27-28
		Feeding Mode			
Power	No	32	31	32	27
	Yes	16-22	27	33	27.5
Feed	No	10	10	13.5	11
	Yes	16.5	20.5	23.5	27

TABLE IX

SUMMARY OF CUTTING FORCES FOR ALUMINUM AT DIFFERENT FEED RATES

Test Conditions

Orthogonal Cut
Wall Thickness: 0.125 in.
Rake and Relief Angles: 15°
Vibration Range: Unknown (full power)

Force Component lb	Vibrated	Feed Rate (ipm and ipr) 518 rpm				46 rpm
		1/4 .00048	1/2 .00097	1 .00192	2 .00385	1/4 .00545
		Tangential Mode				
Power	No	11	16	23.5	35	66
	Yes	4	6.5	10.5	23	26
Feed	No	6	6.5	7.0	5.0	34
	Yes	4.5	4.5	7.5	8.0	10
		Feeding Mode				
Power	No	11	16	26	43	74
	Yes	5.5	11.5	18.5	44	22-24
Feed	No	6	7.5	9	9	32
	Yes	12	15	16.5	21	4-3*

*Two different tests

TABLE X

SUMMARY OF CUTTING FORCES FOR BRASS AT DIFFERENT FEED RATES

Test Conditions

Orthogonal Cut
Wall Thickness: 0.125 in.
Rake and Relief Angles: 15°
Vibration Range: Unknown (full power)

Force Component lb	Vibrated	Feed Rate (ipm and ipr) 518 rpm				46 rpm
		1/4 .00048	1/2 .00097	1 .00192	2 .00385	1/4 .00545
		Tangential Mode				
Power	No	13	17.5	27.5	53	76
	Yes	5	7	13	32	20
Feed	No	6	6	3	2	28
	Yes	9	9	6	2.5	6
		Feeding Mode				
Power	No	15	18	32	57	72
	Yes	11.5	17	33	58	48
Feed	No	15	12	13.5	8	5
	Yes	17	22	23.5	20	9

TABLE XI

CUTTING FORCES AND PERCENTAGE REDUCTION AT DIFFERENT MODES AND SPEED LEVELS

(Vibration in Feed Direction—Low Speed)

Test Conditions

Orthogonal Cut
Speed: 11.4 fpm
Feed: 0.005 ipr
Rake Angle: -2°
Relief Angle: +12°

Material	Vertical Forces, lb		Feed Forces, lb	
	Without US	With US	Without US	With US
Aluminum 2011	67.5	45.0 (-33)	19.2	12.0 (-37)
Steel 1020	237.5	182.5 (-23)	156.0	108.0 (-24)
Steel 1042	267.5	175.0 (-35)	168.0	108.0 (-36)
Brass	52.5	50.0 (-5)	86.4	62.4 (-28)
Copper	125.0	87.5 (-30)	132.0	96.0 (-27)

( ) Percentage change resulting from vibration.

TABLE XII

CUTTING FORCES AND PERCENTAGE REDUCTION AT DIFFERENT MODES AND SPEED LEVELS

(Vibration in Feed Direction—High Speed)

Test Conditions

Orthogonal Cut
Speed: 209 rpm; 51.9 fpm
Feed: 0.0012 ipr
Rake Angle: -2°
Relief Angle: +12°

Material	Vertical Forces, lb		Feed Forces, lb	
	Without US	With US	Without US	With US
Aluminum 2011	15.0	20.0 (33)	8.4	26.4 (215)
Steel 1020	55.0	67.5 (23)	38.4	57.6 (50)
Steel 1042	55.0	65.0 (18)	40.8	55.2 (13)
Brass	22.5	35.0 (55)	19.2	57.6 (200)
Copper	437.5	225.0 (-43)	300.0	156.0 (-48)

( ) Percentage change resulting from vibration.

TABLE XIII

CUTTING FORCES AND PERCENTAGE REDUCTION AT DIFFERENT MODES AND SPEED LEVELS

(Vibration in Tangential Direction—Low Speed)

Test Conditions

Orthogonal Cut
Speed: 46 rpm; 11.4 fpm
Feed: 0.005 ipr
Rake Angle: +5°
Relief Angle: +5°

Material	Vertical Forces, lb		Feed Forces, lb	
	Without US	With US	Without US	With US
Aluminum 2011	67.5	17.5 (-74)	33.6	9.6 (-71)
Steel 1020	200.0	187.5 (-6)	120.0	96.0 (-20)
Steel 1042	225.0	150.0 (-33)	115.0	96.0 (-16)
Brass	57.5	40.0 (-30)	52.8	38.4 (-27)
Copper	312.0	250.0 (-20)	240.0	192.0 (-20)

( ) Percentage change resulting from vibration.

TABLE XIV

CUTTING FORCES AND PERCENTAGE REDUCTION AT DIFFERENT MODES AND SPEED LEVELS

(Vibration in Tangential Direction—High Speed)

Test Conditions

Orthogonal Cut
Speed: 209 rpm; 51.9 fpm
Feed: 0.0012 ipr
Rake Angle: +5°
Relief Angle: +5°

Material	Vertical Forces, lb		Feed Forces, lb	
	Without US	With US	Without US	With US
Aluminum 2011	12.5	16.25 (30)	7.2	18.0 (150)
Steel 1020	62.5	75.0 (20)	38.4	48.0
Steel 1042	62.5	62.5 (0)	50.4	45.6 (-9)
Brass	22.5	17.5 (-22)	48.0	101.0 (110)
Copper	112.5	112.5 (0)	91.4	91.4 (0)

( ) Percentage change resulting from vibration large relief angle of 15°. Consequently, it might be concluded that smaller relief angles in the range of those normally used on cutting tools would further amplify the undesirable results noted in these tables.

Tables XI-XIV present similar information not only for aluminum and brass but also for low and medium carbon steel and unalloyed copper. Tables XI and XII present the results for vibration in the feeding direction at unknown amplitude but full power output. Attention is called to the fact that the rake angle was -2° whereas the relief angle was a +12° for all of these tests.

Table XI summarizes the results obtained for a relatively large size of cut but exceptionally low speed. It will be noted that at least some reduction was achieved through vibration in both of the components of cutting force despite the fact that the principle motion was in the feeding direction. On the other hand, Table XII shows the results for a significantly higher cutting speed and a relatively small size of cut. It will be noted that both components of cutting force increased measurably except when cutting copper. The increases in cutting force ranged from 13% to as much as 215%.

The reduction in cutting forces in the case of copper probably are due to the changes in the relative proportions of vibratory motion in the three different Cartesian coordinate directions. It will be noted throughout Tables XI-XIV that the behavior of copper was substantially different from that of the other materials. Part of this difference is manifested in the fact that the cutting forces for copper were higher in all cases except in Table XI. One must expect that the frictional conditions at the point of support of the ultrasonic horn are altered by changes in magnitude of the cutting forces. Consequently, part of the somewhat unique behavior of copper could be attributed to this factor.

The conclusions which might be drawn from the information presented in Tables VII-XIV are as follows:

1. It is possible for both components of cutting force to be reduced by primary excitation in the feeding direction. This appears to occur principally in the presence of relatively low cutting speeds with relatively large size of cut and probably only with unusually large relief angles.

2. Both components of cutting force can be substantially increased by ultrasonic vibration when the excitation is in the feeding direction and in the presence of relatively high cutting speeds and small sizes of cut. Intermediate combinations of cutting conditions can result in a reduction of the power component at the same time that the feeding component is substantially increased.

3. Both components of cutting force can increase for vibration excitation in the tangential direction in the presence of relatively high cutting

speeds and small size of cut accompanied by relatively small relief angle on the cutting tool. Even though attempts are made to produce vibratory motion in only one direction at ultrasonic frequencies, it is highly probable that the results of earlier investigators as well as with those presented in this report have been influenced substantially by at least small motions in the other Cartesian coordinate directions. Deliberate and more successful attempts at eliminating these other motion components probably would enhance the differences suggested by the results presented in this report. Therefore it would appear that one of the more important problems yet to be investigated and solved in this process surrounds the occurrence and influence of the extraneous motions arising out of the asymmetry and reflections in the ultrasonic horn.

CHIP FORMATION

Vibration of the cutting tool in the tangential direction always exerts a substantial influence on the chip formation when the amplitude is adequate to produce measurable change in the cutting forces. The nature of this influence can be characterized in three ways as follows:

1. The chip always is more uniform as to length, width, and thickness than without vibration.

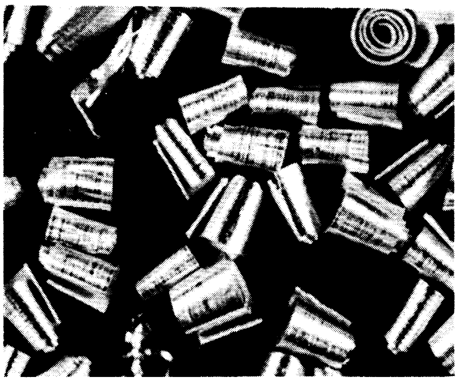
2. The curvature manifested in the "coiling away" of the chip from the rake face of the tool is always less in the presence of vibration.

3. The underside of the chip which is in contact with the rake face of the cutting tool is always smoother with vibration.

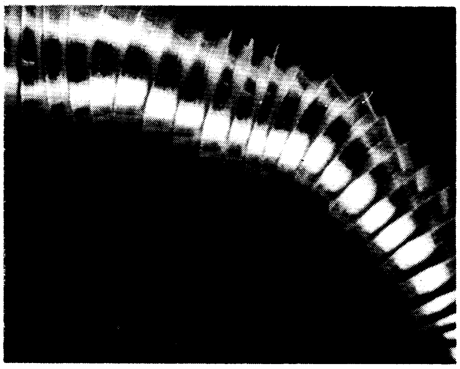
Examples of these manifestations or characteristics are illustrated in Figs. 15-17. Figure 15 shows chips obtained from 2011T3 aluminum for an orthogonal cut of 0.100 in. width, feed rate of 1/2 ipm or slightly less than 0.002 ipr, and a cutting speed of 283 rpm or 752 ipm. Three different conditions are illustrated at (a), (b), and (c).

The chips obtained with vibration are characteristic of the continuous helix shown at (b) in Fig. 15. It will be noted not only that the diameter of the helix is greater than that for the chips at (a) and (c) but also that the outside of the helix which corresponds to the underside of the chip is visibly smoother. The chips shown at (a) and (c) are more broken than those illustrated in (b) and both were obtained without vibration but at otherwise significantly different conditions with regard to the work material.

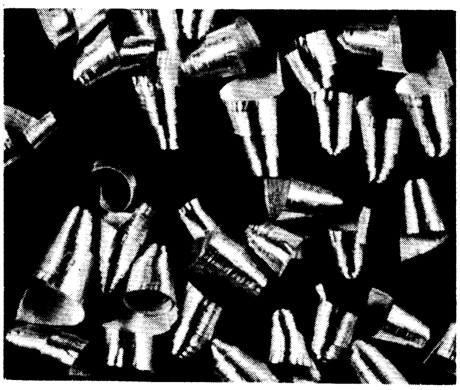
The chips shown at (a) in Fig. 15 are typical of those which are obtained without vibration when the workpiece has not been previously irradiated. That is, no cuts has been made previously wherein the tool was vibrated ultrasonically. On the other hand, the chips shown at (c) near the



(a)

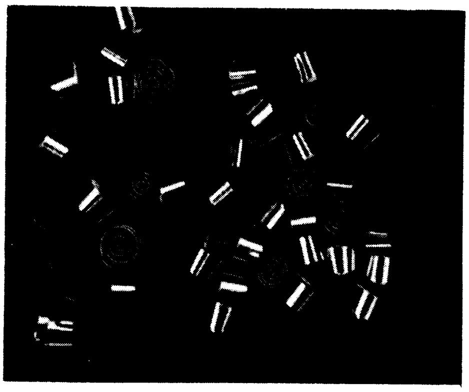


(b)

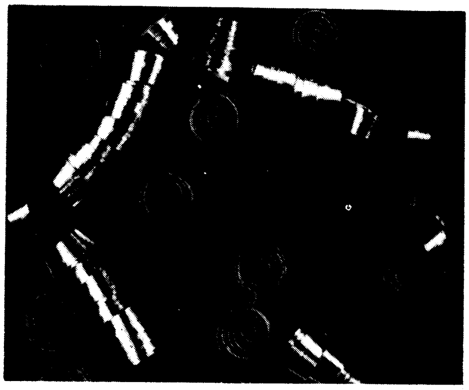


(c)

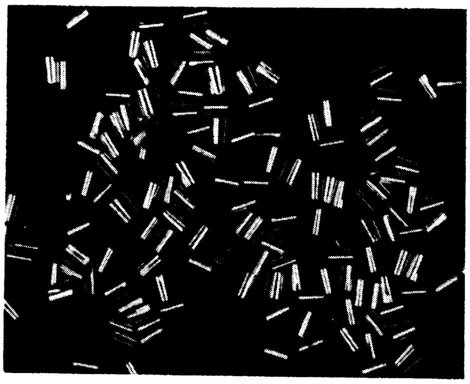
Fig. No. 15 Chips from 2011T3 Aluminum
Width of orthogonal cut =0.100 in.
Feed =1/2 ipm.; Speed =283 rpm.
(a) Original material without vibration
(b) With vibration
(c) Without vibration but with material irradiated
Vibration in tangential mode.



(a)



(b)



(c)

Fig. No. 16 Brass chips from 0.100 in wide orthogonal cut at 283 rpm. and 1/2 ipm. feed.
(a) Original material without vibration
(b) With vibration
(c) Without vibration but with material irradiated
Vibration in tangential mode

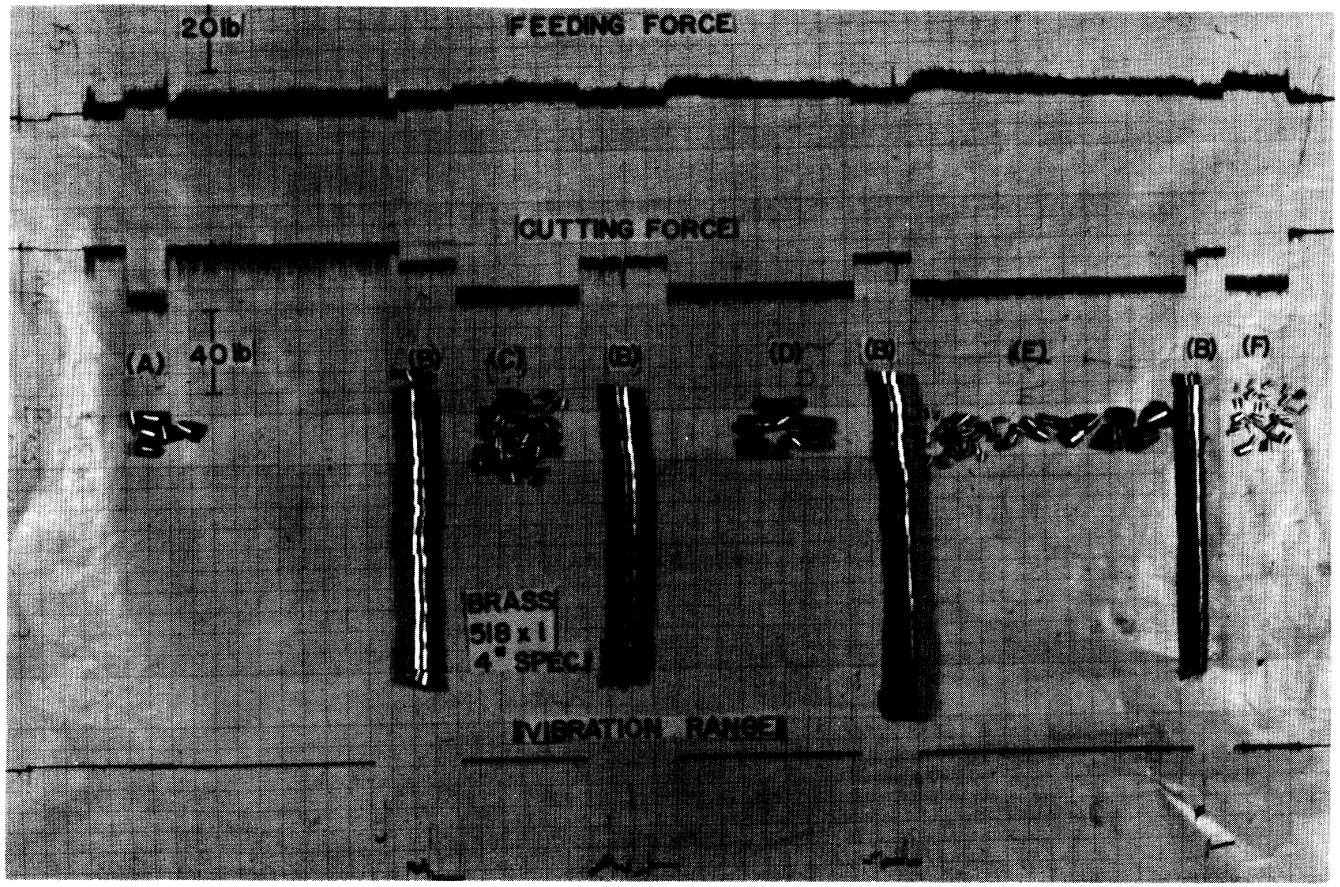


Fig. No. 17 Illustrates changes of cutting force and chip formation when cutting brass with tangential mode of vibration. Power component of cutting force responds instantly to changes in vibration but feeding force changes gradually. Chip formation also changes instantly when vibration is started and stopped but remains constant during vibration while changing gradually after vibration has stopped.

bottom of Fig. 15 are typical of those which would be obtained immediately upon de-energizing the ultrasonic transducer. It is difficult to characterize these differences, but it is believed they are indeed characteristically different.

The differences which were pointed out for aluminum in Fig. 15 are somewhat greater for brass as shown in Fig. 16, where again the cutting conditions are identical with those for the aluminum as shown in Fig. 15. With vibration, however, there was some occurrence of relatively large diameter spirals as well as helices of substantial length. It will be noted also that the chips obtained without vibration for previously irradiated brass are substantially more broken and smaller than the helices shown at the top in (a) for cutting without vibration on a material which had not been previously irradiated.

After the phenomena noted in Figs. 15 and 16 were observed initially, a special test was made with brass to obtain further information about this behavior in relation to the cutting forces. This is illustrated in Fig. 17 where both the cutting forces and chips are shown for cuts made both with and without vibration in a test where cutting was carried out continuously until one complete specimen had been machined entirely into chips.

It will be noted that the chips obtained with vibration as shown at the four positions designated as (B) in the figure were continuous helices. On the other hand, the chips obtained without vibration were of two types. Those obtained immediately after shutting off the ultrasonic generator were highly broken and very small as illustrated at (C) in the figure. On the other hand, it was noted in the interval designated as (D) that although the chips started out in the form of those shown at (C) that eventually in an internal approximately equal to 1 in. of length of the work specimen the chip formation gradually changed to that shown at (D) which was identical to the shape obtained initially without vibration before the work specimen had been exposed to any vibration as shown at (A) in the figure.

Consequently, after the third interval of vibration, the cut was permitted to proceed without vibration for a distance of approximately 1-1/2 in. leading to the chip forms illustrated at (E) in Fig. 17. It will be noted here that the chips began as very small broken particles immediately after vibration and gradually transformed to the conical shaped spirals shown at the right in interval (E).

After a short period of vibration as shown at the fourth interval designated by (B), the generator was shut off and the cut permitted to continue on toward the end of the specimen. This consisted of an interval of approximately 1/2 in. in length during which time the chips were all of the small, highly broken variety. In this period of time they did not even begin to recover toward the original conical form.

Therefore, one might conclude that the vibration had irradiated the work material in such a manner as to alter its properties as much as 1/2 in. or more in ahead of the area being cut. On the other hand, it might be assumed that the conditions prevailing during vibration altered the interface conditions between the chip and cutting tool in such a manner that only gradual recovery could take place. Attempts were made to resolve the latter question by moving to new, unused portions of the cutting edge. The results tended to indicate that the former of these two assumptions was the more valid although there was sufficient difference between the chip formation without vibration as between two consecutive cutting edges so that this conclusion could not be considered completely valid.

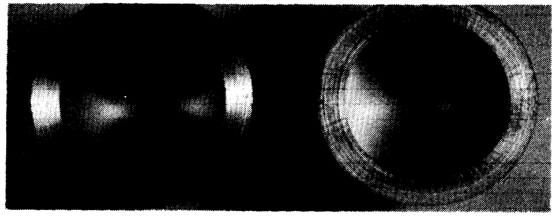
The influence of ultrasonic vibration on chip formation may be considered desirable to the extent that the chips are more uniform during cutting. However, this improvement in uniformity is most pronounced at low cutting speeds where the normal behavior without vibration is most undesirable. On the other hand, the influence of vibration must be considered undesirable when the desired form is one of small broken chips. A tentative conclusion is drawn, however, to the effect that the overall influence of vibration on chip formation is desirable despite the more continuous chips since it is accompanied by lower oscillations of cutting force and better surface finish.

SURFACE FINISH

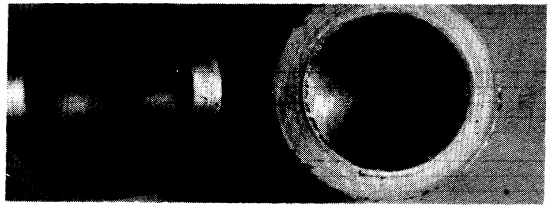
It is extremely difficult to obtain any quantitative information on surface finish in orthogonal cuts for the simple reason that it is nearly impossible to stop the cut fast enough at high cutting speeds to retain any of the original cut surface. If the workpiece rotates more than one revolution, after the feeding has stopped, then there is some cutting during the dwell period and the cutting conditions are not representative of those conditions which prevailed during steady state cutting. As a consequence of this, the specimens made without vibration generally were somewhat improved near the end of the cut or during stopping while those machined with vibration generally deteriorated in the same interval.

Figure 18 is a reproduction of pictures of some of the specimens obtained from orthogonal cuts with vibration both in the feeding direction and in the tangential direction. The aluminum specimens shown in the top row of Fig. 18 were all machined with vibration in the feeding direction when vibration was induced. It will be noted that the surface finish deteriorated at all three of the different speed levels represented by these pictures. The vibrated specimen at the center in the top row is typical of the extent to which vibration in the feeding mode can create large burrs at the edge of the cut and dullness in appearance as a result of the continuous hammering of the surface by the flank of the cutting tool. The vibrated specimen at the left in the upper row is the best of these three, but it was machined at such a low cutting speed that there was practically no rubbing

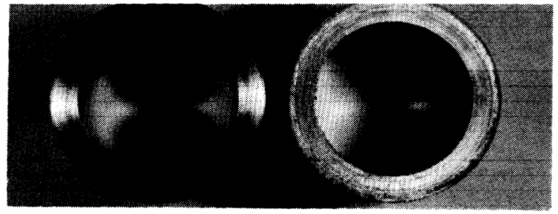
Feeding Mode



NV Aluminum V
46 rpm. x 1/4
(a)

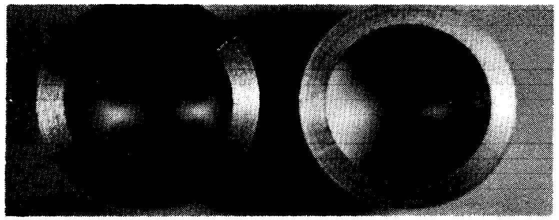


NV Aluminum V
518 rpm. x 1/4
(b)

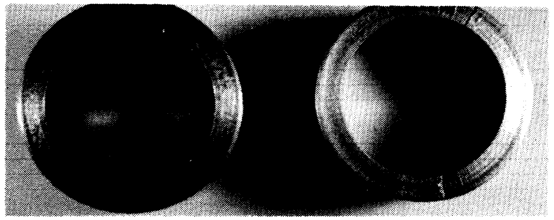


NV Aluminum V
1300 rpm. x 2-1/2
(c)

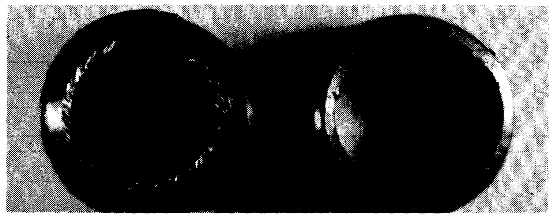
Tangential Mode



NV Aluminum V
46 rpm. x 1/4
(d)



NV Stainless Steel V
46 rpm. x 1/4
(e)



NV Copper V
155 rpm. x 5/16
(f)

Fig. No. 18 Pictures of machined ends of tubular specimens in orthogonal cutting. Note that vibration in the feeding direction causes burrs and a dull surface except at very low speed.
Vibration in tangential direction improves surface generally and inhibits formation of burrs.

between the machined surface and the flank of the cutting tool during the time they were in contact. Furthermore, the individual impressions created by the tool were so close together that they behaved like a diffraction-grating and caused iridescent rainbow colors when viewed in white light.

The three sets of specimens shown at the bottom in Fig. 18 were machined with orthogonal cuts and the vibration when it occurred was in the tangential direction. The aluminum and stainless steel specimens illustrate nothing more than the difficulties associated with trying to obtain representative surfaces in an orthogonal cut.

The copper specimens shown at the extreme right, however, illustrate the profound difference that occurs in the amount of burring. Practically no burr can be seen on the vibrated specimen at the extreme right. On the other hand, a burr more than twice the width of cut is evident on the specimen at the left in this group. The burr was of such great width and thickness without vibration that it was not completely removed during the dwell interval after shutting off the feed.

Despite the difficulties associated with obtaining a representative sample of surface finish during orthogonal cuts, a number of specimens were measured and the results summarized in Table XV. Attempts were made to measure the surface roughness with a tracer type instrument with the tracer diamond being moved in a radial direction at each of the four angular positions illustrated it the top in the table. Despite all the associated difficulties mentioned in connection with getting representative surfaces in this manner, the results do indicate that surface finish is improved with vibration in the tangential direction, and it tends to deteriorate with vibration in the feeding direction.

More significant quantitative information on surface finish can be obtained from surfaces that have been turned. This was done by turning aluminum specieens both with and without vibration. The results are summarized in Table XVI.

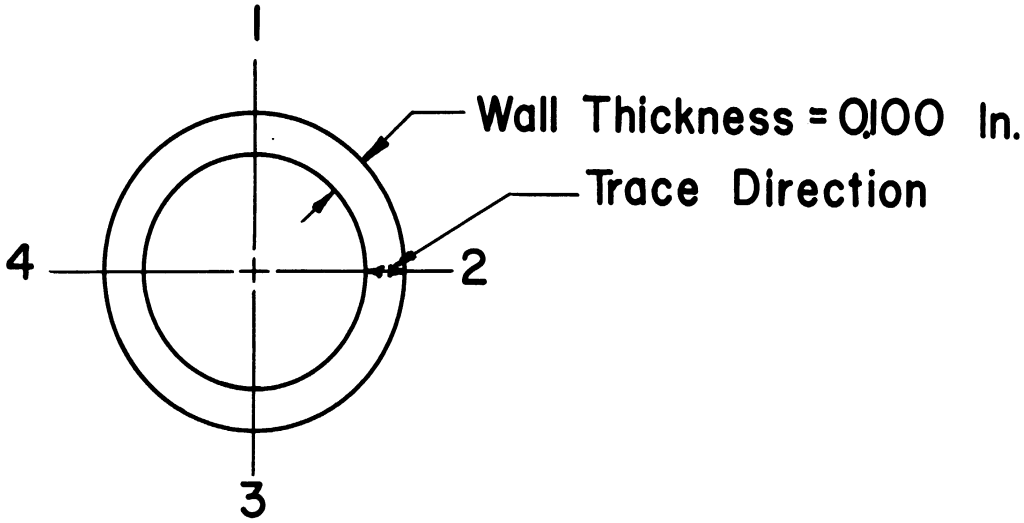
Of the three turned regions shown in the table, the second one was turned while ultrasonic vibration was attempted in the tangential direction. Of the two specimens prepared in this manner, it will be noted that vibration improved the surface finish in both cases. The cutting forces were reduced as would have been predicted and the chip formation changed in the same manner as was illustrated in the previous section.

No attempt was made to monitor any motions of the cutting edge in the feeding direction nor in the direction radial to the workpiece. However, it is quite probable that motions did occur in these directions in which case the measured surface roughness in the section that was vibrated was not as good as it could have been had the motion been uniquely in the tangen-

TABLE XV

SURFACE ROUGHNESS MEASUREMENTS

(Microinches-rms)



Specimen Number	Location of Measurement 1	2	3	4	Remarks
M-67S	30-35	65-75	65-75	40-45	Alum 518 x 1/2
M-68V	35-45	40-45	28-32	34-42	Feed Mode
M-3S	85-95	40-60	55-65	30-40	Alum 46 x 1/4
M-7V	35-42	40-47	42-50	40-45	Feed Mode
M-32S	80-90	65-72	70-82	68-78	Alum 46 x 1/4
M-33V	30-35	14-17	20-25	25-32	Tan Mode
S-9S	38-44	42-50	40-47	43-48	Alum 1300 x 2-1/2
S-10V	42-50	52-58	35-40	50-57	Feed Mode
M-42S	32-38	40-45	38-46	32-35	SS 46 x 1/4
M-43V	48-62	62-78	25-32	38-42	Tan Mode
Cu Vib.*	Not possible				Cu 155 x 5/16
Cu Static*	25-34	72-90	34-58	14-17	Tan Mode

V = Vibrated

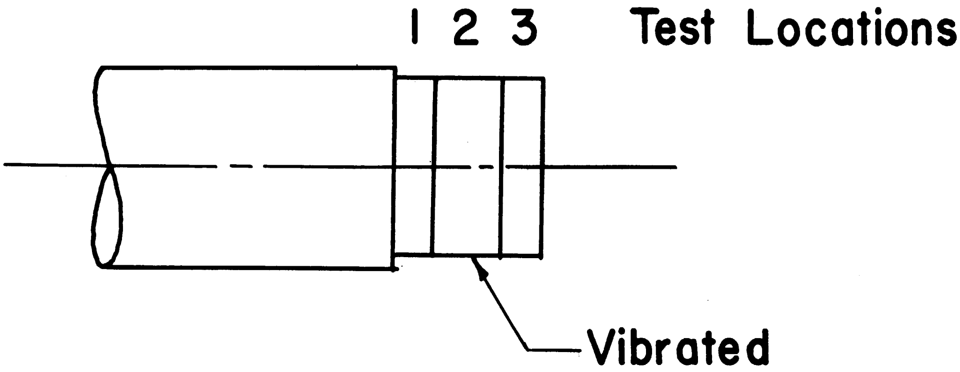
S = Static

*Wall thickness = 0.040 in.

tial direction only. All of the roughness measurements were made by traces parallel to the axis of the work specimen.

TABLE XVI

EXPLORATORY TURNING TESTS



Material: Aluminum 2011

Cutting Conditions

V = 39.3 fpm
f = 0.002 ipr
d = 0.025 in.
Vibration Mode—Tangential

Surface Roughness
(Microinches-rms)

Specimen Number	Location of Measurement 1	2	3
T-0		12-14	18-23
T-1	24-32	16-18	23-25

THE EFFECT OF LUBRICANTS

A short series of tests was carried out to explore the role of lubricants in relation to the beneficial effects to be expected from ultrasonic vibration. The question was raised as to whether or not these same beneficial effects could not be achieved through use of lubricants instead of by vibration.

The results of this brief study are summarized in Table XVII. Here again orthogonal cuts were made on aluminum and brass specimens with vibration in the tangential direction. Cuts were made both with and without vibration and with and without a cutting fluid on both materials. Kerosene was used as the cutting fluid for aluminum whereas a heavy black sulfa-chlorinated base oil was used with the brass. The latter fluid was selected because its chemical affinity for the brass and other copper base alloys is substantial and well known.

TABLE XVII

INFLUENCE OF CUTTING FLUIDS ON FORCES

Cutting Conditions

V = 39 fpm
f = 0.00175 ipr
Wall Thickness = 0.100 in.
Vibration Mode—Tangential

Material and Fluid	Condition	Mininum Power Component, lb		Minimum Feed Component, lb	
		Static	Vibrated	Static	Vibrated
Aluminum 2011	Dry	22.0	10.0	10	10
Kerosene	Wet	22.5	10.5	10	10
Brass 70/30	Dry	26.0	14.0	16	20
Sulfochlorinated base oil	Wet	23.0	13.0	12	20

The cutting forces summarized in Table XVII lead to the conclusion that the cutting fluids had negligible influence both with and without vibration. On the other hand, the vibration did cause substantial reduction in the power component in both materials both with and without a cutting fluid.

There was some improvement in chip formation and surface finish when the cutting fluids were applied to machining without vibration. On the other hand, the improvement in chip formation and surface finish during vibration can be assumed to be substantially a result of the vibration itself.

It should be pointed out that there was no change in the feeding component of cutting force as between conventional and vibrated conditions when machining the aluminum. On the other hand, the feeding forces actually increased as a result of vibration in the cutting of the brass. This series of tests was carried out with the high speed steel horn and cutting edge after the combination had been removed from the test set-up and subsequently replaced. Thus, once more we have an example of probable difference in the true motion of the transducer as between successive set-ups. It is very likely that there was a substantial component of motion in the feeding direction during this series of tests despite the fact that orientation and excitation was in the tangential direction.

CHATTER MANIFESTATIONS

The method required to clamp the horn-tool resulted in a system rigidity less than would normally be set up for turning tests. The reduced rigidity favored chatter, and its occurrence was consistently eliminated at the lower cutting velocities by applying US. The effectiveness of the US diminished at the higher cutting velocities. Chatter was identified by the characteristic noise, and deterioration of surface finish. Chip formation was altered from nonuniform characteristics (length, width, and thickness) during chatter to substantially improved uniformity with US applied. The chatter manifestations were the result of qualitative observations.

TOOL LIFE AND CUTTING TEMPERATURE

Although originally it was intended to carry out some tool life studies, it became increasingly evident that such tests would be inconclusive and perhaps misleading without complete and automatic control over the direction and amplitude of the vibrations. Such information as was obtained indicated that tool life might be reduced by vibration. This evidence consisted of two different occasions wherein stainless steel was being cut satisfactorily with carbide tools and without vibration and where the tools failed very quickly after vibration began. This is contrary to results reported in the technical literature, but it should not be surprising in the case of tool materials which are more susceptible to impact and fatigue. This question cannot be resolved until better control is achieved over the superimposed ultrasonic vibrations.

The only evidence of temperature change was the occurrence of black oxides on the underside of copper chips in the presence of vibration. One might conclude that this indicates higher temperatures, but it may indicate nothing more than the presence of higher oxygen in regions of higher temperature. However, the greater power output in cutting with vibration would lead one to expect higher temperatures.

ANALYSIS OF RESULTS

A relatively simple theoretical analysis of some of the experimental results is made possible by the fact that the amplitude of vibration was measured in some of the experiments. This has been done for the orthogonal cuts on brass and aluminum wherein the tool was vibrated in the tangential direction. The assumption is made that the vibratory motion was confined to the tangential direction only and analyses are developed from the equations summarized in Tables I-IV. From these analyses one derives some information on the speed, time, and power relationships governing behavior under the influence on superimposed ultrasonic vibration. The probable existence of extraneous motions in the other coordinate directions limits the interpretation of the comparative results but might very well explain some of the differences that will be pointed out.

VIBRATION CHARACTERISTICS

A schematic of the geometric relationships applicable to one cycle of vibration is shown in Fig. 19. The two extreme positions of the cutting tool are illustrated by dashed lines while it is assumed that the workpiece moves at an ambient velocity (V) from the left towards the right in the figure. The diameter of the circle represents the full range of vibrations. It will be noted that as the tool moves from left to right that eventually it will leave the underside of the chip providing that its maximum vibratory velocity (ωa) is greater than the ambient velocity (V). If one assumes that elastic relaxation is negligible, then this would occur at θ, where $V = \omega a \cos \theta$.

After leaving the underside of the chip, the cutting tool increases its longitudinal velocity and subsequently decreases it so that eventually the chip will catch up. This cannot occur in the quadrant wherein θ is measured but could occur in any one of the next three quadrants considered in a clockwise direction. Consequently, ϕ, as shown in Fig. 19, can be used to express the time or position at which the chip would catch up with the cutting tool. If ϕ is less than 90°, then the chip would catch up with the tool while it is still moving in a backward direction. On the other hand, it would again be moving forward for values of ϕ is greater than 90°. It is obvious that for very low ambient speeds in relation to the vibration range, the tool would leave the underside of the chip very early and would not again come in contact with it until it had moved well into the quadrant shown at the lower left in Fig. 19.

A summary of the appropriate values of the angles ϕ and θ and the corresponding ratios of cutting time and non-cutting time are summarized

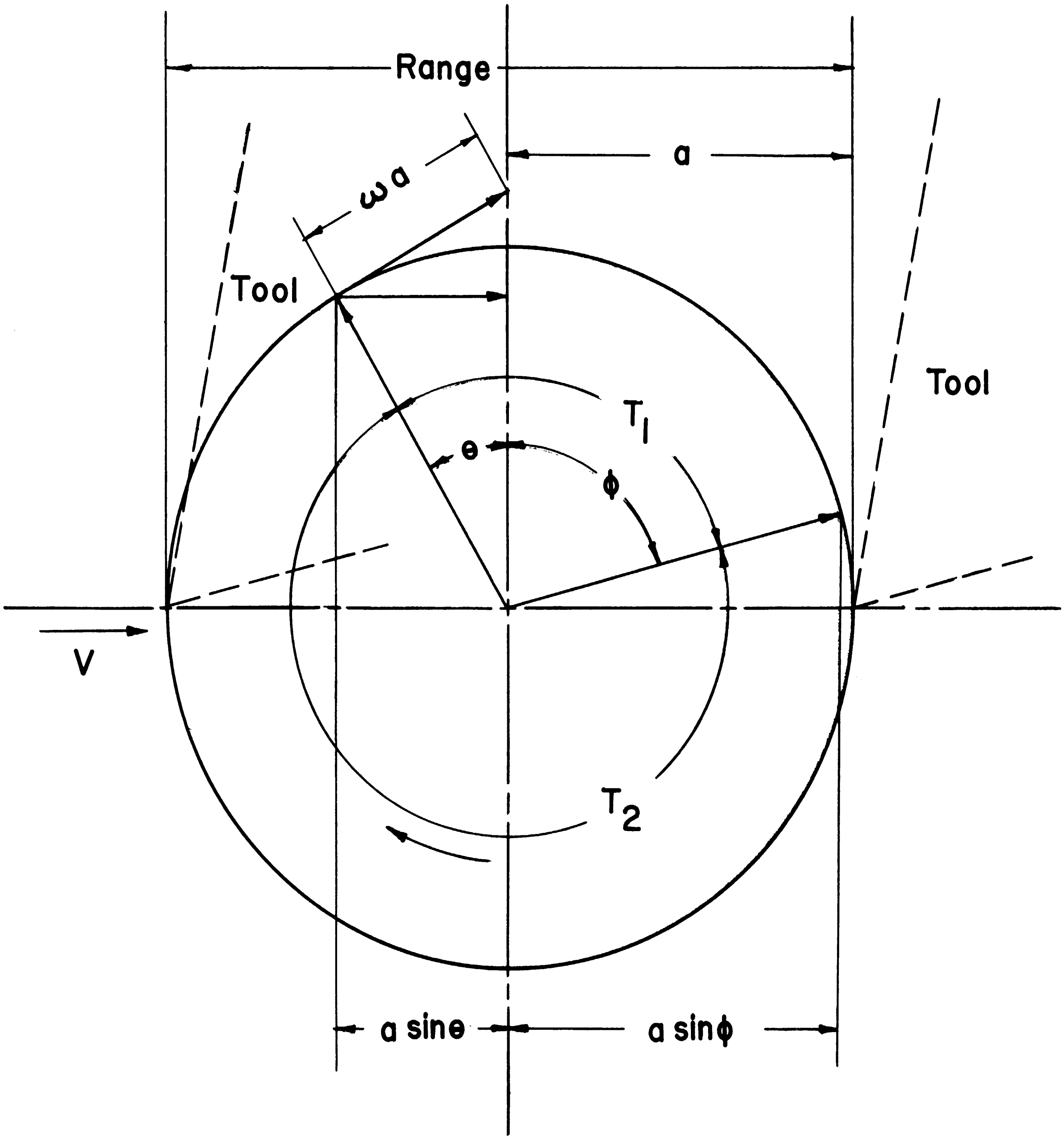


Fig. 19. Geometric relationships for one cycle of tool vibration.

in Table XVIII. Calculations were made for five different ambient cutting speeds. All but the lowest of these speeds were used for the variable amplitude tests summarized in Tables I-IV. The values reported in Table XVIII were calculated for a vibration frequency of 24 kc and a vibration range of 0.001 in. At these conditions in combination with the corresponding ambient cutting speeds, it will be noted that the actual cutting time varies from as little as 10% up to as much as 66% of the total elapsed time. Similarly then, the non-cutting time varies from as much as 90% down to as little as 34%.

TABLE XVIII

SUMMARY OF CUTTING AND NON-CUTTING TIMES PER CYCLE

Ambient Cutting Speed (V)	Angles as Shown in Fig. 19			Ratio of Cutting Time (T_2) to Total Cycle Time (T)		Ratio of Non-Cutting Time (T_1) to Total Cycle Time (T)	
ipm	$\phi°$	$\theta°$ & min	$(\theta+\phi)°$	T_2/T	%	T_1/T	%
128	237	88-22	325	.097	(10)	.903	(90)
412	212	84-45	296	.178	(18)	.822	(82)
752	191	80-23	272	.245	(25)	.755	(75)
1380	163	72-25	235	.348	(35)	.652	(65)
3450	82	39-35	121	.664	(66)	.336	(34)

The relative significance of the ratios and angles summarized in Table XVIII can be grasped more readily from the circular diagrams shown in Fig. 20. Here the shaded portions of the circles represent the cutting time per cycle. Further, the boundaries or straight edges of the shaded portions indicate the points at which the tool leaves the underside of the chip and again when it returns to meet the chip. These points are designated by the letters (a) and (b) as shown on the second cycle from the left in Fig. 20.

It is evident from the circles representing the four highest speeds in Fig. 20 that the maximum cutting speed in all four instances is approximately the sum of the maximum speed of the cutting tool plus that of the ambient velocity of the work. Making the necessary adjustments for the actual values of ϕ shows that the actual maximum relative cutting speed for these four cases ranges from a low of 335 fpm up to 660 fpm even though the ambient velocity varied from 34.3 fpm up to 287 fpm.

Similarly, one could obtain an average relative cutting speed by multiplying the ambient speed by the ratio of total cycle time to the cutting

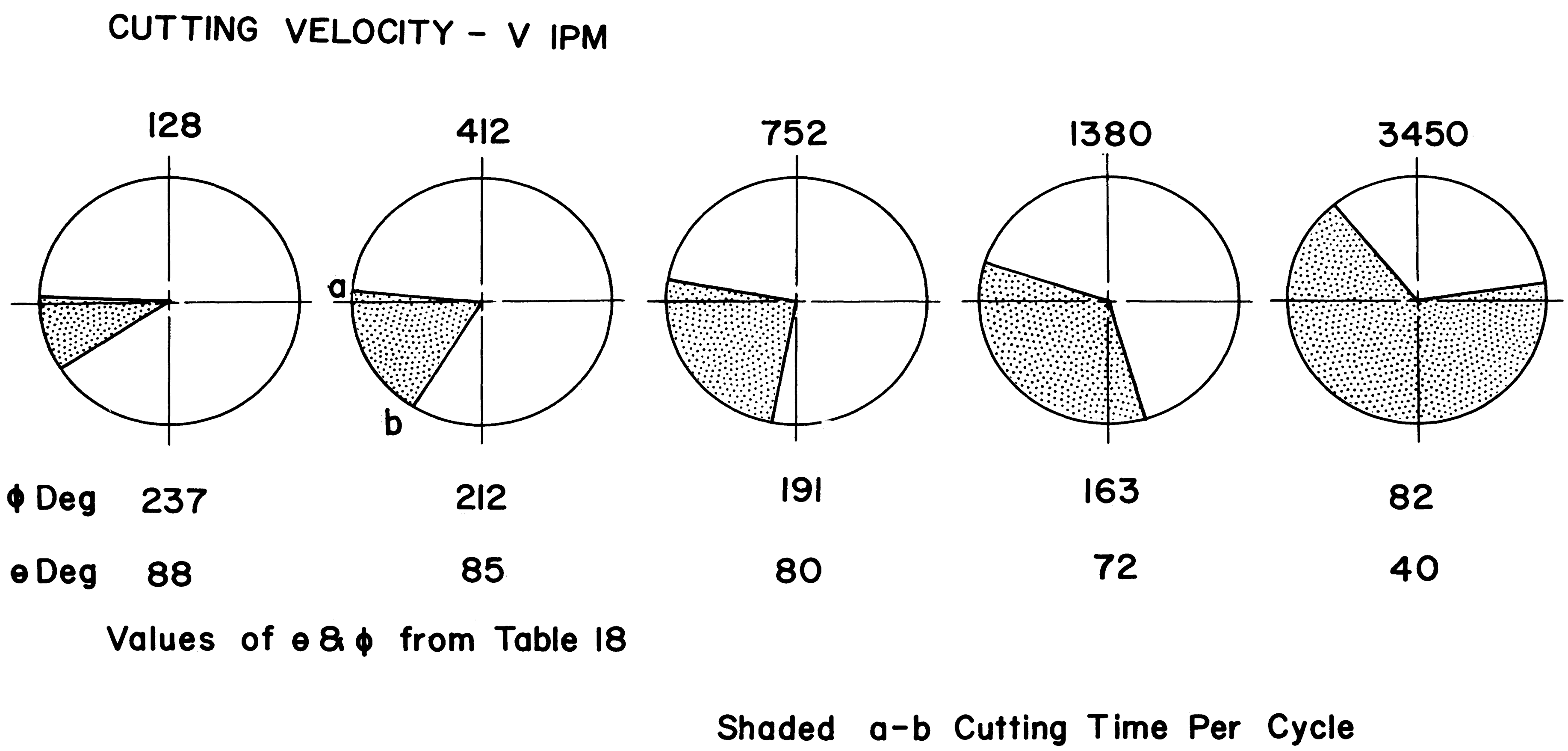


Fig. 20. Relative cutting time per cycle for Table XVIII.

time per cycle. This results in a range from 100 fpm up to 430 fpm for five different conditions illustrated in Fig. 20.

TRENDS SHOWN BY FORCE EQUATIONS

Several trends of undetermined origin may be noted by comparing the equations themselves as summarized in Tables I-IV. These are the equations for the power component of cutting force as obtained for a constant amplitude in the variable amplitude tests. The first feature to be noted is that the sensitivity of cutting forces to changes in feed rate and cutting speed for the static or non-vibrated cutting is quite conventional in that no appreciable change is noted with changes in cutting speed and that the sensitivity to change of feed rate is expressed by an exponent less than 1 for both brass and aluminum. The exponent of feed for brass is 0.86 compared to 0.78 for aluminum. Both of these cases might be said to reflect size of cut or inherent dullness behavior and the fact that the exponent for aluminum is measurably less than that for brass could be attributed to a stronger tendency toward formation of built-up-edge which includes the manifestations of dullness. Significant influences of superimposed vibration may be reflected in the fact that sensitivity of the cutting forces to changes in feed rate and cutting speed are quite different when compared to the conventional static or non-vibrated cutting.

The first example of these differences is to be noted in the influence of variable feed rate. In the case of aluminum the exponent of feed for static cutting is 0.78 whereas that for vibration varies from 0.6 for the lowest cutting speed up to 0.74 for the highest cutting speed, thus showing a tendency for the exponent of feed for vibration to increase with cutting speed

On the other hand, the corresponding exponents for cutting brass with vibration decreased from values well over 1.0 for the lowest cutting speed down to 0.87 for the highest cutting speed, thus again approaching the 0.86 value for static or conventional cutting of brass.

The base of reference and the trends for the above comparisons are summarized in lines 1 and 2 of Table XIX. If (n) is used as the exponent for feed in the equation for aluminum, then it can be shown that the exponent (n) increases as the 0.07 power of the cutting speed. Similarly, the exponent (a) for brass decreases as the 0.098 power of the cutting speed.

Three possibilities present themselves as feasible explanations for the differences in these trends. One is the built-up-edge forming tendency. It might be concluded that the stronger tendency of aluminum to form a built-up-edge would reflect itself in a less than proportionate decrease in cutting force as the feed rate and the cutting speed were reduced. This would appear to be a valid interpretation compared to the exponents measured for brass.

TABLE XIX

COMPARISON OF TRENDS SHOWN BY FORCE EQUATIONS

Condition		Aluminum	Brass
Static:	Variable Feed Variable Speed	$F_c = 2610\ f^{.78}$ $F_c = KV^{\circ}$	$F_c = 5530\ f^{.86}$ $F_c = CV^{\circ}$
Vibrated:	Variable Feed Exponent	$F_{cv} = C_v\ f^n$ $n = .417\ V^{.070}$	$F_c = C_v\ f^a$ $a = 1.93\ V^{-.098}$
Vibrated:	Variable Speed (low) Exponent	$F_{cv} = C_f\ V^m$ $m = 3.55\ f^{.157}$	$F_c = C_f\ V^b$ $b = .182\ f^{.136}$
Virbrated:	Variable Speed (high) Exponent	$F_{cv} = C_f\ V^m$ $m = .6$	$F_c = C_f\ V^b$ $b = .182\ f^{-.136}$
High Speed:	Static Vibrated	$F_c = 2610\ f^{.78}$ $F_{cv} = 1575\ f^{.74}$	$F_c = 5530\ f^{.86}$ $F_{cv} = 3460\ f^{.87}$
Heavy Feed:	Static (high speed) Vibrated	$F_c = 60\ V^{\circ}$ $F_{cv} = .291\ V^{.62}$	$F_c = 86\ V^{\circ}$ $F_{cv} = 3.54\ V^{.33}$
Heavy Feed:	Static (low speed) Vibrated	$F_c = 60\ V^{\circ}$ $F_{cv} = 6.28\ V^{.186}$	$F_c = 86\ V^{\circ}$ $F_{cv} = 3.54\ V^{.33}$

The second possible cause might be the difference in modulus of elasticity as between brass and aluminum. One might contend that the higher modulus of elasticity for brass would make the frictional rubbing at light feed rates less of a factor of influence than in the case of aluminum.

However, neither of these properties alone can explain why the exponent of feed rate increased with cutting speed in the case of aluminum and decreased in the case of brass. Perhaps the two of them together do explain this trend; on the other hand, there is yet a third possibility.

The third possibility arises out of the fact that the experimental tests on aluminum were conducted at a different time than for the brass and that the level of cutting forces for brass were appreciably higher than for the aluminum alloy. The difference in time and force level point to the possibility that the unmeasured motion components in directions other than a tangential direction may have been quite different for these two metals. There are no satisfactory theoretical bases for the first two of these possibilities and the third possibility cannot be resolved without measurements wherein the influences of motions in the other Cartesian coordinate directions are either measured or eliminated.

THE INFLUENCE OF CUTTING SPEED

It will be recalled that cutting speed exerted no influence on the cutting forces in the absence of superimposed vibrations. On the other hand, the presence of vibrations caused the ambient or average cutting forces to be decreased but of lesser magnitude as the cutting speed increased. The influence of speed was substantially continuous in the case of brass, but a marked change with the level of cutting speed was noted for aluminum. These conditions are expressed in lines 3 and 4 of Table XIX.

In the case of brass the cutting force in the presence of vibration increased with increases in cutting speed but at a decreasing rate with increases in the size of cut. For aluminum the cutting force in the presence of vibration also increased with cutting speed. On the other hand, the rate of increase was relatively slow at low cutting speeds and small size of cut but appreciably greater in the same speed range for larger sizes of cut. On the other hand, the influence of cutting speed in the high speed range appeared to be quite insensitive to size of cut and at least three times that for the low speed range.

SPECIFIC CUTTING CONDITIONS—HIGH SPEED

Line 5 of Table XIX shows that the sensitivity of cutting force to changes in feed rate are substantially the same for both brass and aluminum as between static or non-vibrated cutting on the one hand and cutting with superimposed vibration. However, a comparison at heavy feed in the high speed range shows that aluminum has about twice the sensitivity to cutting speed as does brass. On the other hand, in the low speed range at heavy feed rates brass shows approximately twice the sensitivity to cutting speed as does aluminum. These conditions are summarized in lines, 5, 6, and 7 of Table XIX.

The reasons for the differences cited in lines 2-7 of Table XIX may be explained in part by the three possibilities cited for lines 1 and 2 of this table but may also be related to the several characteristics associated with the velocity and cutting time ratios cited in Figs. 19 and 20. Only further studies of a fundamental nature and involving more sophisticated measurements can be expected to answer questions as to the relative significance of the possible contributory factors cited up to this point.

TERMINAL CUTTING SPEED

It will be recalled from Figs. 11-14 that the reduction in power component of cutting force from superimposed ultrasonic vibration decreased to zero at some extrapolated value of cutting speed. Summaries of such values for the variable amplitude tests are given in Table XX. These values show a somewhat erratic dispersion relative to feed rate, but they leave no question but that the limiting values for brass are approximately twice as high as those for aluminum. It was noted earlier that the reduction of the power component of cutting force diminished as the cutting speed increased in the presence of vibration so that persistence of this trend could eventually be expected to result in no reduction in spindle power. The speeds at which this would occur at the conditions used for the variable amplitude series are summarized in Table XX.

TABLE XX

LIMITING SPEED AT WHICH FORCE DURING VIBRATION IS AS LARGE AS WITHOUT

Material	Feed Rate, ipr			
	.001	.002	.004	.008
Aluminum	5,250 ipm	4,900	6,200	6,100
Brass	10,400	10,000	14,500	16,600

The data from this series were compared at a constant amplitude of 0.0005 in. or a full range of 0.001 in. at which condition the maximum vibratory velocity of the cutting tool was 4525 ipm. The motion analysis summarized in Figs. 19, 20, and Table XVIII show that the tool would no longer leave the underside of the chip when the ambient speed reached the calculated value of 4525 ipm.

It is interesting to note that the terminal velocities recorded for aluminum in Table XX are only slightly higher than the maximum vibratory velocity of 4525 ipm. On the other hand, the corresponding values for brass range from two to three times the calculated maximum vibratory velocity. It should be noted that the values for aluminum are as low as they are because of the discontinuity which appeared in the experimental results between the two highest cutting speeds.

There is nothing in the motion analysis which indicates that a discontinuity of this type should occur unless the elastic relaxation which was neglected in this analysis was sufficient to begin to exert a measurable effect between the two higher cutting speeds. Should this be true, then the lower modulus of elasticity of aluminum compared to that for brass could account for the discontinuity not yet having made an appearance in the experimental results obtained for brass. Should this true, then the terminal values reported for brass could be much too high. It should be noted also that had the terminal velocities for aluminum been determined by extrapolation of the lower trends they would have been almost an order of magnitude higher than those reported for brass.

Once more, however, one must be prepared to accept the possibility that the experimental results obtained for aluminum at the highest cutting speed were obtained at conditions which included disproportionately large components of motion in the feeding direction. The only experimental evidence that this might have occurred is in the form of the higher cutting forces. On the other hand, there is no experimental evidence to the effect that disproportionally large motion components in the feeding direction did not occur which leaves this possibility as an undetermined qualification on interpretation of the results recorded in Table XX.

VIBRATORY POWER

No known techniques nor instrumentation are as yet available for measuring the actual mechanical ouptut power of an ultrasonic transducer. Consequently, no direct measurement of this nature was made during this particular investigation. For similar reasons it was impossible to measure the instantaneous values of cutting force acting between the cutting tool and the workpiece. On the other hand, the fundamental principal of action and reaction can be invoked to conclude that whatever instantaneous value existed it acted equally upon the cutting tool and the workpiece so that one can calculate the distribution of work and power as between the transducer and the machine spindle. This makes it possible then to compare the total energy requirement as between conventional cutting and cutting with vibration as well as to compare the relative amounts conrributed by the spindle and the transducer. This was done for aluminum and brass as cut under the conditions of the variable amplitude series, and the results are summarized in Tables XXI-XXIII.

Table XXI summarizes the ratio of transducer work or power to spindle work or power for all five of the ambient cutting speeds illustrated in Fig. 20. It will be noted that the ratio (R) of transducer work to spindle work varied from as much as 9.32 at the lowest cutting speed to as little as 0.623 at the highest cutting speed.

The ratio (R) as listed in Table XXI was used to calculate the ratio of net cutting power during vibration to that required without vibration from the measured cutting forces as represented by the equations in Tables I-IV. The results are summarized in Table XXII.

TABLE XXI

RATIO OF TRANSDUCER WORK TO SPINDLE WORK*

(Range of Vibration = 0.001 in.)

Ambient Cutting Speed (V), ipm	Ratio, R
128	9.32
412	4.59
752	3.14
1380	1.96
3450	0.623

*Ratio = $R = F_{ci} \left[a + a \cos (\phi - 90) \right] / F_{ci} V T_1$

It will be noted from this table that the new power or energy for cutting with vibration was as much as 2.77 times that required without vibration. On the other hand, the use of vibration appeared to reduce the total net cutting power by as much as 25% as manifested in ratios as low as 0.75.

It is interesting that the higher ratios occur primarily at the lowest cutting speed and similarly that the lowest ratios within the experimental range occur primarily at the highest cutting speed. Extrapolations based on the equations in Tables I-IV give rise to some ratios even lower, but these are completely unconfirmed and should be ignored.

There cannot be much doubt that the total input energy of machine tool and the ultrasonic transducer is substantially greater for cutting with vibration than for conventional cutting, since it is extremely doubtful whether the conversion efficiency of the ultrasonic transducer is any better than 50% or even lower whereas the values calculated and tabulated in Table XXII consider only the output power of both the spindle and the transducer.

It should be emphasized at this point that the magnetostrictive, ultrasonic system used for this investigation must be thought of as an unsophisticated and underdeveloped system for conversion of electrical energy into mechanical energy. Consequently, one might reasonably expect that the efficiency of such a system can be substantially improved. Furthermore, the motion analysis indicates that extraneous motions could give rise to substantial frictional rubbing which could dominate estimates of the net power requirements during vibration. This appears to be a reasonable deduction from the relatively high ratios which occurred at the lowest cutting speed. Because of this possibility, one should not try to draw any conclusions with regard to the influence of strain rate and chip-tool interface friction from the calculated or estimated power requirements.

TABLE XXII

RATIO OF NET CUTTING POWER DURING VIBRATION TO THAT REQUIRED WITHOUT VIBRATION*

Ambient Cutting Speed, ipm	Work Material	Feed Rate, ipr .0005	.001	.002	.004	.008
412	Aluminum	2.540**	2.240**	1.970	1.745	1.600
	Brass	0.680**	0.935**	1.330	1.935	2.770
752	Aluminum	1.625**	1.570	1.515	1.460	1.415
	Brass	1.006**	1.130	1.204	1.270	1.470
1380	Aluminum	1.355	1.280	1.215	1.150	1.088
	Brass	1.090	1.150	1.215	1.290	1.360
3450	Aluminum	0.820	0.795	0.775	0.755	0.733**
	Brass	1.020	1.020	1.020	1.020	1.020**

*Ratio = $P_v/P_n = (1+R)\ F_{cv}/F_c$

**Outside of test range

TABLE XXIII

NET POWER IN WATTS AT DIFFERENT CUTTING CONDITIONS

Material	Feed, ipr		Speed, ipm		Conventional	Vibrated Total	Spindle	Transducer
Aluminum	Light	.001	High	3450	78	62	38	24
		.002	Low	412	16	31	5	26
	Heavy	.004	High	3450	226	171	106	65
		.008	Low	412	47	75	14	61
Brass	Light	.001	High	3450	98	100	62	38
		.002	Low	412	21	28	5	23
	Heavy	.004	High	3450	316	323	200	123
		.008	Low	412	67	185	33	152

If one neglected the possibility of frictional energy arising out of extraneous motions, then one could conclude that those ratios less than one indicated a reduction in shear-flow stress. On the other hand, the accompanying changes in chip formation and surface finish indicate an increase in shear angle and a corresponding decrease in the chip-tool interface friction, which also could account for the reductions manifested by those ratios less than one. These latter improvements were even more evident at the lowest cutting speed where the higher ratios of the order of 2.0 also occurred. Thus one might conclude that this is still further evidence of the undetermined role of frictional energy required by extraneous motions.

The power requirements for selected representative conditions were converted to watts and summarized in Table XXIII. It will be noted that the calculated output of the transducer ranged from a low of 23 watts up to a maximum of 152 based on the motion characteristics derived from Fig. 19 and the measured cutting forces as expressed by the equations in Table I-IV. This entire range of transducer output might reasonably be expected from the equipment at hand, although it is clear that the higher values were approaching the maximum capability of the equipment.

CONCLUSIONS AND RECOMMENDATIONS

This study did not answer all of the questions which might be asked with regard to the consequences of superimposing ultrasonic vibrtions on metal cutting. This is especially true for fundamental questions regarding the influence upon shear-flow stress, chip-tool interface friction, total energy requirements, and stress distribution in the shear zone. On the other hand, it has identified and at least partially evaluated the influence of ambient cutting speed and the relation of size of cut to the force carrying and power capabilities of the vibratory system. Further, it has clarified substantially from a practical viewpoint the useful range of application and the benefits to be derived.

The results as well as the experience obtained lead to several recommendations with regard to fundamental studies which will further improve the understanding of the process and equipment design necessary for the practical application of the process.

CONCLUSIONS

It may be concluded that ultrasonic vibrations superimposed on metal cutting can

1. reduce the ambient forces superimposed on the machine tool system by as much as 90% or more;

2. reduce substantially the low frequency oscillatory component of cutting force acting upon the macine tool system;

3. inhibit or eliminate chatter;

4. produce more uniform chips; and

5. improve surface finish.

It may be concluded further that

1. the above benefits can be derived concurrently only when the cutting tool is vibrated substantially in the tangential direction;

2. no substantial decrease in energy requirements may be expected but may even require an increase in total energy;

3. the benefits are most pronounced at low cutting speeds wherein the cutting tool is in contact with the workpiece and the underside of the chip only a small fraction of the total elapsed cutting time;

4. the tool life may be decreased if the tool material is susceptible to cracking by impact and fatigue; and

5. the maximum cutting temperature might increase.

It is evident also that a cutting fluid in the form of a liquid is no more effective in the presence of vibration than it is without. This might be expected because of the considerable forces required to overcome the inertia of the liquid compared to that for air in penetrating the gap which opens up between the chip and the cutting tool in the presence of effective vibration.

RECOMMENDATIONS

As a result of the experience gained during this investigation and looking forward toward applications suggested by the above conclusions, it is recommended that further measures be taken as follows:

1. That consideration be given to improved design for supporting the transducer horn against the cutting forces and reducing the attendent loss of frictional energy at the point of support as indicated in Fig. 21(a);

2. Investigate the feasibility of achieving the desired vibration in a tangential direction with a quarter wavelength tool vibrated in shear as suggested in Fig. 21(b);

3. Consider other ways for exciting the quarter wavelength tool as suggested in Fig. 21(b);

4. Study the complex motion characteristics with combinations of concurrent motion in all three Cartesian coordinate directions in relation to their influence on metal cutting;

5. Study the influence of ultrasonic vibrations created by motion of the cutting tool upon the properties of the work material and the distribution and magnitude of dislocations within the work material; and

6. Develop close -loop control so that the excitation frequency can be changed automatically to achieve maximum amplitude of vibration.

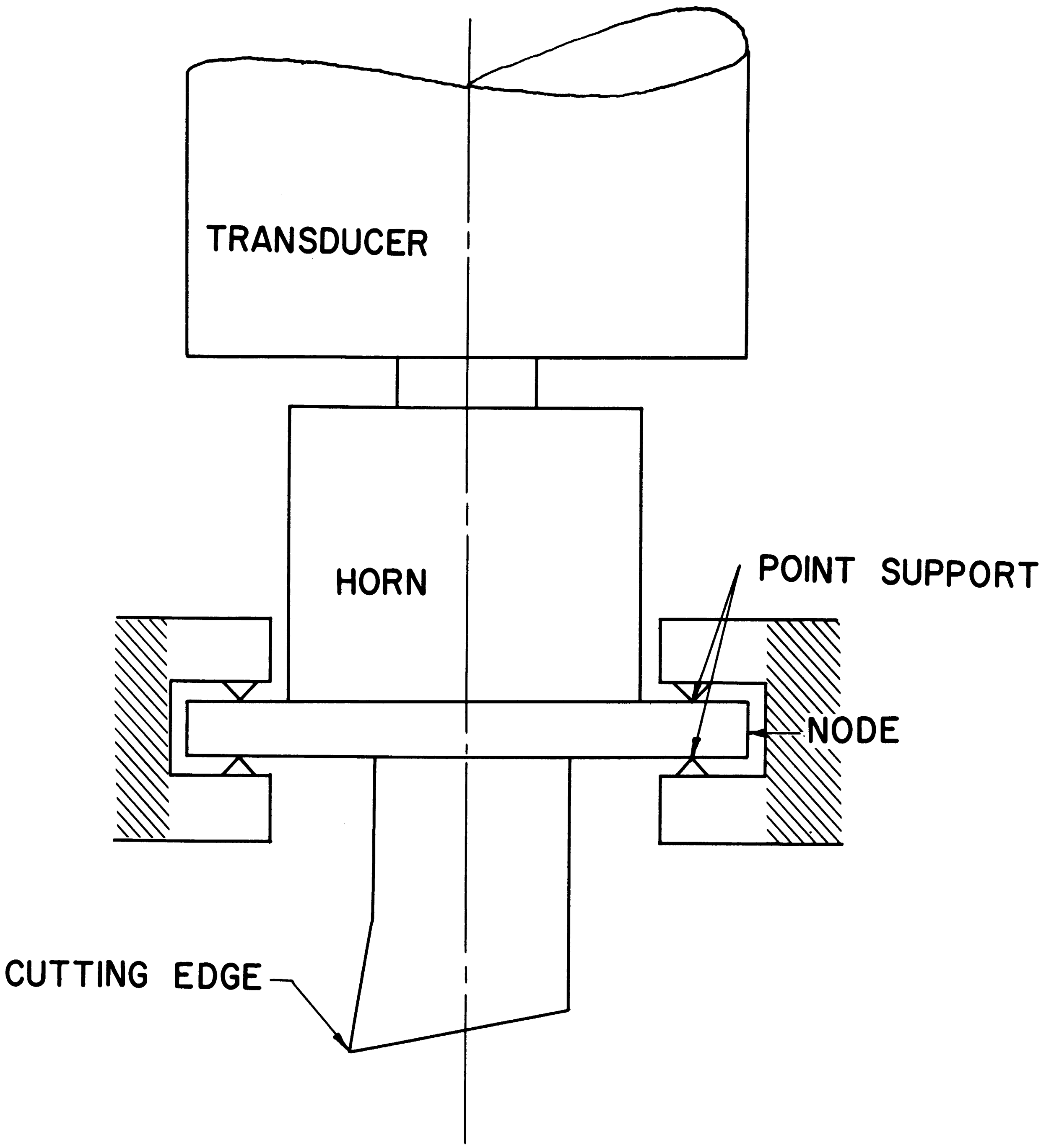


Fig. 21(a). Schematic of tool support system.

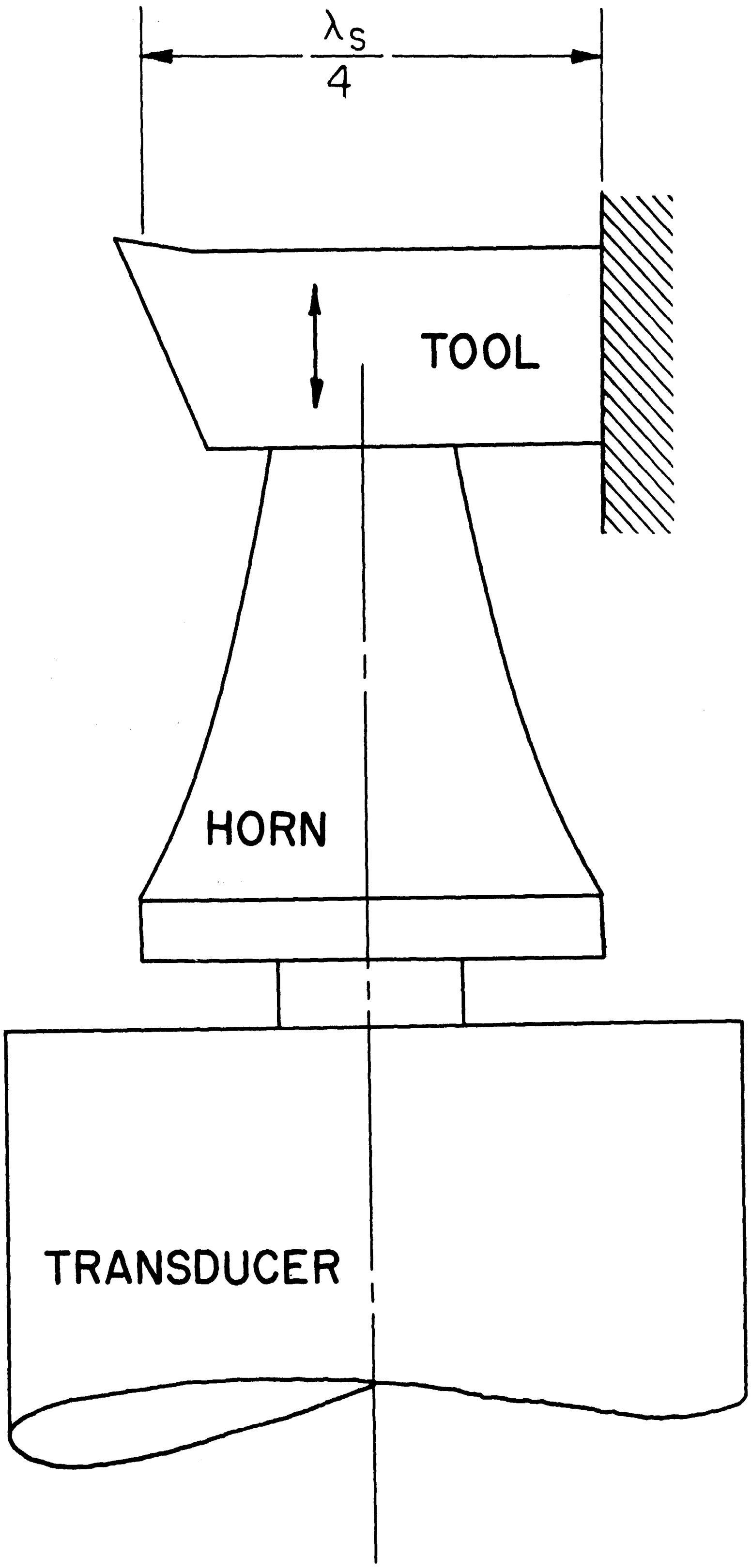


Fig. 21(b). Suggested modification of tool support system.

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2. V. H. Poduraev and Yu. E. Zakharov. (1959) "Turning with Oscillating Tools," Stanki i Instrument 30, No. 12, pp. 11-16.

3. A. A. Voronin and A. I. Markov. (1960) "Effects of Ultrasonic Vibrtions in Machining Creep-Resisting Alloys," Stanki i Instrument 31, No. 11.

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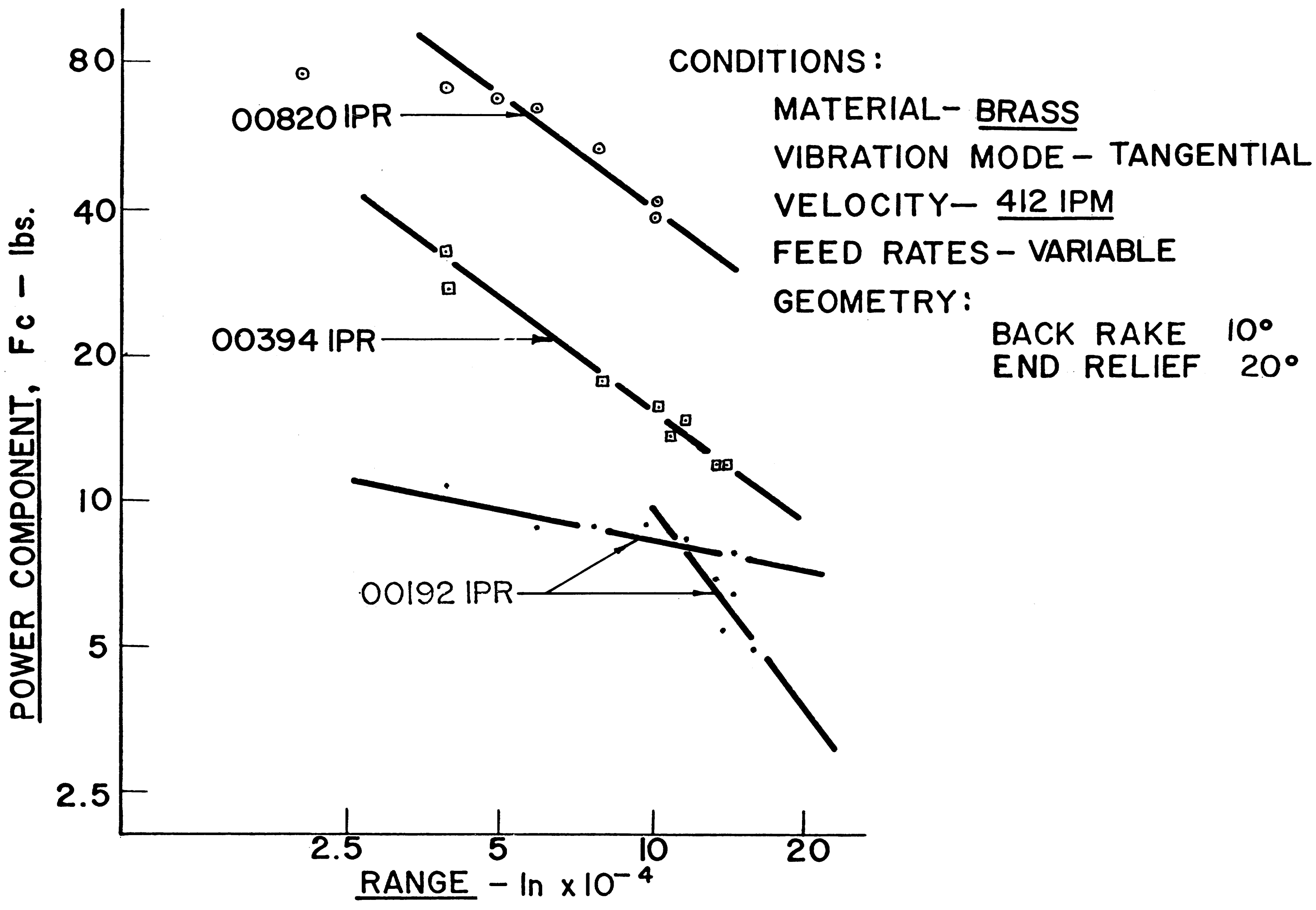
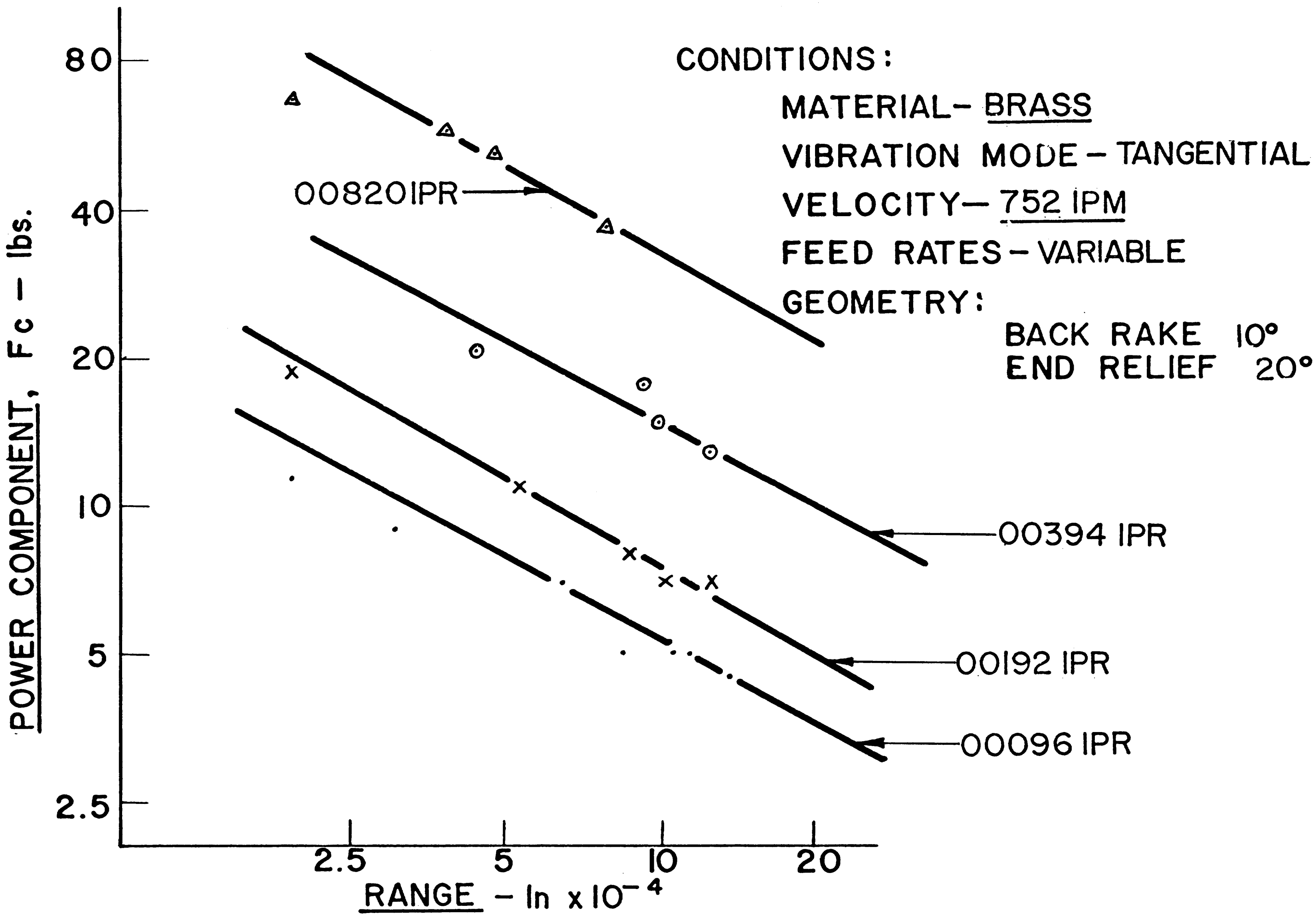
APPENDIX A

ADDITIONAL PLOTS OF ORIGINAL DATA

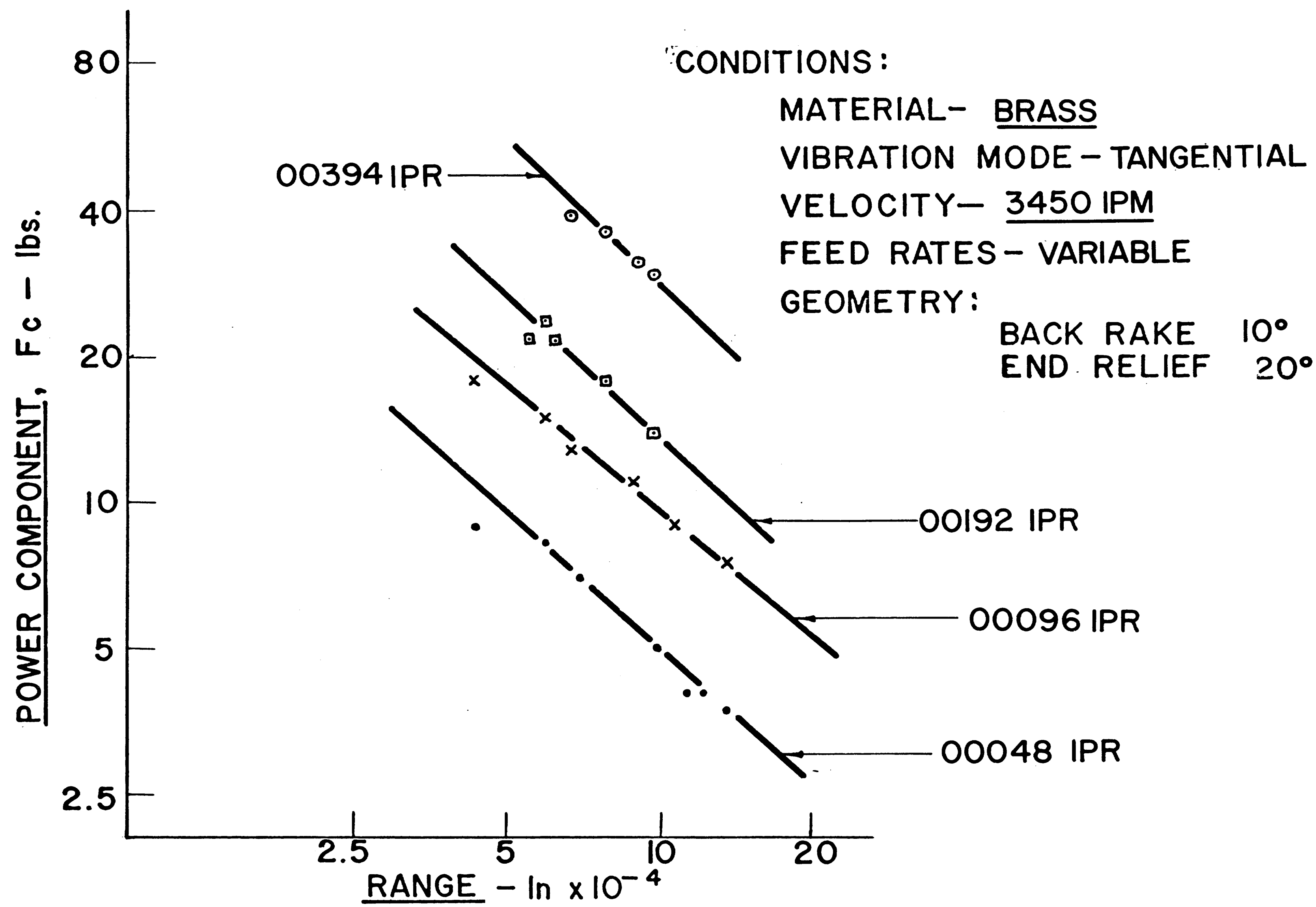


CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 22



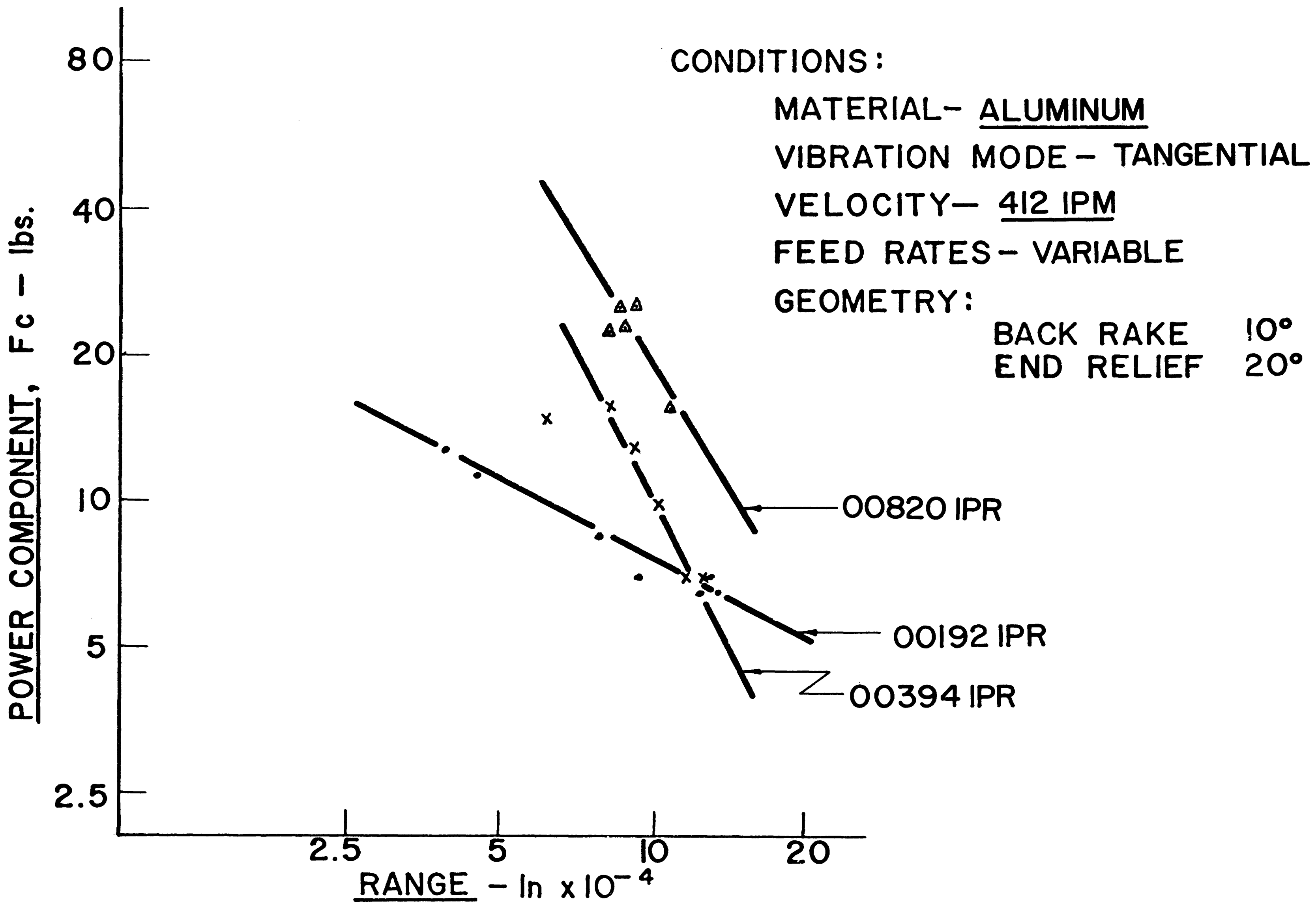
CUTTING FORCE VERSUS VIBRATION RANGE

FIG. NO. 23

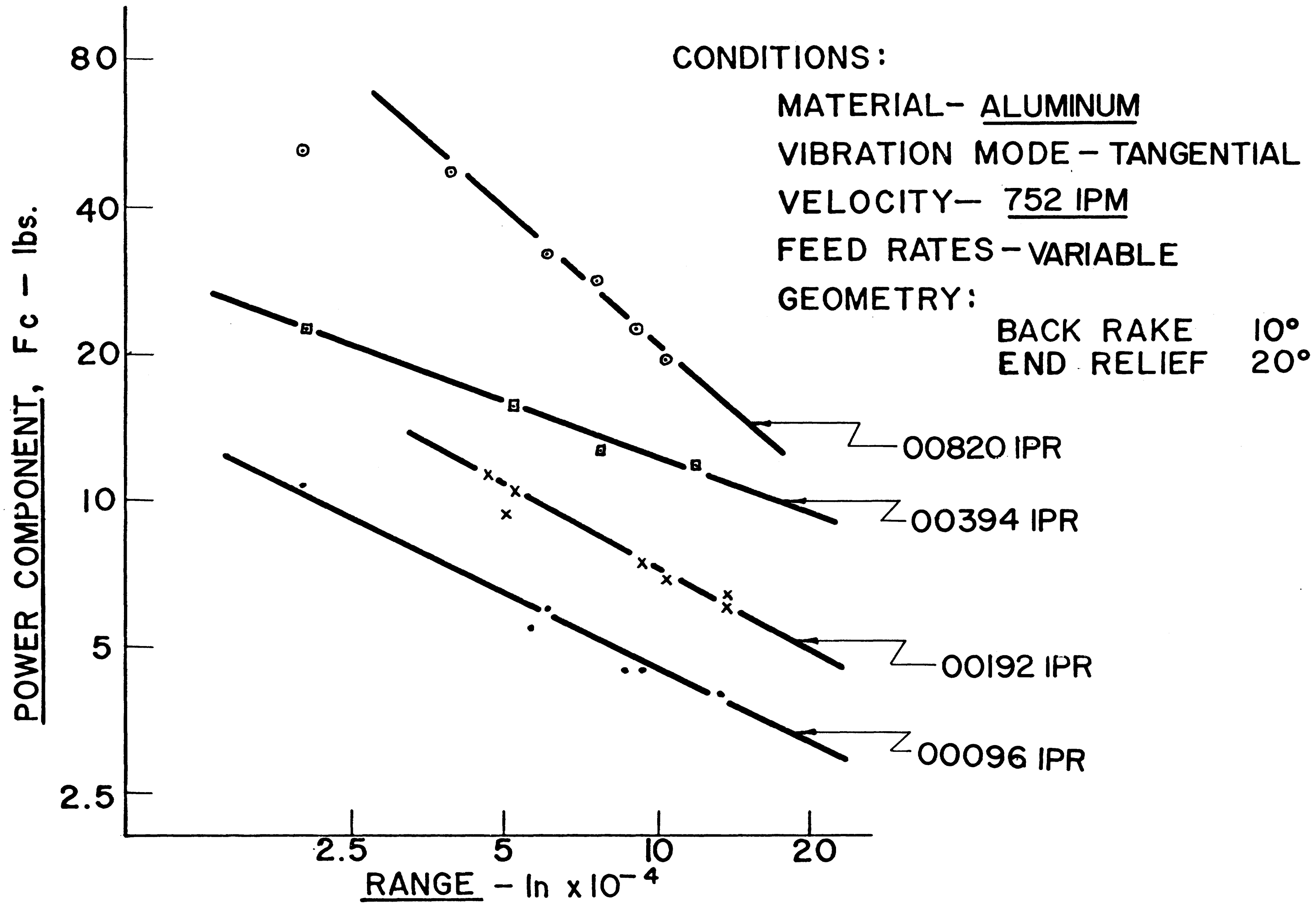


CUTTING FORCE VERSUS VIBRATION RANGE

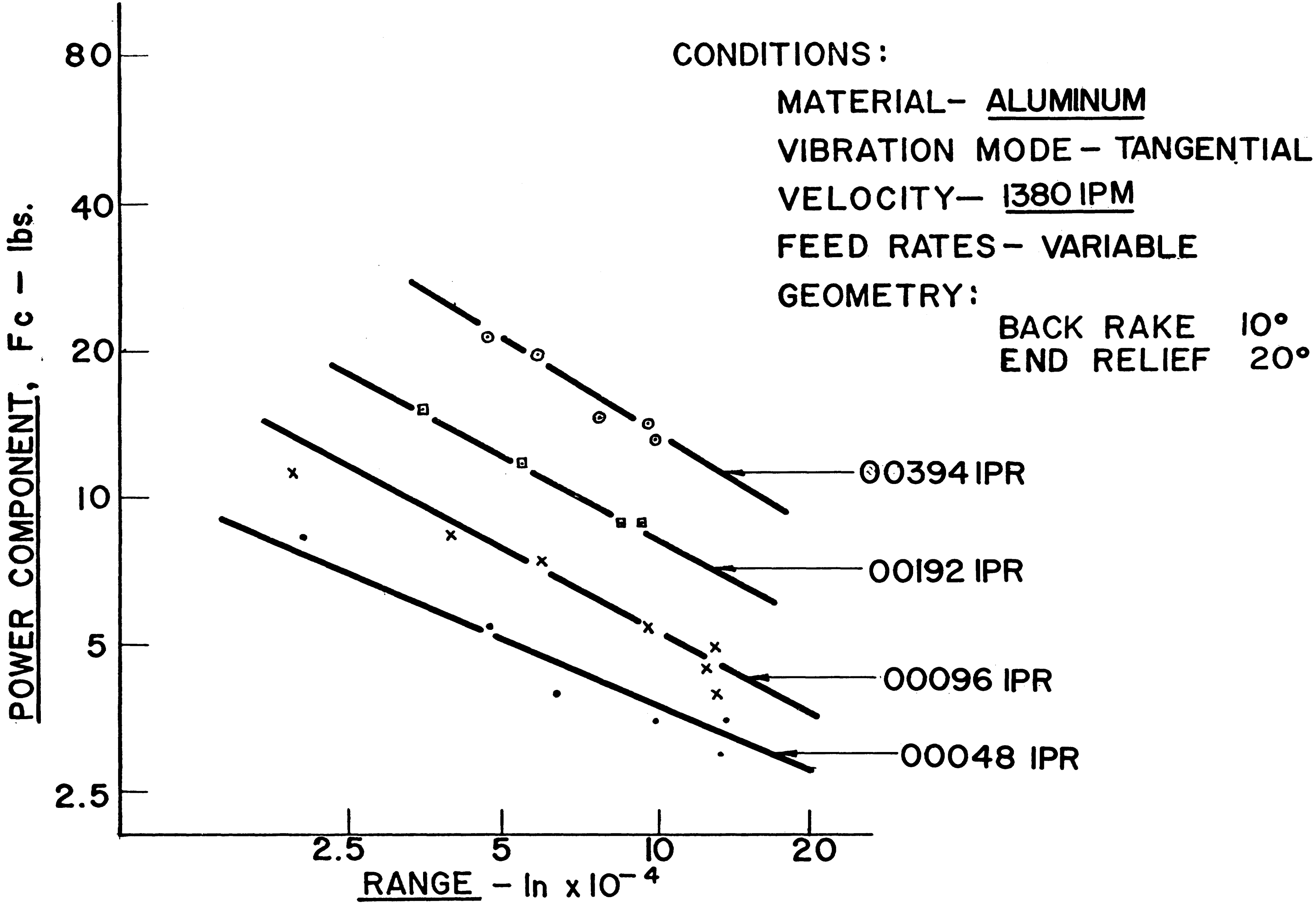
FIG. NO. 24



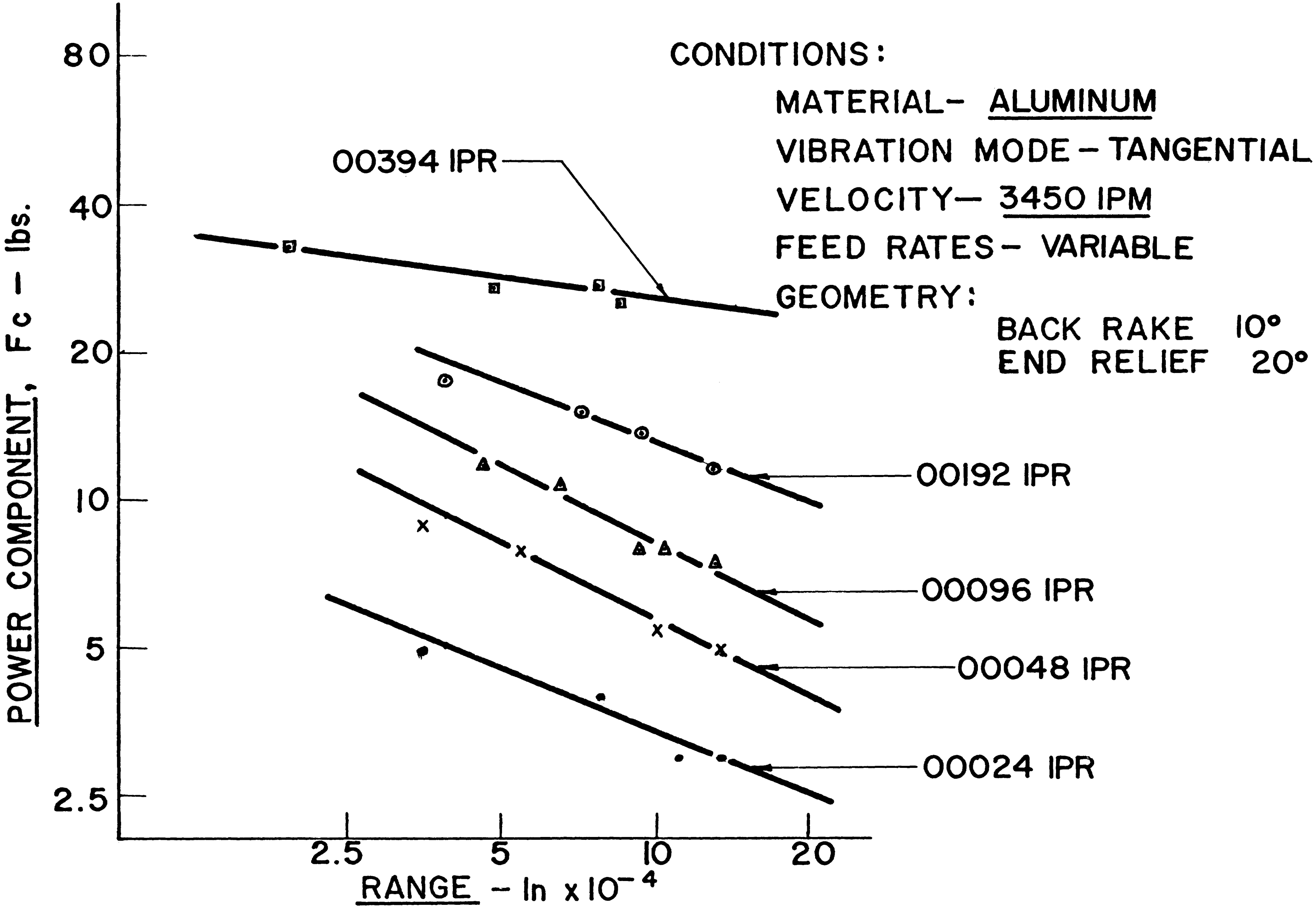
CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 25



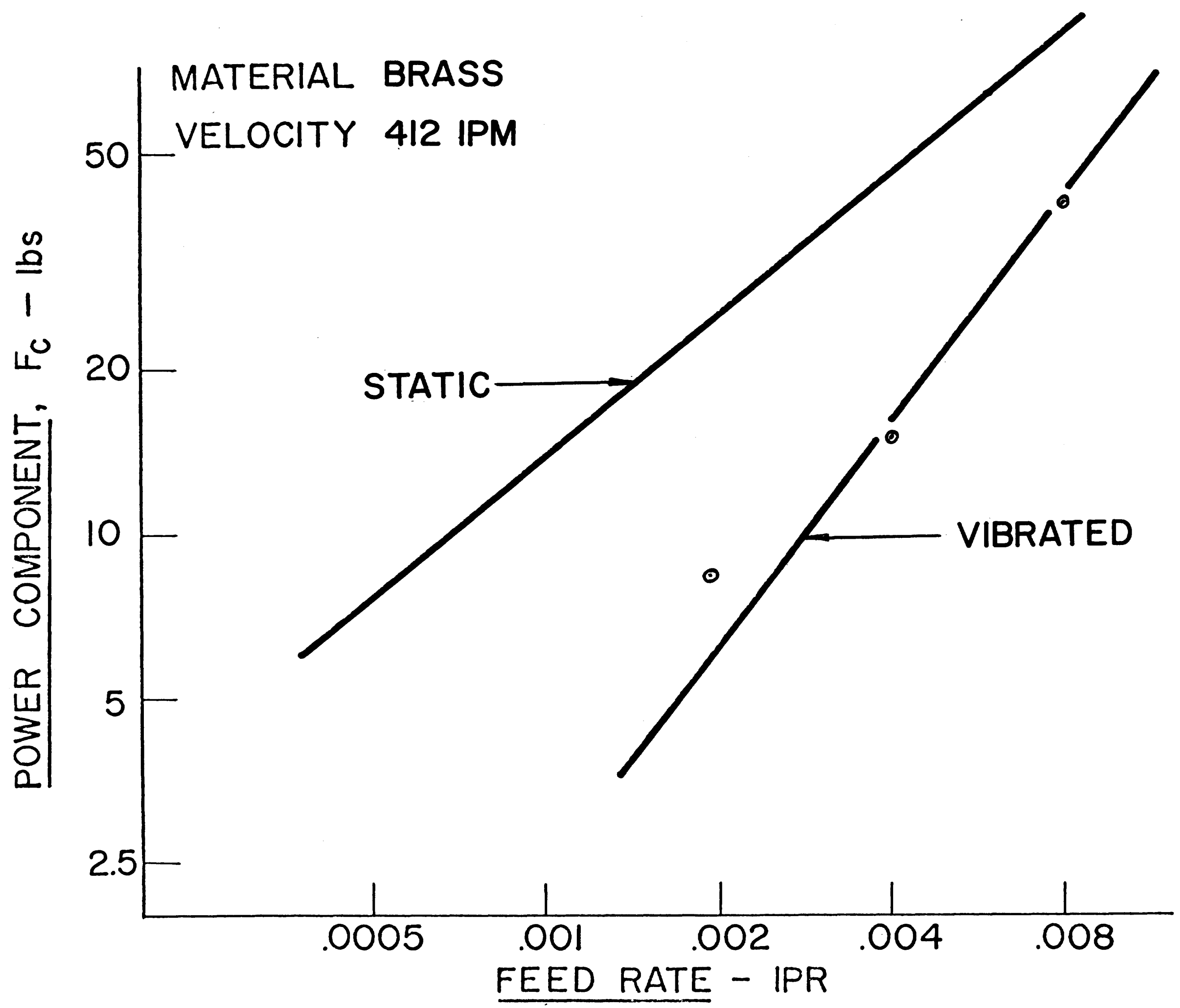
CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 26



CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 27

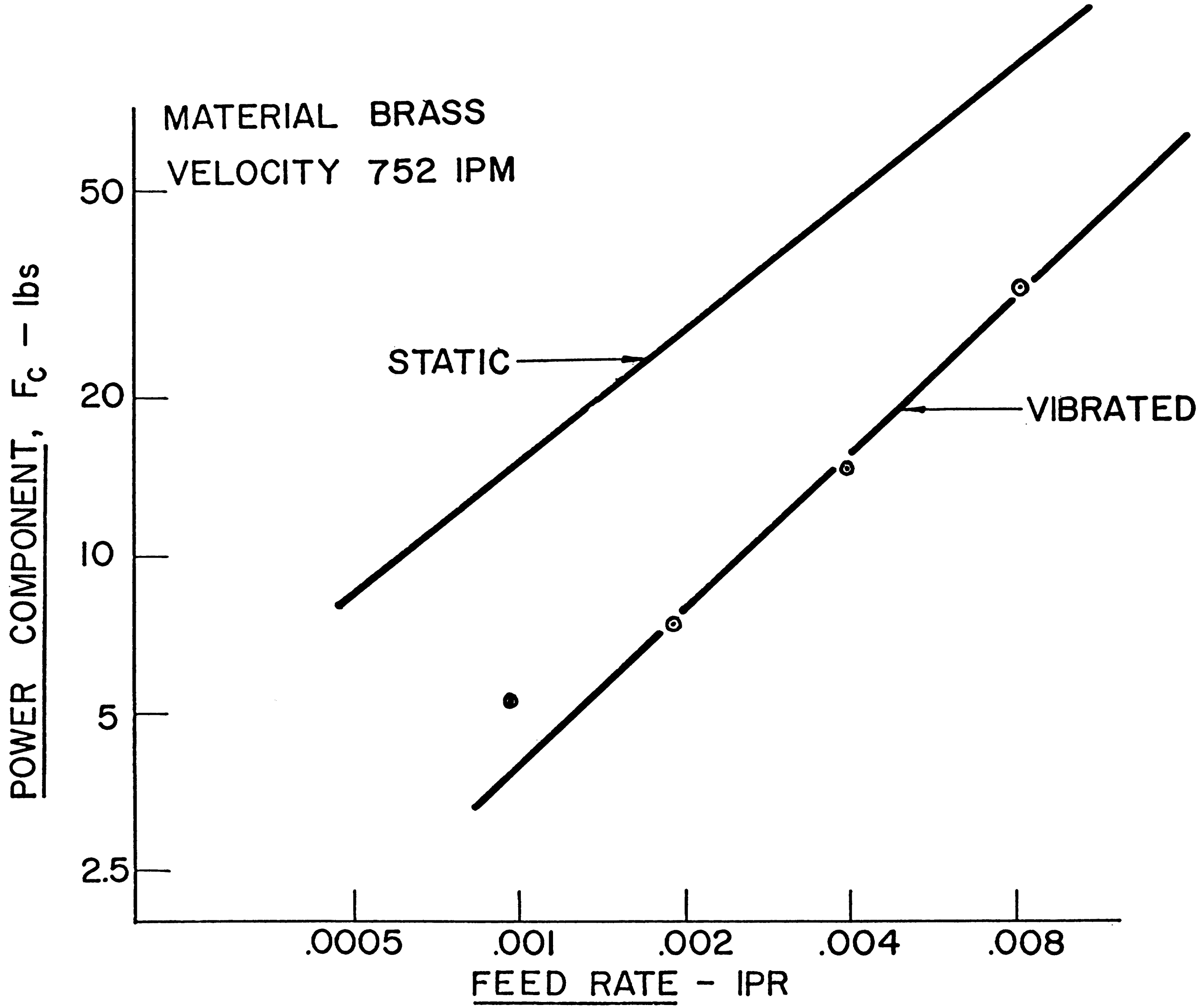


CUTTING FORCE VERSUS VIBRATION RANGE FIG. NO. 28



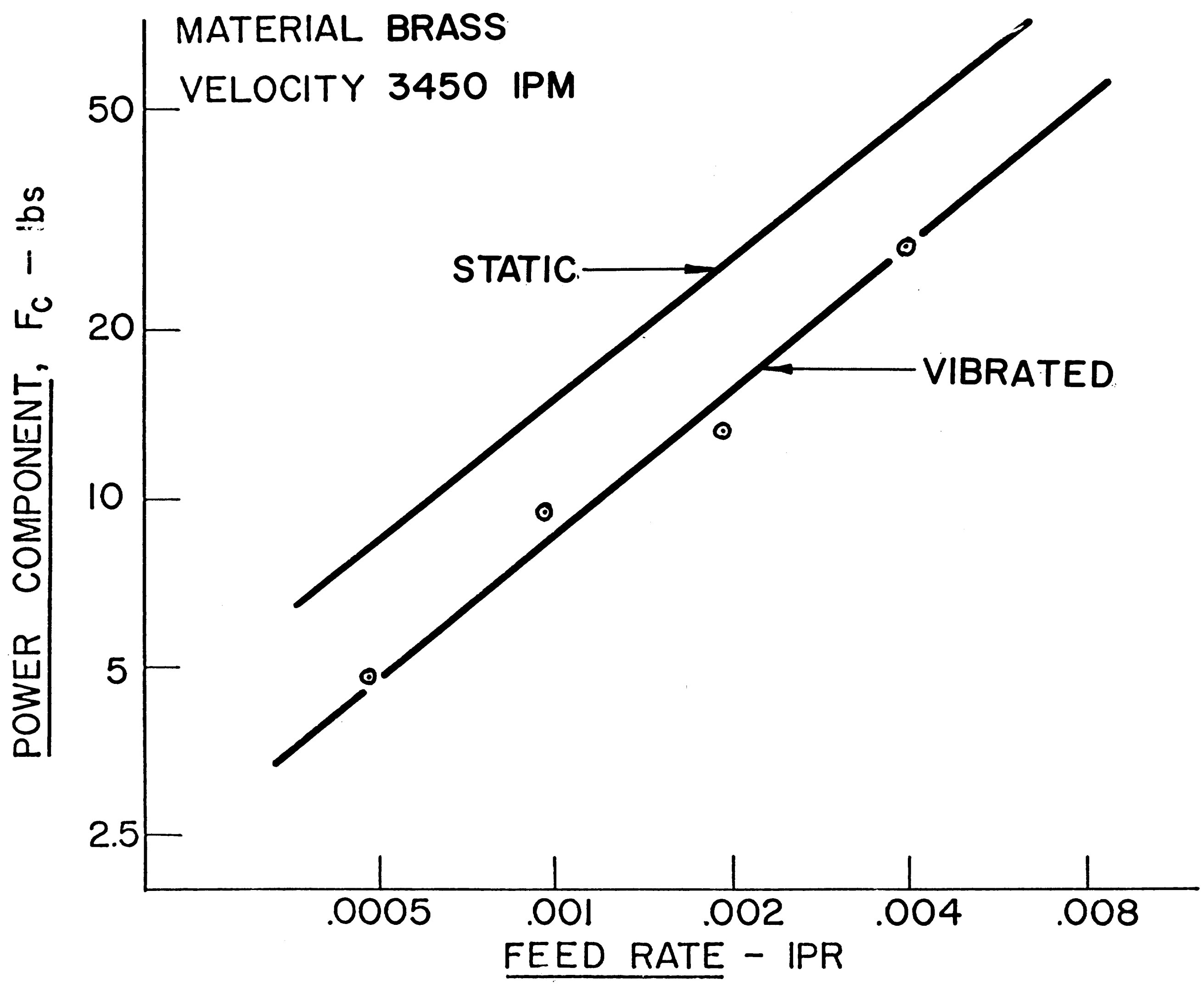
CUTTING FORCE VERSUS FEED RATE

FIG. NO. 29



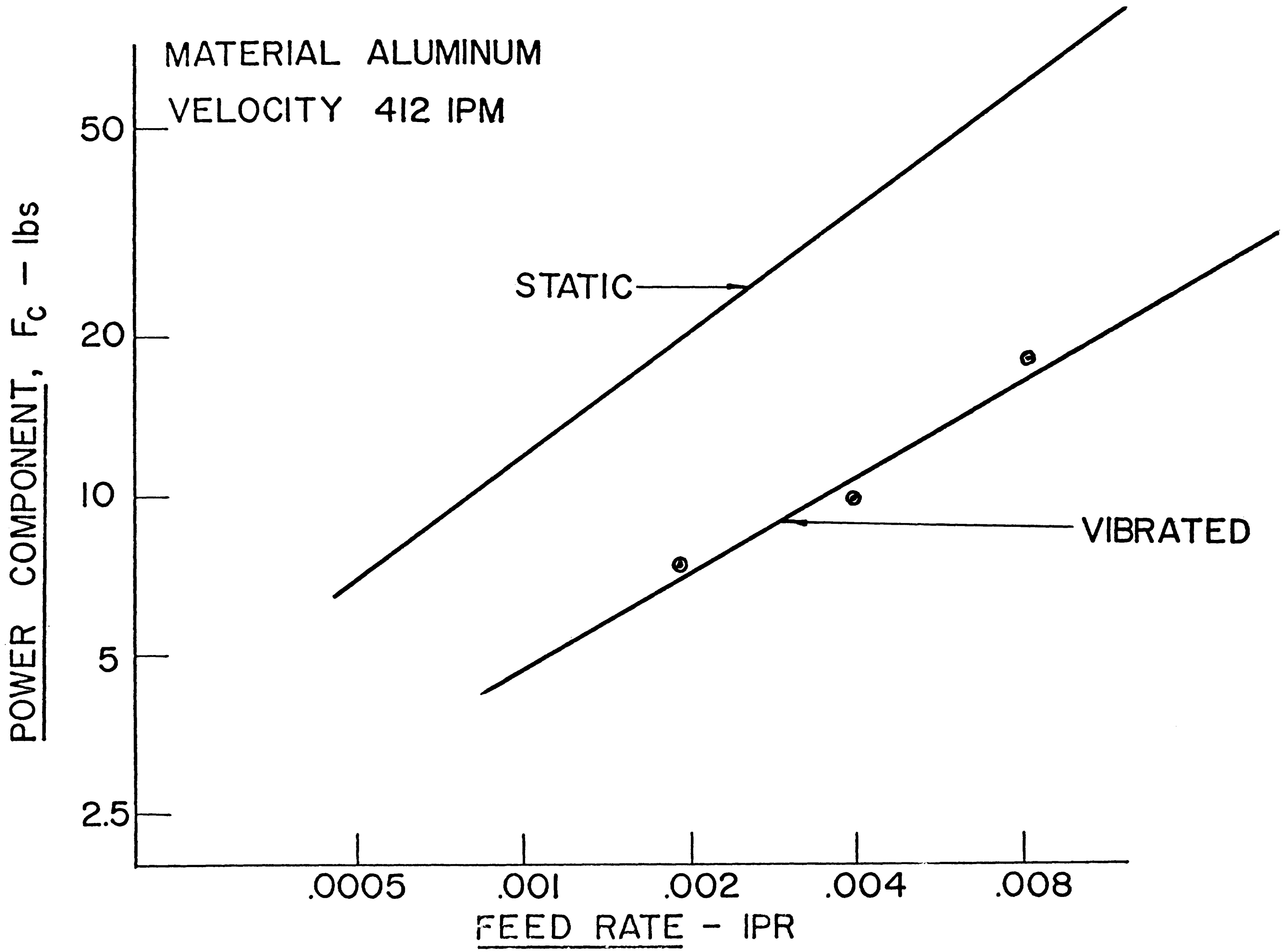
CUTTING FORCE VERSUS FEED RATE

FIG. NO. 30



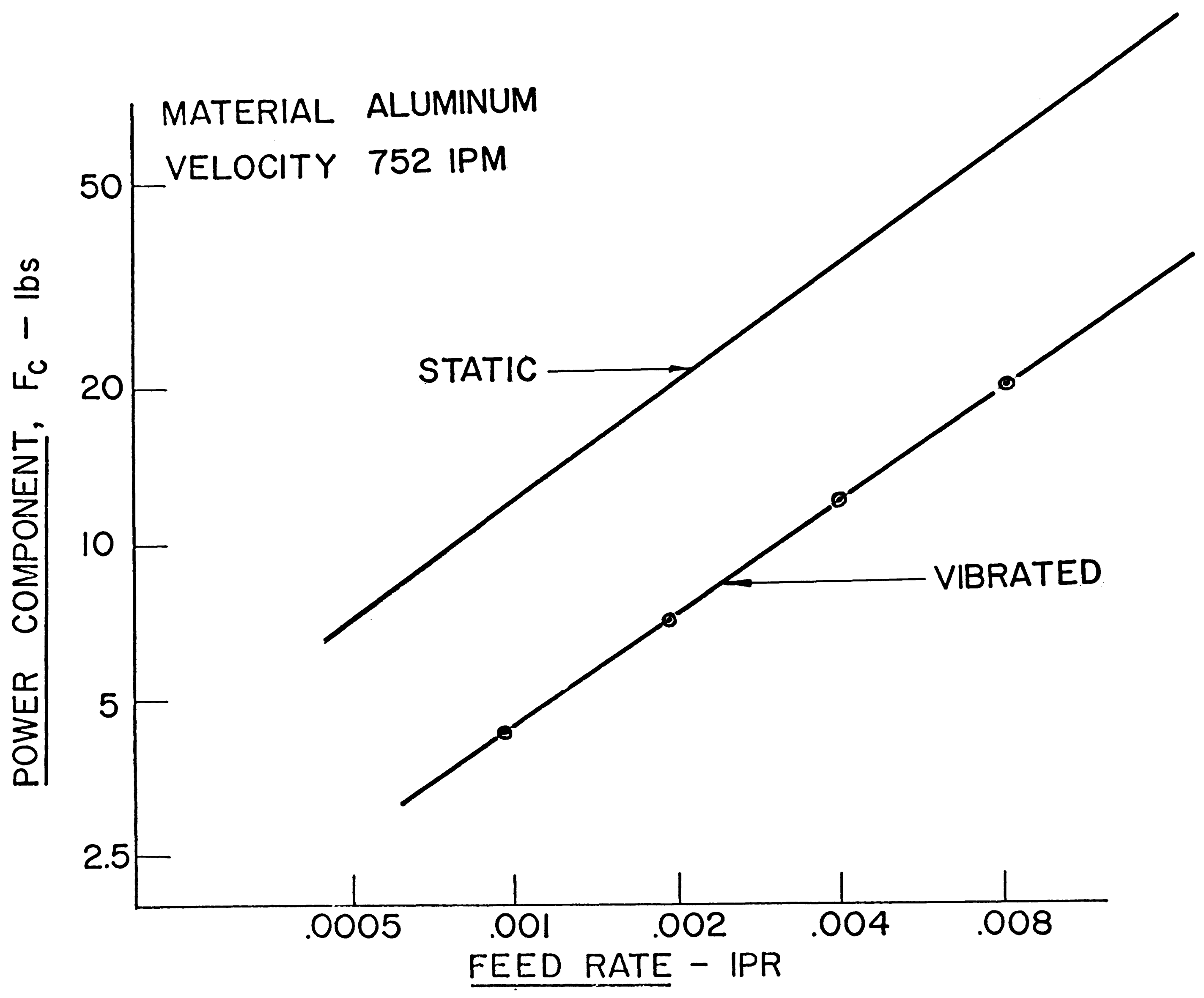
CUTTING FORCE VERSUS FEED RATE

FIG. NO. 31



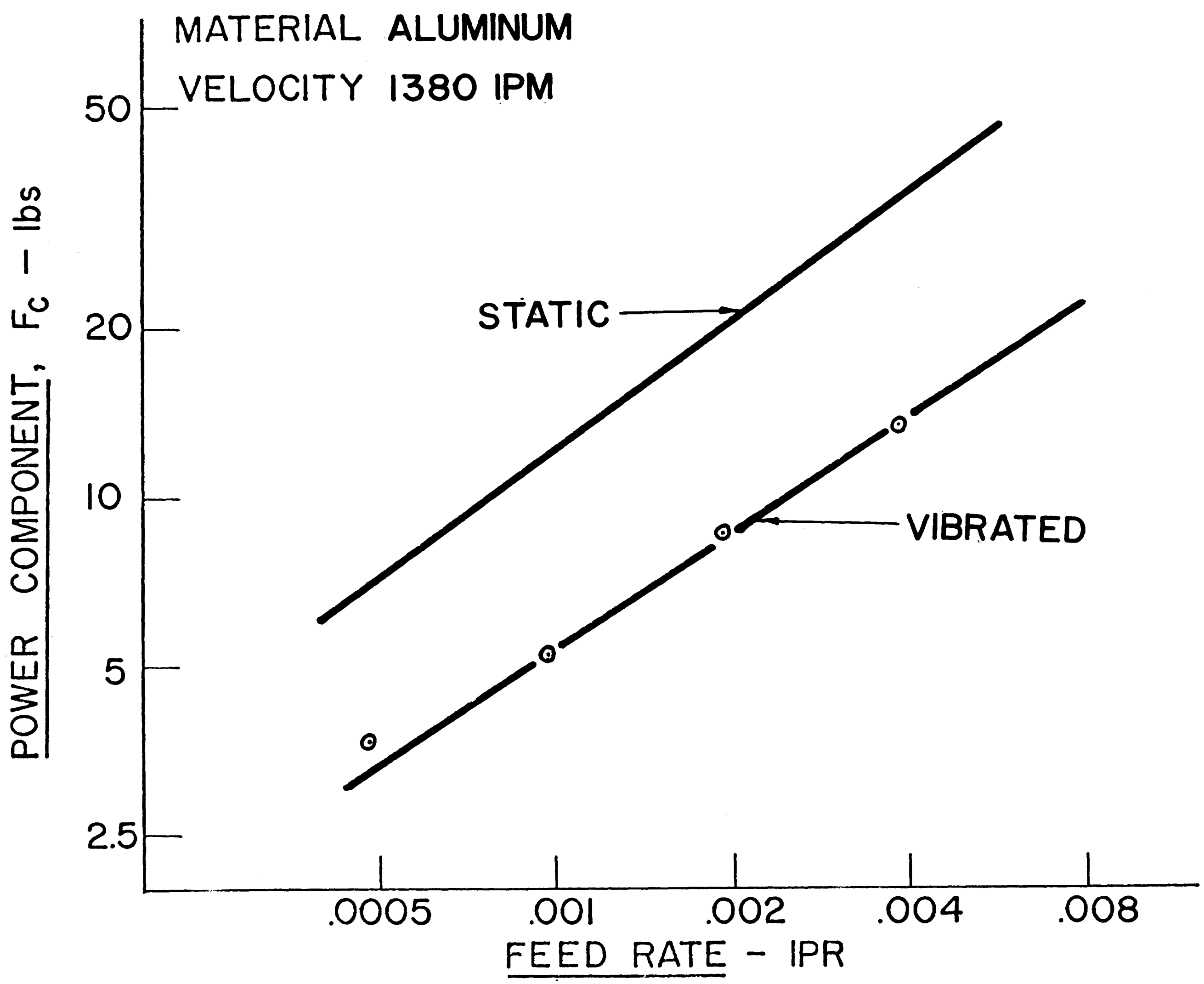
CUTTING FORCE VERSUS FEED RATE

FIG. NO. 32



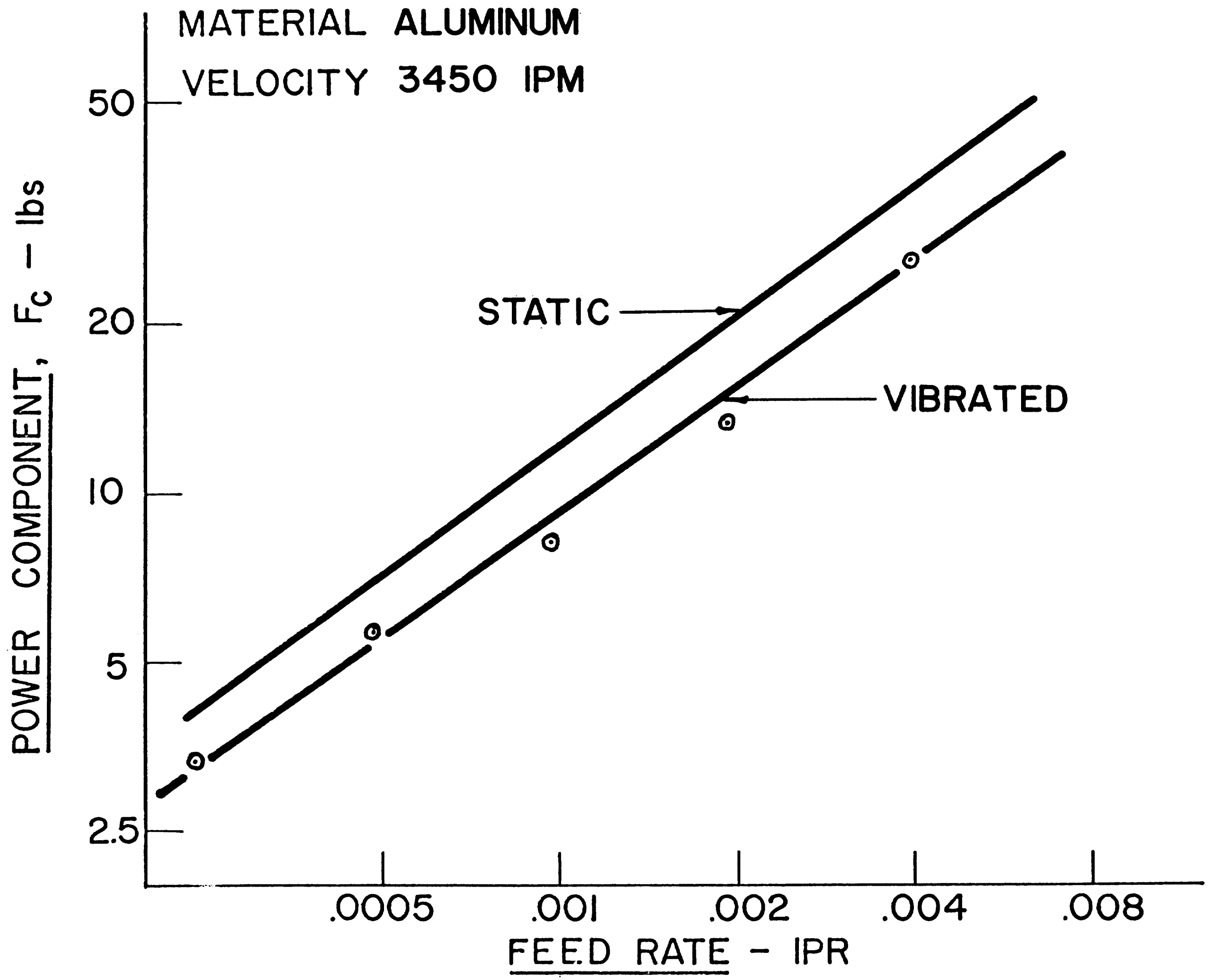
CUTTING FORCE VERSUS FEED RATE

FIG. NO. 33



CUTTING FORCE VERSUS FEED RATE

FIG. NO. 34



CUTTING FORCE VERSUS FEED RATE

FIG. NO. 35

APPENDIX B

TEST MATERIALS

Material	Description	Ultimate Strength, ksi	0.2% Yield Strength, ksi	Hardness
2011-T3*	5-6% Cu, 0.4% Si, 0.7% Iron, 0.3 Zn, Cold rolled	55	43	95 BHN at 500 kg load
2024-T4*	4-5% Cu, 0.5% Si, 0.5% Mn, 1.5% Mg, 0.25% Zn, Cold rolled	68	47	120 BHN at 500 kg load
Brass*	70% Cu, 30% Zn Cold rolled	60	42	116 BHN at 500 kg load
4340	0.4% C, 0.7% Mn, 1.8% Ni, 0.8% Cr, 0.25% Mo, 0.3% Si	168	225	RC 40-42
TZM 7479**	99.4% Mo, 0.5% Ti, 0.08% Zr, Wrought-Stress Relieved	120	18-28	272-281 DPN at 10 kg load
100W 7294**	Commercially Pure Tungsten, Extrusion-Recrystallized			
Rene 41*** (AMS 5712)	0.08% C, 0.005% S, 0.1% Si, 0.10% Mn, 19.1% Cr, 9.7% Mo, 11.0% Co, 3.16% Ti, 1.52% Al, 0.19% Fe, Balance Ni	196	142	RC 35

*Alcoa Screw Machine Stock, 1959.
**Climax Molybdenum Company, "Product Certification."
***Alloy Metals, Inc., "Certificate of Test."