FORCES IN SINGLE GRIT GRINDING

by

ROBERT HALLOWES BROWN

B. Mech. E., University of Melbourne

(1954)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August, 1957

Signature of Author Signature redacted
Department of Mechanical Engineering, August, 1957

Certified by Signature redacted
Thesis Supervisor: Nathan H. Cook
Assistant Professor of Mechanical Engineering

Accepted by Signature redacted
Chairman, Departmental Committee
on Graduate Students

ME
Thesis
1957

August 9, 1957

Professor Leicester Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering from the Massachusetts Institute of Technology I submit this thesis entitled, "Forces in Single Grit Grinding".

Respectfully submitted,

Signature redacted

Robert H. Brown

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor N. H. Cook and Professor M. C. Shaw for their counsel and guidance.

He also expresses his appreciation to the Carborundum Company, Niagara Falls, New York, for their support and cooperation in this project.

Finally, mention must be made of the help and advice received from the staff of the M.I.T. Machine Tool Laboratory. The material help by the preparation of equipment and the advice on theoretical aspects were invaluable.

FORCES IN SINGLE GRIT GRINDING

by

Robert Hallowes Brown

Submitted to the Department of Mechanical Engineering on August 1957 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

A simple strain gauge dynamometer was constructed for the measurement of the tangential force on a cutting tool used in a manner similar to a fly milling cutter. Different types of abrasive grits and later a piece of sintered aluminum oxide were used for the cutting.

Initial tests using actual grinding grits on 1020 steel, 150A titanium, and aluminum indicated an increase in specific energy with decrease in chip depth of cut. However, there was considerable scatter between grits of the same type and in some cases scatter for any one grit.

Force measurements were made using sintered aluminum oxide of known geometry. These gave good repeatability of results and a series of tests were made using different rake angles and different lengths of wear land. It was found that the length of the chips could be measured with moderate accuracy, so that the cutting ratio and shear strain could be calculated, at least approximately.

Rake angle and wear land were found to have a considerable influence on specific energy. Shear strain was much higher than in conventional turning. These results suggest that the calculated shear stress for grinding wheels should be considerably lower than previously determined.

Wear studies were conducted with the ceramic tools and wear land measurements were made. From this, grinding ratio values were calculated and found to be considerably lower than the values previously found for aluminum oxide and silicon carbide in single grit cutting.

A brief discussion of surface temperature calculation in grinding indicates that these temperatures may be lower than has been suggested in the past.

Thesis Supervisor: Nathan H. Cook
Title: Assistant Professor of Mechanical Engineering

TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONTD)

INTRODUCTION

This study was suggested by the previous work carried out at M.I.T. on wear studies in single abrasive grits. It seemed that similar apparatus could be used for measurement of the cutting force of single grits. This appeared to be an interesting line of approach since it would allow direct measurement of force per grain, of width of cut, and of depth of cut. So that average values did not have to be resorted to, as has been necessary in all previous force measurements in grinding.

One of the initial major objectives was the investigation of the "size effect" which has been reported in all types of wheel grinding and in belt grinding. It was felt that a demonstration of the existence of size effect in single grit grinding would be of significance, since the effects of chips jamming between grits would be eliminated, and hence, would be effectively discounted as a source of the size effect. Furthermore, the depth and width of cut would be known with more certainty than was possible where many cutting points are simultaneously employed. Thus it was hoped to indicate whether the "size effect" in grinding was basically caused by the reduced depth of cut or whether it resulted from other variables not previously considered.

SUMMARY

A simple strain gauge dynamometer was constructed for the measurement of the tangential force on a cutting tool used in a manner similar to a fly milling cutter. Different types of abrasive grits and later a piece of sintered aluminum oxide were used for the cutting.

Initial tests using actual grinding grits on 1020 steel, 150A titanium, and aluminum indicated an increase in specific energy with decrease in chip depth of cut. However, there was considerable scatter between grits of the same type and in some cases scatter for any one grit.

Force measurements were made using sintered aluminum oxide grits of known geometry. These gave good repeatability of results and a series of tests were made using different rake angles and different lengths of wear land. It was found that the length of the chips could be measured with some degree of accuracy so that the cutting ratio and shear strain could be calculated, at least approximately.

Rake angle and wear land were found to have a considerable influence on specific energy. Shear strain was much higher than in conventional turning. These results suggest that the calculated shear stress for grinding wheels should be considerably lower than previously determined.

Wear studies were conducted with the ceramic tools and wear land measurements were made. From this, grinding ratio values were calculated and found to be considerably lower than the values previously determined with aluminum oxide and silicon carbide grits.

A brief discussion of surface temperature calculation indicates that these temperatures are lower than previously thought.

DISCUSSION OF THE GRINDING PROCESS

As has been pointed out several times in recent articles, knowledge of the grinding process is far less complete than that of single point cutting. There are a number of reasons why this is so, the most important being the technical difficulty of grinding studies. This difficulty arises from the random geometry of the cutting points, the small depths of cut, the high speeds, the relatively small forces involved, and the small laterial extent of the grinding grits.

In grinding (as for other metal removal processes) the basic objective is to obtain a surface, which corresponds with a satisfactory accuracy, to a desired geometrical form; at the same time the process should be as economical as possible. The degree of accuracy required for any particular surface depends on its functional requirements. Since the cost of the process, in general, increases as the accuracy is increased, it is obvious that accuracy of the surface should not be better than absolutely necessary for correct function.

Grinding is usually considered to be a finishing process, since it is often preceded by rougher and faster stock removal processes. However, whether preceded by coarse machining or used directly on forged or cast surfaces, a certain amount of stock must always be removed to obtain the desired dimensions. For this reason the rate of metal removal is a variable of interest in considering the economics of the process.

To achieve the basic objectives, a complete knowledge of how each independent control variable affects the process, is obviously desirable. If this knowledge was available, values for the grinding variables could be selected to produce a particular surface - alternative selections could be evaluated from the economic considerations of cutting rate and rate of wheel wear.

A further factor which should be specifically mentioned at this stage, although it has been tacitly assumed by the word, "accuracy," is the injury which ground surfaces may suffer. Cracks, residual stresses and burn may be left in the surface if conditions are not satisfactory. An understanding of the defects and the method of eliminating these by correct control of the grinding variables, in the same way that accuracy should be controlled, is necessary.

At first sight it seems strange that the influence of all the variables in grinding has not been investigated and general empirical rules laid down for all types of operations. Although several attempts have been made to do this, the large number of variables involved and the complex interactions between them have led to results which are not completely satisfactory. A more useful approach to the problem seems to be by a step by step analysis of the basic mechanics of the process. This should (and has already, to a large extent) led to a simplified selection of conditions in any practical application and also aid in determination of basic improvements in the process.

It is worthwhile considering briefly the work which has been carried out in an attempt to understand the mechanics of the process. This is discussed in two sections, firstly, under the heading, "forces," and secondly, "wear."

Forces

Before 1914 it was realized that the mechanism of grinding was basically similar to single point cutting. Alden (1)[1] seems to have been the first to directly apply this knowledge. He found a relation, in cylindrical grinding, for the maximum chip depth of cut (t) in terms of the wheel and work speeds, the wheel and work arcs of contact, and mean grit spacing. He then assumed

---

[1] Numbers in parentheses refer to the bibliography at the end of the paper.

that the tangential, or cutting force was directly proportional to the chip depth of cut. Guest (2) extended the work of Alden to give a simpler chip thickness relation depending on the radii of wheel and work. This had the form:

$$t = \frac{v}{nV} \sqrt{\frac{(R + r)\ 2d}{R.r}}$$

where v and V are work and wheel rim velocities, respectively

r " R " " " " " radii

n is the number of cutting grits per unit wheel length

d is the wheel depth of cut (or downfeed)

Guest assumed that the cutting force was proportional to the area of cut and with the further assumption that the projecting portions of the grits were approximately triangular in shape was led to the relationship

$$\text{cutting force, } F = \frac{k\, v^2}{V^2} \quad \frac{(R + r)\ 2d}{R.r}$$

where k, he claimed, was a constant for the particular grinding wheel.

This relation was of direct practical use since it indicated the way in which v, V and d were inter-related in determining whether the force was too low, causing the wheel to glaze, or too high, causing rapid wheel wear.

Since Guest presented his relationfor the maximum chip thickness there have been several other relations presented (3),(4), and (5), all of which are based on assumptions that do not appear to be justified. Although the expression in (4) did not include the factor n (which is difficult if not impossible, to measure) its assumptions make it unsatisfactory for the calculation of chip depth of cut.

Not until 1952 was a suitable method for evaluation of n suggested. Backer, Marshall and Shaw (6) expressed n in terms of the mean number of cutting points per unit area, and the ratio of scratch depth to width; they then suggested a method to evaluate these quantities by a fairly simple experimental technique. In calculating the chip depth of cut Backer, Marshall and Shaw used a relation of exactly the same form as that originally predicted by Guest. Later, more accurate relations for the calculation of t were suggested by Kalpakcioglu (7) and these have been expanded and published in (15).

From the time of Guest the problem of the force in grinding was not seriously examined. McKee, Moore and Boston (22) measured the horse-power in grinding, but direct force measurements were not made until 1949, when Marshall (29) constructed a grinding dynamometer. Results of these force measurements were published by Marshall and Shaw (30), the most surprising conclusion they reached was that the grinding forces and specific energy are independent of the hardness of the workpiece. To explain this result they introduced the concept of size effect in metal cutting - due to the small size of the stressed area the probability of finding inhomogeneities which might result in the formation of dislocations is low, so that the apparent yield stress of the material increases.

Size effects have been observed in various materials tests (8), (9) and (10) and the evidence for the existence of such a phenomena is fairly good. However, the explanation of the basic mechanism of the effect is still subject to some discussion by different authorities. Although the explanation by dislocation formation is commonly accepted there is still some doubt about the influence of surface films. Roscoe (11), and Cottrell and Gibbons (12), found that surface films increased the strength of single crystals. It would appear reasonable to assume that this effect would become more important as the size of the crystal was decreased. However, Makin (13) concluded that the surface film effect did not increase with decrease in crystal size. Walker (14) considers the altered strain hardening characteristics to be of some importance and has extended the simplified dislocation explanation to allow for this. Thus, it is seen that even in the simplest material tests the mechanics of size effect are not understood with complete certainty. When the effect is considered for the far more complex stress picture existing in metal cutting, further uncertainties are introduced.

The fact that grinding exhibits a "size effect," to the extent that the specific energy (per unit volume of metal removed) rises as the chip depth of cut decreases, has been fairly conclusively established (6) and (15); but the explanation of this effect is not so clear. Shaw and Marshall (6) introduced several assumptions and arrived at a relation between the shear stress and total specific energy. This indicated that below about 30 micro-inch depth of cut the shear stress approached the theoretical value calculated for a perfect lattice arrangement of the material ($\frac{G}{4}$ to $\frac{G}{2\pi}$ where G = shear modulus of elasticity). This result suggests that the size effect in grinding is of the same type as that observed in the materials tests mentioned and indicates that the dislocation theory is a possible explanation. However, there seems to be some room for doubt about the validity of the assumptions used to calculate the shear stress; furthermore, there appear to be other considerations in the grinding process, which have been neglected.

In calculating the shear stress in grinding Backer, Marshall and Shaw related the grinding results to those found in a fine milling process, known as micromilling. For this purpose they made the following assumptions:

1. In grinding the mean rake angle of the cutting grits is zero.

2. The cutting ratio (ratio of undeformed chip thickness to chip thickness) in grinding was assumed to be the same as that measured in micromilling. It was found, in support of this assumption that the cutting ratio was approximately constant for different depths of cut in micromilling.

3. It was assumed that a plot of the ratio u_s/u against chip depth of cut could be extrapolated by a smooth curve down to the grinding range (where u_s is the shear specific energy and u is the total specific energy).

From these assumptions the shear stress may be found in terms of the total specific energy, using the well known relations developed by Merchant (16)

$$\text{shear angle } \phi = \tan^{-1} \left(\frac{r_c \cos \alpha}{1 - r_c \sin \alpha}\right)$$

where r_c = cutting ratio and α = rake angle.

$$\text{Shear strain, } \gamma = \frac{\cos}{\sin \phi \cos (\phi - \alpha)}$$

$$\text{Shear stress, } \tau = \frac{u_s}{\gamma} = \frac{(u_s/u)}{\gamma} u$$

Some doubt is introduced by the use of these equations since they are based on the assumptions of a very sharp tool with no force on the clearance face and that there is a sharp corner at the junction of the chip and the free work surface. In fact, for all tools a small wear land is very rapidly formed and for a grinding grit this wear land will be large compared to the chip depth of cut. Also, as has been pointed out by Shaw and Finnie (17), the chip-work surface junction is not sharp but a "pre-flow" region is usually present, which increases the assumed length of the shear plane by a small amount. Since the analysis neglects this the calculated shear stress will be higher than the actual stress.

It seems certain that there is a force acting normal to the clearance face of the tool and this produces a friction force which will be added to the measured total force in the direction of cutting. Thompson, Lapsley and Grassi (18) claim that a major portion of this force will appear as deformation of the work surface. They further suggest that the deformation is independent of the depth of cut, so that at smaller depths (as used in grinding) this force will be of greater importance. It seems probable that although part of this force will go to plastic deformation of the work surface, a considerable portion will be in the form of a friction force producing heat. The fact that such a force exists seems difficult to contradict in view of the fact that wear occurs on the clearance face of the tool. For an exact calculation of the shear stress this force should be evaluated & subtracted from the measured cutting force.

In addition to the two approximations introduced by the use of Merchant's relations it appears that some doubt can exist about the validity of the three assumptions made by Backer, Marshall and Shaw. This aspect is considered in more detail in the discussion of results.

Since the publication of the force measurements in surface grinding by Backer, Marshall and Shaw, measurements of the forces in internal and external grinding and also in belt grinding have been carried out by various investigators, including Walker (19) and Reichenbach (20). These and other results have been reported in reference (15).

Reichenbach, Shaw, Mayer and Kalpakcioglu (15) have extended Guest's relation for the calculation of chip thickness to reduce the approximations involved when the wheel advance between successive cuts becomes large compared to the wheel depth of cut (or down feed). Relations have been formulated for five different cutting conditions and the expressions have been set out in a table to simplify calculations.

Wear

The rate of grinding wheel wear is a subject of considerable interest and much speculation has been presented as to the nature of this wear and the influence of the grinding variables. It is apparent that removal of material from the wheel occurs by three mechanisms: firstly, the grits wear by removal of small particles, to form a wear land (this wear land has been observed and reported by several authors, including Letner (21)); secondly, fracture of individual grits occurs, so that new cutting edges are presented; and thirdly, complete grits may be torn from the bond.

To maintain accuracy and to reduce the adjustments required during grinding it is, of course, desirable that grinding wheel wear be fairly small. On the other hand, to maintain a high cutting rate it is necessary that the grits be either fractured or torn out of the wheel when they become dulled. Thus a high resistance to attrition wear is desirable, but resistance to fracture of the grits or fracture from the bond should be fairly low.

The relations of Alden (1) and Guest (2) are useful in that they indicate qualitatively the way in which wheel speed, work speed and wheel depth (or downfeed) should be adjusted to increase or decrease the force on the grits, which in turn regulates the rate at which the grits are fractured or torn from the bond.

A measure of grinding wheel wear which has been found useful by many investigators is the ratio of volume of metal removed to volume of material worn from the grinding wheel. This ratio has been given several different names including, "Specific Wheel Wear," "Volume Ratio," "Grinding Ratio," and "Efficiency Ratio;" for the purposes of this paper the term "Grinding Ratio" will be used throughout. Woxen (32) was one of the first investigators to make a study of wear in grinding using this ratio. He concluded that wear rate was not solely determined by the chip thickness as Alden had supposed, but the radial depth of cut, the ratio of work speed to wheel speed and the rate of metal removal all act as independent variables in determining the wear. Several later investigators have used the grinding ratio as a measure of effectiveness in studying different variables, including McKee, Moore and Boston (22), and Shaw and Yang (31).

Wear studies of grinding wheels are of considerable practical value, but since there are three mechanisms causing wear of a grinding wheel (attrition, grit fracture and fracture from the bond) theoretical studies should be directed to the individual mechanisms. An attempt has been made to do this by wear studies of individually mounted grits (23), (24) and (25). This proceedure eliminates the removal of grits from the bond as a source of wear, so that wear by attrition and grit fracture can be measured without the influence of the bond. Distel (25) found that the grinding ratio was higher for single grits than for a grinding wheel. He suggested that the elimination of the effect of the bond was the main reason for this increase, but he also suggested that rewelding of the chips to the workpiece was reduced by the single grit technique, which, of course, also increases the grinding ratio, since the rate of metal removal is increased.

Distel (25) decided that the mean wear of the grits was a simpler parameter than the grinding ratio for wear studies with individual grits. He measured this by the change in scratch depth during cutting over a fixed length of work material. He investigated the wear with several different work materials, different grits and different speeds. Heyman (26), using the same equipment, examined the influence of several cutting fluids.

These tests are of some interest in learning the effect of different variables on wear and tests at higher speeds would appear useful. It would seem desirable to develop some method of separating attrition wear from wear due to grit fracture. These two mechanisms are probably quite distinct. Fracture resistance depending simply on body strength of the abrasive material, but attrition resistance is a rather complicated phenomena which may depend on penetration or scratch hardness and also on the relative solubility of the abrasive in the work material (27 and 28). The solubility effect is thought to explain the relatively greater wear of aluminum oxide than silicon carbide when cutting glass, but the inverse relative wear of the two when cutting steel; since it is known that aluminum oxide is relatively more soluble than silicon carbide in glass and that the reverse is true in steel.

EQUIPMENT FOR FORCE MEASUREMENTS

A method has been devised to measure the tangential force when cutting with a single grit. The force measuring device, in principle, was the same as the now, widely used, strain gauge method for measuring tool forces.

The experiments were carried out on a Milwaukee horizontal milling machine, with the conventional milling cutter replaced by a special, single tool, fly cutter. A general view of the apparatus is shown in Fig. 1 and in Figs. 2 and 3 the details of the fly cutter can be seen. This consisted of a single grit mounted in the end of an aluminum bar. The aluminum bar was held by a clamp to the cylinder mounted on the spindle of the milling machine.

When a force is applied to the end of the aluminum bar it will deflect in the form of a cantilever beam. Strain gauges were cemented to both sides of the bar close to the built-in end. By wiring these strain gauges into a Wheatstone Bridge network it was possible to measure their change of resistance when strained and from this, the deflection of the cantilever and hence the force applied, could be found.

At first it was hoped to have four strain gauges on the cantilever, so there would be four active arms in the Wheatstone circuit. However, to obtain sufficient deflection the physical size of the cantilever had to be made so small that there was insufficient width for the extra gauges. Thus, the other two arms in the network were inactive resistances and electrical sensitivity was half the value it would otherwise have been. Although they were inactive, it was decided for convenience, to use strain gauges as the two other resistances.

The cutting action was similar to a surface grinding operation. The fly cutter and cantilever measuring device were rotated by the spindle of the milling machine. While the work piece, held in a vice on the table of the machine, was fed past at right angles to the spindle axis. Since this process, unlike force measurements on a lathe, involved rotation of the dynamometer element, the problem of electrical connection from the rotating strain gauges to an instrument for detecting resistance charges, arose. Any type of slip rings would have introduced errors, due to change in commutation resistance, so it was decided to use the method of a copper disk rotating in a mercury bath. As can be seen in the general view of the apparatus, these disks and mercury baths were mounted on an extension of the main spindle, beyond the supporting bearing. To make connection between the disks and the fly cutter, wires were run in a shielded rubber covered cable, along the keyway of the spindle and hence inside this supporting bearing.

The connections between the four resistances in the wheatstone bridge network were made on the rotating section, rather than bringing out the wires from each resistance separately. In this way it was felt that any effect of difference in the resistance of the mercury contacts would be eliminated. The inactive gauges were cemented to an aluminum bar of the same section as that holding the cutting grit and the two bars were clamped side by side, but the "dummy" bar was arranged to be slightly shorter than the active bar, so that it did not touch the work.

A cathode ray oscilloscope was used for detecting the amount of unbalance in the Wheatstone circuit. It is obvious that the time of force application is very short (of the order of one milli-second) thus, an instrument with a very high speed of response is required. For this purpose an oscilloscope was found to be satisfactory and had the advantage that the nature of the force rise and the time of contact could be observed.

The electrical circuit is shown diagramatically in Fig. 4. The EMF source was a six volt dry cell. The strain gauges were a standard American pattern, having resistances of 300 ± 2 ohm and gauge factor of 2.96 ± 2%. Gauges S_1 and S_2 were cemented to the cutting cantilever, while R_1 and R_2 were cemented to the dummy. The active strain gauges were of course on opposite sides of the cantilever so that when a force was applied, one gauge was in compression and the other in tension, which means that their change in resistance was of opposite sign. The oscilloscope used was a Du Monte type 324, fitted with a "Polarid" camera for photographing the trace obtained.

The null method of measuring resistances, often used with the Wheatstone Bridge circuit, could not be applied in this case due to the short time of force application. However, the resistances S_1, S_2, R_1 and R_2 were all similar strain gauges, so the circuit was initially in approximate balance - i.e., the potential difference between points A and B was close to zero. Change in the resistance S_1 and S_2 alters this potential, which is detected by a deflection of the spot on the oscilloscope. No attempt was made to exactly balance the circuit, but it was necessary to add the 40,000 ohm resistance, shown in the figure, to improve the balance and bring the oscilloscope spot onto the screen. This was caused by small differences in the initial resistance of the gauges. Later one of the gauges had to be replaced and then it was found that the balancing resistance was unnecessary.

The size of the aluminum cantilever used is shown in Fig. 5. With these dimensions the calculated strain at the gauge section is 20×10^{-6} inches/inch under a load of 1/2 pound applied to the end of the beam and 200×10^{-6} inches/inch under a load of 5 lbs. The calculated natural frequency of vibration of the beam is 1240 cycles/second.

As in Ref. 25, the grits were mounted in a 3/64" hole at the end of the cantilever and held in place by a porcelain cement commercially known as "Insa-Lute." Grits were removed when worn by soaking the cement in water, and a fresh grit then cemented in place. The larger ceramic tools used in later tests were cemented directly to the end of the cantilever.

TESTING PROCEDURE

The work pieces were the same as those used by Distel (25); i.e., they were ground to give a flat surface with a 1:20 slope on each side. The technique of testing was very similar to Distel's. The work first was aligned in a vice on the milling machine table using a dial indicator. Next the table was raised until the cutter just touched the work surface, then the work was fed off to one side of the cutter and the table raised to give the required depth of cut. The cross feed was then engaged to make the cut across the work piece.

Initial and final depths of cut could be found by measuring the length of scratch in the entry and exit sloped sections of the specimen (by virtue of the known slope). However, a better procedure for measuring scratch depth and width was found to be by use of a stylus type surface measuring instrument. This was traversed across the scratch and produced a magnified trace of the scratch profile. Traces were taken at 1/8 inch intervals along the length of the scratch and a graph could be drawn showing variation in depth and width during the cut. The surface analyser used for these measurements is shown in Fig. 6. It is of the electromagnetic type, position sensitive (independent of the wavelength of the surface roughness). The measuring head was connected to a 'Sanborn' recorder which produced the magnified trace. The maximum magnifications of the equipment was 1600 times vertically and 24 times horizontally - adequate for these measurements. A sample scratch profile is shown in Fig. 7.

The oscilloscope for measuring the cantilever deflections (and hence, force on the grit) was used with sweep rates of 1 to 5 milli-seconds per inch and vertical magnifications of 0.01 to 0.004 volts for full scale deflection (4 inches on the oscilloscope screen). A 'Polaroid-Land' camera was used to record all force traces. A typical picture of the oscilloscope deflection is shown in Fig. 8. For this particular trace each division on the vertical scale represents 0·5 pounds and on the horizontal scale each division is 0·5 milli-sec. The natural frequency of vibration of the cantilever is seen to effect the shape of the trace to some extent. However, the general behaviour of the force during the cut can be read from the picture. Force rise to maximum value occurs in 0·001 seconds, the force then remains constant at 1·9 pounds for 0·0015 seconds, during which time the cantilever vibrates about its deflected position with a period of 0·0005 seconds, finally, the force falls to zero in 0·0007 seconds. After this the cantilever has a damped vibration at its natural frequency.

In the early tests with grinding grits continuous cuts were made across the work piece, and force pictures were taken at known times from the start of cutting. The maximum force readings were plotted to give a smooth curve against length of cut and this curve was used in conjunction with the width and depth curves to give the force at any particular width and depth. In later test it was found better to take short cuts into the work, measuring the force in five or six consecutive cuts and then depth and width at the exact cutting position could be measured with the surface finish instrument.

CALCULATIONS FROM BASIC MEASUREMENTS

Nomenclature

A' = chip area of cut (inch^2)

a = scratch cross sectional area (inch^2)

D = diameter of grinding grit path (inch)

d = scratch depth of cut (inch)

d_T = scratch depth at time T after start of cut (inch)

F = force in direction of cutting (lb.)

F_N = force normal to cutting direction (lb.)

F_s = force parallel to shear plane (lb.)

f = feed per revolution of cutter (inches)

K = number of cutting grits on wheel periphery (=1 for single grit)

l = length of grit profile, or true chip width of cut (inch)

N = wheel speed (R.P.M.)

r = cutting ratio, or chip length ratio

r_t = proportion of time grit is actually cutting

s = arc length swept out by the grit in time T. (inch)

T^* = total cutting time during one revolution (sec.).

T = some time after the start of a certain cut (sec.)

t = maximum chip depth of cut (micro-inch).

$\bar{t}$ = mean chip depth of cut (micro-inch)

U = total specific energy (inch lb./inch^3)

U_s = shear energy (inch lb./inch^3)

V = wheel or grit speed (cutting speed) (fpm).

V_s = velocity of chip relative to work, directed along shear plane (fpm)

v = work speed or table feed (ipm).

W = top width of scratch (inch)

W_T = effective top width of scratch at time T after the start of a cut (inch).

α = rake angle of cutting tool

γ = shear strain (inches/inch)

ϕ = shear angle

τ = shear stress (psi)

The force values themselves are of little interest. To be useful the force must be related to the size of cut. The depth and width of the scratch can be easily measured, either from the surface profile of the scratch, or by use of a microscope on the entry and exit slopes. More fundamental variables are the chip depth of cut, the chip area of cut, and the chip width of cut.

The Chip Depth of Cut

This can be calculated from the formulae presented by Reichenbach, Shaw, Mayer and Kalpakcioglu (15). These can be simplified considerably since the exact number of cutting points per unit length of wheel periphery is known (and = 1 for this investigation). With this simplification the formulae can be written:

$$B = \frac{12\ v}{NK \sqrt{dD}} \qquad \text{(in all these tests } K = 1\text{)}$$

(a) Type I and II chips. If $B < 1$, $t = d\beta(2 - B)$, and the equation $t = 2dB$ can be used if $B < 0.1$, with less than 5% error.

(b) Type III and IV chips. If $B \geqslant 1$, $t = d$

(c) Type V chip. If $B \geqslant \frac{3}{2}\ \frac{1}{\left(1 + \frac{12\ v}{DN}\right)}$, then $d = \left(\frac{3}{4}\ \frac{B}{1 + \frac{v}{V}} - \frac{1}{2}\right) i$

It was found in all tests that B was less than 0.1 so the relation $t = 2dB$, or

$$t = \frac{24\ v}{NK} \sqrt{\frac{d}{B}}$$

, could be used.

In single grit grinding, unlike conventional wheel grinding, the feed between successive cuts is very large compared to the feed during an actual cut.

Thus to a good approximation the chip depth of cut is constant during the cut, except for a length at the beginning and end equal to the feed between cuts. This idea is shown in Fig. 9 (a).

Chip Width of Cut

Looking at the cross section of the scratch shown in Fig. 9(b) it is seen that the chip width of cut is not the direct width of the scratch (W), but is equal to the length of the profile of the scratch (l). Since this is difficult to measure some assumption must be made as to the relation between profile length and scratch width and depth. Some previous workers (2) have assumed a triangular grit section, but it is felt that due to the general unevenness of the profile a rectangular section is more valid - i.e., profile length $= W + 2d$. Rough measurements of scratch profiles drawn out to a large scale with equal magnifications in both directions indicate that this assumption is fairly good for most grinding grits.

Area of Cut

The true chip area of cut will have a shape somewhat as shown shaded in Fig. 10 (a). Provided no re-entrant corners are present in the grit profile, (and only once in all the tests were these observed) then the area of cut will exactly equal the area shown in Fig. 10 (b). The reason for this is that the area of cut is the difference between two identical cross sections, one of the cross sections being cut off at a depth t less than the other. Thus the smaller cross section can be considered to be moved to a different position inside the other, without altering the area difference between them. Thus the area of cut (A') is equal to the area (bW).

Mean Value of Chip Thickness

The chip thickness will vary along the actual width of cut (or scratch profile length). The maximum value of chip thickness (calculated above) will occur at the lowest point of the scratch profile and wherever the profile is horizontal.

The mean value of chip depth of cut will be given by

$$\bar{t} = \frac{\text{area of cut } A'}{\text{actual width of cut}} = \frac{t.W}{(W + 2d)}$$

Instantaneous Values of Scratch Width and Depth

In fact the width and depth of the scratch will vary during one cut taken by the grit. The cut will be more or less boat shaped as indicated in Fig. 11.

The scratch or wheel depth of cut at a time T after the start of the cut is given by

$$d_T = d - \frac{s^2}{D}$$

where s = arc length swept out by the grit in time T.

If the total time for a single cut is time T^*, then, since the total arc length = $\sqrt{Dd}$ to a close approximation,

$$d_T = \alpha \left[1 - \left(\frac{T}{T^*}\right)^2 \right]$$

The scratch width at this depth of cut can be determined by measurement on the scratch profile obtained with the surface measuring instrument. This width is used in calculating the chip area of cut at any time T. The chip depth of cut is, of course, based on the maximum scratch depth, d.

Calculation of Specific Energy

The cutting energy per unit time = FV

Now volume of material removed per unit time = $A'V$

$$\text{Specific energy} = \frac{F}{A'} \text{ inch lb./inch}^3 \qquad \text{(a)}$$

Alternatively the average rate of metal removal while cutting per unit time can be written as av.

The cutting is discontinuous, thus the volume removed per unit time $= avr_t$.

Where r_t = proportion of time the grit is actually cutting

$$\text{Specific energy} = \frac{FV}{ar_t v} \text{ inch lb./inch}^3 \qquad \text{(b)}$$

The second method of calculation is cumbersome and not much use in this case, but it is included since it corresponds to the method which has to be used for calculations with complete grinding wheels.

Cutting Ratio

This is the ratio of depth of cut to chip thickness and is equal to $r = \frac{t}{t_1} = \frac{l_2}{l_1}$; l_2 = chip length, l_1 = length of cut, t_1 = chip thickness

t = depth of cut.

Shear Angle

Merchant (16) has developed the relation, $\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}$

Shear Strain

$$\gamma = \frac{\cos \alpha}{\sin \phi \cos (\phi - \alpha)}$$

Shear Energy Per Unit Volume

Shear Energy, $u_s = \frac{F_s V_s}{Vbt}$

and $$V_s = \frac{\cos \alpha}{\cos (\phi - \alpha)} \cdot V$$

$$F_s = F \left(\cos \phi - \frac{F_N}{F} \sin \phi\right)$$

Thus, $$u_s = \frac{F}{bt} \left(\cos \phi - \frac{F_N}{F} \sin \phi\right) \frac{\cos \alpha}{\cos (\phi - \alpha)}$$

$$= u \left(\cos \phi - \frac{F_N}{F} \sin \phi\right) \frac{\cos \alpha}{\cos (\phi - \alpha)}$$

Shear Stress

It can be shown that $u_s = \tau \gamma$

Thus $$\tau = \frac{u_s}{\gamma}$$

$$= \frac{\frac{u_s}{u}}{\gamma} \cdot u$$

FORCE MEASUREMENTS FOR ABRASIVE GRITS

In these tests standard abrasive grains supplied by the Carborundum Co. were used as cutting tools. The work piece was fed under the cutter and a cut made across its complete width. In some cases the workpiece was level and parallel with the table traverse, in others it was sloped slightly so that depth of cut either increased or decreased as the cut proceeded (maximum slope used 0.003" across the 1 1/2" width of block). Pictures of the oscilloscope deflection were taken at intervals during the cut (usually about 7 pictures during one cut). When a picture was taken the time after the start of cutting was noted and at the completion of cutting this time was related to distance across the specimen, so that the width and depth of the cut at that particular instant could be measured with the surface finish instrument. When a picture was taken the film was exposed for between 1 to 4 seconds so that the force picture for several consecutive cuts was obtained, the mean value of the force was calculated from these.

Aluminum Oxide Grits

In the first series of tests Lot 212 20/24 aluminum oxide was used to cut 1020 steel, 150A titanium and aluminum. The standard cutting conditions were a speed of 93 rpm (250 fpm) and a feed of 1/2 inch/minute; the depth of cut of course varied continuously, both due to wear of the grit and to the slope of the workpiece.

Force Against Chip Area of Cut

In Fig. 12 (a) the measured cutting force is shown plotted against the chip area of cut (the total width of scratch multiplied by the chip depth of cut). Graphs are given for each of the three work materials used and for each material the results of tests with two different grits are presented.

It is seen that there is fair correlation between force and area of cut for any one grit and that the force rises almost linearly with increase in area of cut. However, different grits give considerable variation in the force at any particular area of cut.

It should be pointed out that the results shown in Fig. 12 were selected from a large number of tests - in many other tests, particularly with steel and titanium there was a lot of scatter in the force readings and it was impossible to draw any type of curve through the plotted points. The plotted points for grit 8 in Fig. 12 (b) give some suggestion as to the cause of variation. It is seen that the points for this particular grit appear to fall on two distinct curves, the initial four points being on the lower curve and the later points being on the upper one. The most likely explanation for this effect seems to be that the grit chipped during the cutting and for the later test an entirely different shaped cutting edge was used.

The variation in force for different grits is most likely explained by the difference in geometry of the grits. Due to this variation the curves in Fig. 12 are of no great practical value but are presented to illustrate the magnitude of the variation between grits; to indicate the relation between force and area of cut; and in particular, to give some idea of the actual value of the forces on a single grit. (Notice the change in scales for Fig. 12 (a) and Figs. 12 (b) and (c).

Force Against Chip Depth of Cut

The measured cutting force for the same grits shown in Fig. 12 is plotted against chip depth of cut in Fig. 13. It is seen that the variation between grits is somewhat greater when the forces are plotted in this manner. The general shape of the curve is essentially uncertain though it appears that the force rises as depth of cut is increased. Again there was considerable scatter in many of the tests which are not shown and grit 8 when cutting steel seems to have two distinct curves.

Force Per Unit Width of Cut Against Chip Depth of Cut

The measured force divided by the assumed cutting width of the grit (scratch width plus twice the scratch depth) is shown plotted against chip depth of cut in Fig. 14 The use of these parameters gives better correlation than a direct plot of force against chip depth of cut. There is still a variation between grits and also some scatter of points for any one grit. Again it must be pointed out that these curves are selected from a number of tests, some of the tests with steel and titanium work materials gave a meaningless distribution of points on these axes. This might indicate a lack of correlation between the two variables, but it is thought to be due to variation in the grit geometry due to chipping and also to random variations in the depth of cut, as will be explained later.

Specific Energy Against Chip Depth of Cut

The two methods of calculating specific energy are compared in Fig. 15 for the aluminum work material. It is seen that the methods give basically similar results, though the calculation of energy from average width of cut is slightly higher than that based on the chip area of cut. For steel and titanium it was found that the average width of cut method gave much higher values and introduced considerable scatter. Hence it was decided that this method introduced too many errors and the chip area of cut was used for all succeeding calculations.

Also shown in Fig. 15 is a plot of $\frac{F}{A'}$ against the mean value of chip thickness (obtained by dividing the chip area of cut by the width of cut on the assumption that the width of cut is equal to the scratch width plus twice the scratch depth). It is seen that use of mean chip thickness gives slightly lower specific energies at any particular chip thickness. A relationship between specific energy and mean chip thickness is perhaps more basic than one between specific energy and maximum chip thickness although both are only approximations to the ideal case of uniform chip thickness. However, the difference between the two is not very great and since the calculation of mean chip thickness is based on an assumption as to the shape of the grit; there is probably little advantage in using it. In all later tests the maximum chip thickness was used.

In Fig. 16 values of specific energy $(\frac{F'}{A})$ are plotted against the chip depth of cut (max.) for the steel and the titanium workpiece. For steel the values obtained with two different grits are shown and for titanium two curves are shown for a grit when it was first mounted and after it had been used for several cuts on all three materials.

Figure 17 is a plot of specific energy against chip depth of cut for the aluminum specimen with three different grits.

Effect of Wear on Specific Energy

It was apparent from these initial tests that specific energy at any depth of cut varied over time for any one grit - i.e., there was scatter in results and poor repetition in succeeding tests with the same grit (variation from one grit to the next was accepted as a result of change in geometrical form). It was thought that some uniform wear of a grit may occur during cutting and presumably this would give rise to a uniform increase in specific energy. To investigate this, several successive cuts were made with one grit on the 1020 steel work piece. The work was sloped upwards from the entry side, so that the depth of cut increased during each complete pass of the cutter. The results of this test are shown in Fig. 18, the points for grits 4 and 5 are plotted for comparison on the same graph. There is considerable scatter in the results for each cut but there does not seem to be any observable trend of specific energy either decreasing or increasing as cutting proceeds - the specific energy for cut 1 is a little higher than for cuts 2, 3 and 4, but on the other hand for cut 4 it appears higher than cuts 2 and 3.

The Effect of Cutting Speed on Specific Energy

Although Backer, Marshall and Shaw (6) found that speed had no influence on the specific energy v's chip depth of cut curve, it was felt that this aspect should be investigated using the single grit equipment. For this purpose the aluminum workpiece was used since this gave the least scatter in results and speeds of 250, 410 and 670 fpm were employed. The results of these measurements are presented in Fig. 19 where it can be seen that, to within the accuracy of results, variation in cutting speed has no influence on the specific energy - chip depth curve.

Silicon Carbide Grit

With the wide scatter which had been present for the aluminum oxide grits it seemed doubtful that any significant difference would be detected when cutting with silicon carbide. However, some tests were run using silicon carbide grits. A plot of specific energy against chip depth for the steel workpiece is given in Fig. 18. Figure 14 shows similar points obtained for the titanium work material together with those values found when cutting titanium with aluminum oxide. As was expected the scatter was too great to draw any conclusions.

Summary

Although some general quantitative conclusions can be drawn from these tests, it is fairly obvious that the experimental variation severely limits their usefulness. It is worth considering the causes of this variation and the way in which some of these causes were eliminated in the next series of tests.

(a) Sensitivity of Instruments

A load of 1 lb. gave a deflection of 1 1/2 divisions on the oscilloscope, so that forces could be read to an accuracy of about 1/10 lb.

The scratch depth could be read to an accuracy of at least ± 0.001".

Scratch width was accurate to ± 0.0002.

(b) Chip Geometry - This is an unknown variable and is expected to vary from grit to grit and also to vary by a chipping process during cutting with one grit.

(c) Variation in Depth of Cut During One Cut - In later tests it was noticed that the sound made by the cutter was not regular, but varied in intensity during successive revolutions. This variation could be accounted for by either non-uniformity in the table feed, or by variation in the depth of cut. Evidence found later seems to indicate that the latter is the more likely cause.

This effect was not present when cutting the aluminum work material although it occurred for both steel and titanium.

Thus, to obtain satisfactory results it seemed that the chip geometry should be standardized in some way, the variation in depth of cut should be eliminated (and the simplest method of doing this was to restrict the tests to aluminum). The accuracy of measurement of scratch width and depth was considered to be good. The sensitivity of force measurements might have been improved somewhat, but this was not considered worthwhile in the light of the other sources of variation. To achieve a standard geometry the use of grinding grits was discontinued and instead small pieces of ceramic tool of known shape were used.

FORCE MEASUREMENTS FOR GRITS OF KNOWN GEOMETRY

In the light of the previous results it was decided to carry out tests using small ceramic tools in place of the grinding grits. The ceramic used was supplied by the Carborundum Company and is known as "Stupalox". It was cut to the form of a small almost triangular prism, but had one corner replaced by a radius of about 1/16 inch. The tool was cemented to the force measuring cantilever with the rounded edge out so that the cross section of the scratch made in the work piece would theoretically be part of a circle.

Aluminum work material was used for most of the tests since this had given the best "repeat-ability' in previous measurements with grinding grits.

The rake angle was adjusted by the way in which the ceramic was cemented in place. Negative rakes were used in all cases. The clearance angle was, of course, numerically equal to the rake angle, since the piece of ceramic had a 90° angle between the clearance and rake faces.

Effect of Speed and Feed and Depth of Cut

In the first tests a -15° rake angle was employed and two different conditions of both feed and speed were used. The standard condition was a speed of 246 fpm with feed of 1/2 ipm and conditions were altered to 1 ipm feed at 246 fpm and then 406 fpm speed at 1/2 ipm feed. Several different depths of cut were used.

The procedure differed slightly from the previous grinding grit tests in that the block of work material was level at all times and for each depth of cut three to six short cuts were made, the force being measured about four times for each cut. Thus the force values are the mean of between 12 and 24 individual measurements.

Some care was taken to ensure that the scratch depth remained constant for any given cut and that the feed was uniform and equal to the value set on the machine. To check scratch depth uniformity the surface finish stylus was traversed along each scratch in the direction of the cutter. The method of doing this is shown in Fig. 21 and a sample of the resulting trace is given in Fig. 22. To measure and check uniformity of feed a short cut was made and the machine stopped with feed engaged, a mark was drawn at the end of the scratch and then the main drive was again engaged and the cutter allowed to make several revolutions. These revolutions were counted (speed of 93 rpm (246 sfpm) was used) and the machine again stopped. The advance of the scratch from its former position was then measured with a Brinell microscope. This was repeated several times. To within the measuring accuracy, the feed was found to be uniform and equal to the values marked on the machine for 1/2 ipm and 1 ipm feeds.

The basic data of force against scratch depth is given in Fig. 23. This is of some interest in indicating the general shape of the curves, but the relative positions of the curves for the three different cutting conditions is not of much use since the chip area of cut is not taken into account, and this of course has a basic influence on the forces.

The chip area can be introduced by dividing it into the force to give force per unit area (which has previously been shown to be equal to the specific energy). A plot of specific energy against scratch depth is given in Fig. 24. The relative position of the curves now has real meaning; when speed is increased or feed is decreased the force per unit area at any given scratch depth is increased.

Eliminating the effect of speed and feed by combining them in the parameter, chip depth of cut, gives a single curve for all three conditions as shown in Fig. 25.

Force is plotted against chip depth of cut in Fig. 26.

Effect of Rake Angle

Several different rake angles were investigated by relocating the ceramic grit relative to the cutter axis. Since the rake and clearance angles are equal (90° angle on the tool) it is satisfactory to measure the clearance angle to obtain a value for the rake angle. This was done by use of a Brinell microscope. The workpiece block was set level and raised so that the cutter just cleared it. The cutter was then rotated back and forth by hand until the cutting edge was in its lowest position, while in this position the Brinell microscope was used to measure the height of both the cutting and the trailing edges of the tool above the workpiece. From the known length between these two edges the clearance angle and hence the rake angle, could be calculated.

In the first of these tests different tools were used for each rake angle. Figure 27 shows the results of these plotted on specific energy against chip depth of cut axes. It appears that the specific energy rises as rake angle becomes more negative, but this is not indicated very conclusively. It was felt that there was likely to be some variation between the grits and a more definite result could be obtained by using the same grit for each rake angle. This was carried out and Fig. 28 shows the result for the three rake angles tested. The order in which the angles were tested was -34° rake, -9° rake and -63° rake. It is probable that the grit dulled to some extent during each test and so increased the specific energy in succeeding tests. This is probably part of the reason for the change in specific energy between -9° and -34° being less than the change between -34° and -63°.

The percentage increase in specific energy per degree decrease in rake angle from -9° is:

(a) for -34° rake 1.2% at chip depth of 100 microinch,

and 1.8% " " " " 150 "

(b) for -63° rake 2.4% at chip depth of 100 microinch,

and 2.8% " " " " 150 "

Thus average percentage change in specific energy is 2.1 ± 0.8% per degree. About the same value as has been found for lathe tools.

The Effect of a Wear Land

To determine if wear land had any significant effect on the specific energy, measurements were made firstly with a sharp tool and then with the same tool after a wear land had been formed on it. The aluminum work material was used for the test and speed of 246 fpm, feed of 1/2 ipm were employed.

To form the wear land the ceramic tool was used to make several cuts over a steel workpiece. Observation with a microscope indicated that this gave a suitably flat wear surface parallel to the surface of the workpiece. No crater wear could be observed, although there was some slight rounding of the cutting edge (this was of the order of 0.0005" to 0.001" radius). The length of wear land was measured with a Brinell microscope directed at the side profile of the cutting tool.

Figure 29 shows specific energy plotted against chip depth of cut for two different rake angles with and without wear land. It is apparent that the specific energy of a worn tool is considerably higher than that of a sharp tool. It is felt that most of this increase is due to the formation of wear land rather than the rounding of the cutting edge. This seems likely when it is noticed that the basic rake angle of the tool, even when worn, still influences the specific energy. The different lengths of wear land must be taken into account, although it seems unlikely that this could cause such a large difference in the specific energies.

CUTTING RATIO MEASUREMENTS

During the previously described force measurements with ceramic tools the cutting chips were collected and their length measured with a Brinell microscope. From this and the length of cut, found from the cutting time indicated on the oscilloscope, it was possible to determine the cutting ratio (ratio of chip length to length of cut). The method, however, can only be regarded as approximate. There seemed to be a fairly large variation in chip lengths, due probably to small particles fracturing from the chips during or soon after forming - care was taken to prevent loss of fragments, but it is likely that some were lost. As about 12 to 24 individual cuts were made at each depth, the chip length was taken as the average length of about this many chips. The length of any small fragments obtained, being added in before calculating the average value. (The orientation of the chips and fragments could be easily identified from the longitudinal flow lines on the shiny back of the chip or the rough lines across the width of the face of the chip, where it had been curled over while being formed.) Figure 30 shows a group of chips formed by the ceramic tool.

Figure 31 (a) and (b) shows the results of cutting ratio measurements against chip depth of cut for several different rake angles. In Fig. 31 (b) the tests were all made with the same grit, its angle of inclination being altered to obtain the different rake angles. In Fig. 31 (a) different cutting tips were used for each rake. Aluminum work material was employed and cutting conditions were: feed 1/2 ipm and speed 246 fpm.

There appears to be a trend for the cutting ratio to increase with increasing depth of cut, but the scatter in results is fairly large and the conclusion is not very definite.

RATIO OF SHEAR ENERGY TO TOTAL ENERGY

An attempt was made to establish values for the ratio of shear to total specific energies. To do this it was necessary to measure both the cutting and the normal forces on the grit. For this purpose the M.I.T. surface grinding dynamometer was clamped to the table of the milling machine. This dynamometer is capable of measuring forces of 0.03 lb. in the vertical direction and 0.01 lb. in the horizontal direction. The natural frequency of the unit is 400 cps. in the vertical direction. A very small work piece (aluminum) was bolted directly to the dynamometer. The arrangement is shown in Fig. 32. During cutting. forces were also measured with the cantilever dynamometer on the rotating cutter. A Sanborn pen recorder was used for indicating the deflections of the two component dynamometer.

This method of measurement is not entirely satisfactory and the results obtained should be treated with caution. The pen recorder is not considered suitable for frequencies much higher than 120 cps. (or a pulse of shorter duration than 2 milli seconds). Furthermore, the natural frequency of the dynamometer is rather lower than desirable - in the vertical direction the time for one quarter oscillation is about 0.6 milli sec. at the natural frequency and about 0.9 milli sec. in the horizontal direction (the horizontal stiffness is roughly half that of the vertical and assuming equal vibrating mass the natural frequency depends on the square root of the stiffness). The duration of a cut varied from 1 to 5 milli seconds, depending on depth of the cut.

Due to the short cutting time and the low frequency of response the force indication consisted of a single pulse on the recording paper for each revolution of the cutter, as shown in Fig. 33. To reduce the influence of pen inertia the magnifications were adjusted to give approximately equal deflections of the pens for both vertical and horizontal forces (the ratio of these, not their absolute values was the quantity desired). The difference in the natural frequencies of vibration in the vertical and horizontal directions was a factor not accounted for. This could have an important influence in view of the fact that the natural frequencies are fairly close to the exciting frequency, so that resonance is just about to occur - this will be more closely approached in the horizontal than the vertical direction. The values might be corrected by means of vibration theory, but this refinement is hardly justified in view of the assumptions and other approximations involved.

A further difficulty which arose in these tests was caused by the lack of rigidity in the system. The force measurement cantilever dynamometer showed considerably more vibration than in the previous tests when the work was held in a vice. Surface finish measurement along the scratches indicated that the depth of cut had varied quite widely. As a result of these variations the specific energy against chip depth of cut gave rather more scatter than in previous tests.

The basic results of force measurements by both the two component dynamometer and the cantilever dynamometer are given in Appendix A. It should be noticed that the horizontal force, as measured by the two component dynamometer, is considerably lower than the force measured by the cantilever dynamometer. The main reason for this is probably the inertia of the pen recorder.

Four different rake angles were investigated. Chip lengths were measured in each test (except the -64° rake, which produced discontinuous chips) and the cutting ratio was calculated from the measured cutting time obtained from the oscilloscope recording. The cutting ratio values were even more approximate than those obtained in previous tests (due to lack of rigidity in work mounting), so it seems reasonable to use an average value for all depths - though in the case of the -12° rake, calculations were based both on an average value and on the individual values for each depth. For the -63° rake, as it was impossible to measure chip length, a value of cutting ratio some what below that for -26° rake was assumed.

The ratio of shear energy to total energy $(\frac{u_s}{u})$ were calculated from Merchant's relations. Fig. 34 shows a plot of these values against chip depth of cut. Some results obtained by Backer, Marshall and Shaw (6) in micro-milling 1112 steel at 5350 fpm speed, 4 fpm feed, and -15° rake are also plotted on this graph. For the -12° rake, curves are shown both for the average cutting ratio value and the cutting ratio values for the individual depths (obtained by plotting the measured values against chip depth of cut and drawing a smooth curve through them).

From the values of the energy ratio and the values of shear strain and total specific energy, values of the shear stress can be calculated. The results of this calculation are shown in Table 1. A plot of specific energy against chip depth of cut is given in Fig. 35 and shear stress against specific energy in Fig. 36.

The cutting tool used for these tests was the same as that used to obtain the data for Fig. 28. However, between the time of the tests of Fig. 28 and these tests the grit was used for several other cuts. This is thought to explain the higher values of specific energy obtained in this case. The order of testing was -63°, -12°, -18°, and -26° rakes.

The position and shape of the curves in Fig. 36 is probably not exactly as shown. This does not completely nullify the usefulness of this test, however, the magnitude of the shear stress is of considerable interest. As can be seen this did not rise above 200,000 psi. The measured ratio of the forces $(\frac{H}{V})$ is perhaps of doubtful accuracy, but errors is this have only a secondary effect on the ratio of energies and this ratio would have to be increased considerably to increase the shear stress to any extent.

Table 1

Cutting Tool: Ceramic; Work Material: Aluminum; Speed: 246 fpm; Feed: 1/2 ipm

	Chip Depth of Cut (x10 inches)	$\frac{u_s}{u}$	u (x10 $\frac{\text{inch lb}}{\text{inch}^3}$)	τ (lb./sq.in.)
	33	.997	-	.033u = -
-63° Rake	47	.995	3.35	.032u = 107,000
$\phi = 1.7°$	60	.991	1.53	.031u = 47,000
$\gamma = 33$ in./in.	62	.998	1.44	.033u = 57,000
	67	.990	1.88	.03 u = 54,000
	112	.989	1.34	.03 u = 40,000
	63	.74	1.02	.093u = 95,000
	106	.77	0.88	.097u = 85,000
-12° Rake	111	.83	0.75	.104u = 78,000
$\phi = 7.6°$	136	.82	0.86	.102u = 88,000
$\gamma = 8$ in./in.	170	.86	0.53	.107u = 57,000
	192	.87	0.51	.109u = 56,000
	210	.87	0.47	.109u = 51,000
	95	.75	-	.084u = -
-18° Rake	106	.85	0.87	.096u = 84,000
$\phi = 6.8°$	125	.87	0.93	.098u = 91,000
$\gamma = 8.9$ in./in.	138	.89	0.90	.10 u = 90,000
	47	.86	2.5	.08 u = 200,000
-26° Rake	82	.93	1.3	.086u = 114,000
$\phi = 5.6°$	106	.93	1.0	.086u = 86,000
$\gamma = 10.8$ in./in.	138	.94	0.8	.087u = 70,000
	195	.95	0.55	.088u = 48,000

TURNING TESTS

Tests were carried out using a ceramic tool cutting and 4" diameter aluminum work piece. The tool had -11° back and side rake angles, 45° side cutting edge angle, 5° clearance angles, and zero nose radius.

For calculating the chip width and depth of cut, the force normal to the cutting edge and the effective rake angle it was assumed that chip flow was at right angles to the cutting edge (a fairly good approximation) . Thus, the effective rake was -15°, chip depth of cut was equal to the feed per revolution divided by $\sqrt{2}$, and chip width was $\sqrt{2}$ times the tool depth of cut.

The results of tests measuring cutting forces with a two component lathe dynamometer are given in Appendix B. The cutting speed for all tests was 240 sfpm. Chip thickness was measured using a micrometer with pointed anvils.

Values obtained for specific energy, cutting ratio, and the ratio of shear to total energy are plotted against chip depth of cut in Fig. 37. Briefly, the points to notice about these curves can be listed as:

1. Specific energy rises with decreasing depth of cut.

2. Cutting ratio decreases with decreasing depth of cut and could link up with the values obtained in the grinding test, as shown by the dotted line. This probably indicates that the slope of the cutting ratio line found in grinding is too large, as previously suspected.

3. The ratio of shear to total energy appears to be constant at 0.8. This possibly indicates that the values found in grinding are too high, though the shape of curve in grinding is probably correct.

The specific energy values from these turning tests and the grinding tests at -15° rake are shown plotted against chip depth of cut on log-log paper in Fig. 38. It appears that a continuous curve may be drawn through all these points.

In Fig. 39 the shear stress values for turning are shown with the shear stress obtained with -26° rake single grit cutter (ceramic). Unfortunately -15° rake data was not obtained for the grinding test, but as can be seen in Fig. 36 the shear stress did not seem to be affected greatly by change in rake angle from -12° to -26°.

WEAR MEASUREMENTS

These tests were considered of secondary importance to the main investigation of the forces in single grit grinding. At first the objective was to explain some of the variations encountered in the initial force measurements with abrasive grits. Later when ceramic tools were used some tests were aimed more directly at wear measurements. Basically the method of testing differs from that of Distel (25) in that the surface roughness equipment was used for measuring the scratches and secondly, with ceramic tools it was possible to measure wear land.

The surface finish equipment was found to be very satisfactory for scratch measurements. The depth of cut by this method was always slightly less than that measured from the tapered entry and exit. This is probably due to elasticity in the system causing the grit to move away from the work when cutting proceeds beyond the entry or exit slope.

Surface traces along the bottom of the scratch are very suitable for detecting sudden chipping or other fluctuations in the depth of cut.

Traces taken along the scratches indicate that when steel or titanium are cut with either aluminum oxide or silicon carbide considerable variation in the depth of cut occurred. This was not found when cutting the aluminum work material. The variations were not particularly uniform, the change in depth varying from zero at times up to about 0.001". The distance between peaks of the variation ranged from about 0.06 inches of cutting legnth to about 0.2 inches, which corresponds to times of approximately 7 seconds to 24 seconds. The fluctuations appeared to be greater at larger depths of cut.

The very long period of the fluctuations indicates that they are certainly not caused by mechanical vibrations. Previous investigators who have observed this phenomenon have suggested that it is caused by periodic expansion and contraction of the work material. The high specific energies at small depths of cut causing temperature rise and hence local expansion, results in increased depth of cut and lower specific energy, therefore contraction, the cycle then repeats. Another possible explanation is by the formation of built-up edge on the clearance face. Considerable built-up material was observed on this face. It seems likely that this would grow more rapidly when the depth of cut is small. At larger depths the ratio of normal force on the clearance face to apparent area of contact is increased, so that the rate of removal of built-up edge by wear could be large as the region of very rapid wear is approached - this is based on the wear theory presented by Shaw and Dirke (40).

The more generally accepted temperature fluctuation, is perhaps the more likely explanation of this phenomenon, but the built-up edge effect may be worthy of further consideration.

Wear Land Measurements

Tests were run using ceramic tools and steel work material. Measurements were made of the wear land produced in a fixed length of cut and the decrease of depth of cut in this length. 1/2 ipm feed was used for all tests and several different speeds and rake angles were employed.

As mentioned previously considerable built-up edge was formed on the clearance face of the tools. Both the built-up edge and the wear land surface were flat and parallel to the surface of the work piece (this was observed by setting the work so that the tool cleared it by approximately 0.001". The side profile of the cutting tool and work surface were then observed with a Brinell microscope and the cutter rotated by hand until the cutting edge was in its lowest position). The built-up edge extended back beyond the wear land and apparently covered it as indicated in Fig. 40. It was not possible to measure the thickness of the built-up layer. To obtain a wear land measurement the built-up material was removed by disolving it in 10% nitric acid. The portions of built-up edge at the back of the wear land appeared to be fairly loosely attached, while that directly covering the wear land was firmly held in place and was marked with lines parallel to the direction of cutting, no doubt caused by rubbing on the work piece.

Since the wear land was parallel to the work surface the height of material removed from the tool could be directly calculated from the equation

$$W_h = W_t \sin\alpha \cos\alpha$$

where the symbols have the meaning shown in Fig. 41.

Figure 42 shows the results for height of material worn from the tool as calculated from the wear land, compared with change in depth of scratch. The abscissa of the graph is length of cut, each wear measurement being taken at the end of a cut over a 1 1/2" length of work material. The depth of cut was adjusted before each 1 1/2 inch cut, to be approximately 0.003", though this was difficult to set and was unfortunately not very well standardized. At low speeds the two methods of wear measurement gave very similar results, but at higher speeds the wear measured by wear land was greater than that measured by change in depth of cut. This is difficult to explain, but it may be tied in with the built-up edge formation. Possibly at higher speeds the built-up edge is more unstable and periodically fractures from the tool allowing extensive wear to occur for a few revolutions before the built-up edge again forms and brings the depth of cut back to about the same value.

The wear land measurements allowed calculation of volume of material worn from the grit and hence grinding ratio. To simplify calculations the wear land is assumed flat across the width of the tool and the initial grit shape is assumed to be triangular. Calculations indicated that the wear land is very slightly curved as shown in Fig. 43 (a). (h can be calculated from the known width of wear land y, and the radius of curvature of the grit R; $h = \frac{2R \pm \sqrt{4R^2 - y^2}}{2}$). Figure 43 (b) shows the assumed wear volume.

It can be seen that the volume of material worn from the grit is given by the relation

$$V_G = \frac{1}{4} W_1{}^2 \, y \sin \alpha \cos \alpha$$

where the symbols have the meaning shown in Fig. 43 (b).

Again assuming a triangular shape of tool (to be consistent), the material cut from the work piece is given by

$$V_M = \frac{b_1 d_1 + b_2 d_2}{4} \, l$$

where b_1 and b_2 are initial and final scratch widths

d_1 and d_2 are initial and final scratch depths

l is the length of cut.

The grinding ratio is given by $G = \frac{V_M}{V_G}$. Four measured values are given in Table 2 for cuts made at different speeds. Each value is the average of five or six consecutive tests.

Table 2

Grinding ratio measurements: Grit: Ceramic; Work: 1020 Steel; Feed: 1/2 ipm, Speed: as shown.

Rake Angle(α)	Speed	Grinding Ratio
-10°	246 fpm	52 ± 23
-6°	1090 "	63 ± 32
-12°	2880 "	47 ± 30
-20°	2880 "	47 ± 40

SUMMARY OF RESULTS

The results of these experiments may be summarized as below.

1. Force measurements with abrasive grits.

Considerable variations in force occur due to difference in geometry between grits, random variation in geometry of any particular grit due to chipping, and variation in depth of cut when steel or titanium are used as work material. However, the following conclusions can be drawn:

(a) Cutting force increases with increase in chip area of cut.

(b) Cutting force increases with increasing chip depth of cut.

(c) Force per unit width increases with decrease in chip depth of cut.

(d) Specific energy increases with decrease in chip depth of cut.

(e) Cutting speed appeared to have no influence on the specific energy at any given chip depth of cut

(f) No difference in specific energy could be observed when cutting with silicon carbide or aluminum oxide, but this was not clearly shown.

2. Force measurements with ceramic tools of known geometry.

(a) Cutting force rises linearly with increasing chip depth of cut.

(b) Force per unit area increases with decreasing scratch depth of cut. Increasing the speed was found to increase the specific energy at any given scratch depth, while increasing the feed had the reverse effect.

(c) Specific energy rose with decreasing chip depth of cut and the relation between these two variables was independent of speed and feed.

(d) Rake angle was found to have a significant effect on the specific energy at any given chip depth of cut. The percentage increase in specific energy per degree decrease in rake angle from -9° is approximately 2%.

(e) Tool wear is of considerable importance in determining specific energy. This is thought to be due mainly to the formation of a wear land on the clearance face.

(f) The chip length ratio or cutting ratio (when cutting aluminum at 243 fpm speed, 1/2 ipm feed, with chip depths of cut between 50 and 325 micro-inches) varies between 0.08 and 0.3. Decreasing the rake angle decreases the cutting ratio. Furthermore, it appears that the cutting ratio decreases with decreasing depth of cut. The turning tests indicate that the slope of this relationship is somewhat less than shown in Fig. 31, but they appear to support the conclusion that the curve does have a real positive slope, as suggested.

(g) Shear strain was found to be considerably higher than for conventional machining. Strains of up to 15 inches/inch were measured with the -34° rake tool.

(h) The ratio of shear energy to total energy decreases with decreasing chip depth of cut and depends on rake angle, increasing as the rake angle is made more negative.

Although the relative values of the ratio of the energies at different rakes and depths of cut (as shown in Fig. 34) is probably satisfactory, there is some doubt about the suitability of the measuring equipment and the absolute values may be somewhat in error. They appear to be very high, the ratio being close to 1 for -63° rake. The turning tests also suggest that the values of $\frac{u_s}{u}$ are too high. For -15° rake at depths above 2000 micro inches the ratio has a constant value of 0.8. It is unlikely that at smaller depths of cut the ratio would have a value greater than this.

(i) The calculated shear stress rises with decrease in chip depth of cut.

The shear stress with a -26° rake tool was found to rise to about 200,000 psi at 50 micro inch chip depth of cut when cutting aluminum at 246 fpm speed and 1/2 ipm feed. Examination of all the specific energy and shear strain measurements indicates that it is unlikely that the calculated shear stress exceeds this value when cutting aluminum with a sharp tool at chip depths above 50 micro inches.

From the turning tests it appears that a continuous shear stress curve can be drawn from the grinding range down to the range of depths of cut used in lathe cutting.

DISCUSSION

The fact that the general rake angle of the ceramic tools has a significant effect on the specific energy seems to throw considerable doubt on the assumption of Backer, Marshall and Shaw (6), that the average rake angle of a grinding grit is zero. This assumption is based on the theory that the general rake angle (or the angle of the mean surface profile) of each grit is of no importance, but the angle of layers forming the surface structure determine the rake. In view of the results reported here this theory does not appear to be correct. The objection may be raised that the surface of a grinding grit is different to that of a ceramic tool. However in both cases a surface roughness will exist and if this determines the rake angle in one case it should do so in the other. The general rake of the grit profiles in a grinding wheel will certainly be negative, but the average value of the rake angle is essentially uncertain. An average of -30°, suggested by Backer and Merchant (42), is possible of the right order, but their method of arriving at this figure is open to considerable doubt. The ratio of vertical to horizontal force seems to vary with depth of cut and a direct comparison with turning data, as they apparently used, is liable to considerable error.

The evidence for decrease in cutting ratio with decreasing chip depth of cut at depths below 300 micro inches, although not as conclusive as one might wish, seems to be fairly good. This certainly occurs in the range of cuts used for turning and it seems reasonable that it would continue at finer depths. There was some mention of this point in the discussion to the paper by Backer, Marshall and Shaw (6), although they felt the accuracy of measurement in micromilling was insufficient to support this conclusion. With the larger micromilling chips their accuracy was probably better than that of this investigation. However, it is possible that the effect is less marked when cutting steel at higher speeds and furthermore, it appears that the slope of the cutting ratio to depth of cut curve becomes steeper at very small cuts.

With these considerations in mind it is of interest to look again at the shear stress values found by Backer, Marshall and Shaw. Putting a negative rake of say 30° into their calculations and reducing the cutting ratio correspondingly, will increase the calculated value of shear strain - in fact, it will more than double it, if a cutting ratio of 0.24 is taken as a reasonable value at -30° rake (they found cutting ratios of 0.362 at 0° rake and 0.296 at -15° rake in micromilling). As well as these alterations the ratio of shear to total energy $(\frac{u_s}{u})$ must be increased if a negative rake is to be considered. This increase certainly would not be greater than about half the previous value. The net effect of these adjustments will be a reduction in the proportinality constant in the relation between shear stress and specific energy. The reduction might be of the order of one quarter. If an allowance is made for decrease in cutting ratio with decrease in depth of cut the reduction in the proportionality constant would be approximately one half. Thus the calculated shear stress in cutting steel, although probably less than that found by Backer, et al, is still of the order of 10^6 psi at about 25 microinch depth of cut.

The calculated shear stress for grinding steel at small depths of cut is certainly above the yield value. This investigation indicates that the same is true when cutting aluminum with a single tool. Attention should next be directed to the method for stress calculation. A basic fallacy seems to be neglection of the forces on the clearance face of the tool. The large increase in specific energy found when a wear land is formed on the tool indicates that the forces on the clearance face can be as large or larger than those on the rake face, For a perfectly sharp tool it is theoretically possible for no force to exist on the clearance face. It is doubtful that this condition is ever achieved in practice, if obtained it would only exist momentarily as some wear will rapidly occur to give a real area of contact between the clearance face and the newly formed work surface. That this occurs in grinding has been observed in this investigation and is shown by Letner (21) for a complete grinding wheel. Pictures in Letner's paper indicate that some wear land has been formed after removing 0.046 cubic inches of work material and after 0.86 cubic inches the wear land on the grits varies between 0.001 to 0.005 inches length - unfortunately his grinding conditions are not stated.

Thus it is highly likely that part of the total force measured in metal cutting arises from clearance rubbing and is not due to the shear process. From the assumption that all the measured force is due to shearing, the calculated shear stress will be higher than the actual stress. It is probable that the rubbing forces become more important as the depth of cut is decreased, so that this consideration has greater influence in grinding than in the more common metal cutting processes. As previously mentioned, Thompson, Lapsley and Grassi (18) have discussed this aspect. Their method of estimating the rubbing force by extrapolation of the cutting force back to zero depth of cut (as indicated in Fig. 26) is open to some question. Further investigation of this could be of great importance.

Another aspect neglected in the calculation of shear stress is the "pre-flow region" - the region of plastic flow where the uncut work surface bends around to form the back of the chip. As Shaw and Finnie (17) have pointed out the radius of this region can make the shear plane longer than the length assumed in Merchant's analysis with a sharp corner. Thus neglecting the radius will have the effect of making the calculated shear stress higher than the actual value. With a fairly large negative rake and small depth of cut, the shear plane could conceivably be twice as long as that calculated on the assumption of a sharp corner at the work-chip junction. This would make the calculated shear stress double the actual value.

These remarks on the calculation of shear stress are merely speculative as no quantitative values can be determined with existing knowledge. However, they suggest that the calculated shear stress - both in this paper and the value of approximately 10^6 psi indicated from the results of Backer, et al - are excessively high. Whether the actual stress is of the order of the conventional yield value or not cannot be determined at this time. Size effect may exist - the theoretical strength may be lower than previously assumed, or alternatively the shear stress in grinding may not rise as high as the theoretical value.

The region at small depths of cut where specific energy appears to become independent of depth of cut, as reported by Reichenbach, Shaw, Mayer and Kalpakcioglu (15), is of considerable interest. This region seems to be reasonably well established although confirmatory evidence in single grit cutting would be desirable. Backer, Marshall and Shaw (6) and Reichenbach, et al, (15) suggested that the region corresponds to the shear stress of the material reaching its theoretical strength. As indicated in this paper the value of the true shear stress in the level region is probably considerably lower than that calculated in (6) and (15). This indicates either that the theoretical strength is considerably lower than previously thought or that some other effect is causing the specific energy to be independent of depth.

It seems quite possible that the theoretical strength is lower than the values $\frac{G}{2\pi}$ or $\frac{G}{4}$ which have been frequently suggested. Brenner (10) measured tensile stresses of approximately 1.7×10^6 and 0.9×10^6 psi for iron whiskers in different crystalographic directions. Cottrell (39) has proposed that the theoretical strength may be as low as $\frac{G}{30}$ (0.4×10^6 psi, for steel), but concluded that it could not be much lower than this.

The fact that at small depths of cut the forces and specific energy are practically independent of the hardness of the material, as reported by Marshall and Shaw (30), requires explanation. It can be nicely explained by the size effect theory. However, it can also be explained from the theory that the specific energy at small depths of cut rises due to increased influence of the forces on the clearance face. The friction force on the clearance face is more or less independent of the hardness of the material, or it could be lower for a harder material. Thus when (if) the rubbing force becomes large relative to the shearing component in the direction of cutting, then the total measured cutting force will be independent of the hardness of the work material.

To conclude this section of the discussion a summary of the points considered might be made. It is certain that specific energy rises as depth of cut is decreased. There appear to be two possible explanations for this:

1. The shear strength of the material increases with decreased specimen size.

2. The friction force on the clearance face becomes relatively more important at small depths of cut. In addition to this the 'pre-flow' region may also become more important.

It is likely that the first point plays a definite part in this phenomena, but the evidence that theoretical strength is reached is not conclusive.

The evidence that the second factor has quite a considerable influence seems good. As Colding (39) has pointed out the growth of a wear land in lathe cutting does not seem to have a very large influence on the measured cutting force (although many tests have been effected by crater wear); however, at the small depths used in this investigation, the influence of wear land is large, indicating the greater importance of friction force on measured cutting force at small depths. Furthermore, as Thompson, Lapsley and Grassi (18) suggest, there seems no reason why the clearance face forces should decrease at smaller depths.

Until further work is carried out on these aspects it appears that the explanation of specific energy increase by size effect alone, should be treated with some doubt.

Grinding Ratio Measurements

Although the results of these measurements are not considered to be very reliable, the description of the test procedure has been included because it is felt to offer a useful method for future studies of grinding grit wear. With the use of grits of a definite geometrical form it should be feasible to find how the rate of wear varies over cutting time (the few tests carried out in this investigation indicate that a constant rate of wear is reached after a short cutting time). Tool life tests, similar to those in single point turning, could be carried out and might be of considerable interest.

The grinding ratio values obtained at 2910 fpm are approximately half those found by Distel (25) for the same steel under the same conditions. This could be due to less wear resistance of the ceramic tool or may indicate errors in the assumptions made in determining the material worn from the grit. The error may have occurred in this investigation or in that of Distel; however, since the calculation is more direct from wear land measurements this is considered to be the better method.

The variation in wear as measured by change in depth of scratch and by wear land is most unexpected. The explanation by built-up edge formation may be correct, but further examination of this is probably worthwhile and may lead to a better understanding of the grinding process.

Temperatures in Grinding

Although not strictly connected with the previous work some consideration has been given to the temperatures existing at the work surface just behind a grinding grit. Outwater and Shaw (33) have made calculations and Mayer (43) has measured temperatures by an indirect procedure, both methods have suggested temperatures above the melting point of the material. This result seems strange since both Bowden at Cambridge, England, and Sternlicht at General Electric Co., have found that the surface temperatures in sliding at very high speeds (in excess of 60,000 fpm) never exceed the melting point of the rubbing materials. The short time of contact in grinding may have some influence on this, but it seems doubtful as the molten layer could be infinitesimally thin. Mayer, in a private discussion has since suggested that one of his calibration curves was probably in error and that the measured temperatures were below the melting point.

The calculation of Outwater and Shaw (33) should probably be modified in the light of this discussion. Firstly, some doubt exists as to the validity of their method of surface temperature calculation. Although the procedure of Loewen and Shaw (34) for applying Jaeger's solution to finding shear plane temperatures is probably justified, it does not seem that the same method can be applied directly for calculation of surface temperatures. The fraction of heat flowing from the shear plane, away from the chip flow direction, will certainly pass into the uncut work piece, but there seems no reason to assume that this will flow into the freshly cut work surface. In fact it would seem that most of this heat will go to raising the temperature of the material about to form a chip.

Outwater and Shaw in determining a suitable value of specific heat assumed that the short cutting time would prevent the steel phase transformations which normally occur at 1400 and 1600°F and reduce specific heat. Since they observed a transformed surface layer this assumption seems dubious - if taken into account, the lower value of specific heat gives a higher calculated temperature.

If a transformed layer is formed, the heat absorbed in transformation may be of some importance. A rough calculation can show, however, that this factor is negligible. Metals Handbook (36) gives the heat of transformation at the A_3 line as 5.6 calories/gram at 1600°F. This becomes smaller if the transformation is delayed to higher temperatures, which may occur due to rapid temperature rise. From this it can be shown that the energy per cubic inch of metal cut, to transform a surface layer δ inches thick, is

$$E_{(\text{transformation})} = 0\ 024 \times 10^{6} \frac{\delta}{t} \text{ inch lb./inch}^{3}$$

where t is the chip depth of cut.

Compared to this, the energy to raise the temperature of a layer of thickness δ , to 1600°F is, (taking the mean specific heat as 0.25)

$$E_{(\text{temperature rise})} = 1.05 \times 10 \frac{\delta}{t} \text{ inch lb./inch}^{3}$$

This it is seen that the energy required for transformation is negligible compared with the energy to raise the temperature and may be omitted, as Outwater and Shaw assumed.

The next question is the temperature developed by friction on the clearance face, This can be found by a direct application of the Jaeger solution (35). The heat developed by friction is

$$q = \frac{W_f'}{l_W\, b'\ 12J}$$

where W_f' = friction work done on the clearance face

l_W = length of clearance face wear land

b' = width of cut (total)

J = mechanical equivalent of heat.

This can be written as,

$$q = \frac{U_f\, V_{\cancel{s}}\, t}{12J\ l_W} \qquad (1)$$

where U_f = friction energy on the clearance face per unit volume of material cut

V = cutting velocity

t = chip depth of cut.

By Jaeger's solution, the mean temperature under the rubbing surface can be written as

$$\bar{\theta} = 0.752 \frac{1}{k \sqrt{L}} \qquad (2)$$

where k = coefficient of thermal conductivity

L = dimensionless velocity parameter = $\frac{Vl}{2K}$

and K = thermal diffusivity = $\frac{k}{\gamma c}$

γ = specific density of the material

c = specific heat of the material

Combining Eqs. 1 and 2 and simplifying gives

$$\bar{\theta} = 0.752 \frac{U_f' t}{12J k} \sqrt{\frac{2KV}{l_W}} \qquad (3)$$

substituting the values t = 30×10^6 inches

V = 6000 fpm

and assuming a wear land of $l_W = 0.005$ inches (photographs by Letner (21) and others suggest this is farily rapidly formed on average grinding wheels).

If the temperature from shear work is 2000°F then k = 2.2, c = 0.25, thus $K = \frac{k}{\gamma c} = 31.4$ ($\gamma = \cdot 283$ lb./in.^{3})

from Eq. 3 $\bar{\theta} = 9.3 \times 10^6 \times U_f'$

If $U_f' = 10^6$ inch lb./inch^3 , $\bar{\theta} = 9.3$°F

If temperature from shear work is 1400°F , k = 4 , c = 0.25 (c is more or less constant from about 1400°F up to about 2000°F, due to the phase transformations)

thus K = 57

and so $\bar{\theta} = 6.9 \times 10^6 \times U_f'$

To cause a significant rise in temperature U would have to be very large. This is an important aspect. It has been shown previously, that probably about half the measured total specific energy is produced by rubbing and now it is seen that this energy has little tendency to raise the temperature of the work surface. Thus it seems that the total energy should be divided by about 2 before calculating the temperature rise due to shear.

The solution of the temperature problem is far from complete and probably cannot be solved until a better understanding of the basic division of energy has been developed.

FUTURE TESTS

Several tests might be carried out on the same or similar equipment to that used in this investigation including:

1. Examination of the change in specific energy as wear land is increased progressively.

2. Determination of grinding ratio under different conditions from wear land measurements.

3. Construction of tool-life curves from wear land measurements and further investigation of variation in wear rate over time. There seems no major practical difficulty preventing these and the test of point 2 being carried out at speeds approaching those used in grinding.

4. Grits of aluminum oxide and silicon carbide of a known geometry could be used for wear tests and force measurements. Cole (44) mentioned that such grits could be produced by a jeweler.

5. Examination of specific energy when cutting fluids are applied to single tool cutting at very small depths.

Other useful investigations might be:

6. Measurement of forces on grits with a two component dynamometer. It seems that a strain ring on the rotating spindle might have a low enough mass to make this practicable, at least for low speed cutting.

7. Temperature measurements by the chip tool thermo-couple technique, using a single carbide cutter at small depths might produce new evidence.

8. The possibility of constructing a special tool to measure the clearance face forces independently of the rake face might be considered. This is certainly not simple and probably could not be used at very small depths, but the results of measurements over a range of different depths would be interesting.

9. Force measurements when cutting single crystals of material, with known preferred orientation, by a similar technique as was used in this paper, may throw some light on the division of energy in cutting.

APPENDIX A

Data obtained for determination of the Ratio of Shear to Total Energy.

Speed 246 fpm, 1/2 ipm feed, Ceramic grit, Aluminum work.

(a) -63° Rake

Cantilever Dynamometer	Two Component Dynamometer		$\frac{H}{V}$	Scratch Depth of Cut (inches)	Scratch Width (inches)	Cutting Ratio
Horizontal Force (lb.)	Hor.(H) (lb.)	Vert.(V) (lb.)				
-	0.031	0.013	2.4	0.0001	0.008	
3.8	1.15	0.71	1.62	0.0011	0.03	Discontinuous Chips. Average value assumed to be 0.07. (An estimate based on the values found at larger rake angles).
1.1	0.16	0.05	3.2	0.00035	0.017	
1.92	0.25	0.10	2.5	0.00035	0.017	
1.57	0.22	0.10	2.2	0.0002	0.01	
-	0.02	-	-	0.0003	0.017	
1.57	0.17	0.10	1.7	0.0003	0.017	
5.1	1.2	0.85	1.4	0.00115	0.034	
2.05	0.35	0.21	1.6	0.0004	0.017	

(b) -12° Rake

Cantilever Dynamometer	Two Component Dynamometer		$\frac{H}{V}$	Scratch Depth of Cut (inches)	Scratch Width (inches)	Cutting Ratio
1.4	0.46	0.85	0.54	0.001	0.015	-
1.68	0.78	1.0	0.78	0.0011	0.017	-
2.62	0.94	1.4	0.67	0.0017	0.022	-
-	0.89	1.3	0.68	0.0016	0.022	-
0.70	0.15	0.32	0.47	0.00035	0.011	-
1.36	0.7	1.15	0.61	0.0011	0.020	.12
2.62	1.65	2.1	0.79	0.0026	0.029	.12) Average
3.8	2.8	3.5	0.80	0.004	0.038	.15) value
3.4	2.6	3.25	0.80	0.0033	0.035	.17) 0.14

(c) -18° Rake

Cantilever Dynamometer	Two Component Dynamometer		$\frac{H}{V}$	Scratch Depth	Scratch Width	Cutting Ratio	
	Hor.	Vert.					
1.85	0.83	1.30	0.64	0.001	0.02	.14)	Average
2.9	1.1	1.50	0.73	0.0014	0.025	.13)	value
4.4	2.7	3.24	0.83	0.0017	0.035	.12)	0.13

(d) -26° Rake

0.95	0.39	0.75	0.52	0.0002	0.008	.12)	
1.97	0.68	1.06	0.64	0.001	0.017	.11)	
2.76	1.5	2.1	0.72	0.0017	0.025	.09)	Average
3.7	2.7	3.4	0.80	0.0034	0.035	.086)	value
1.36	0.7	1.06	0.66	0.0006	0.013	.08)	0.096
1.63	1.04	1.7	0.61	0.001	0.016	.09)	

APPENDIX B

Data from Turning Test. Material: Aluminum; Tool: Ceramic ("Stupalox"); Speed: 240 fpm

Chip Depth of Cut (in.)	Chip Width of Cut (in.)	Force		Area of Cut (in^2)	Specific Energy (F/A') (in.lb./in^3)	Chip Thickness (in.)	Cutting Ratio	Shear Angle	F_N (lb)	$(\frac{F}{F_N})$	τ (psi)
		Cutting (F)(lb)	Normal (lb)								
.00262	.085	27	23	22.4	.120	.010	.262	13.4	33	.84	19,700
.0031	.085	32	24	26.4	.121	.012	.260	13.3	34	.94	20,200
.0041	.085	39	27	34.8	.114	.014	.293	14.7	38.2	1.02	21,600
.00615	.085	51	32	52.2	.098	.018	.342	16.9	45.1	1.13	20,100
.0082	.085	62	37	69.5	.089	.020	.41	20.0	52.3	1.18	20,200
.0123	.085	79	39	104	.076	.026	.474	22.2	55.2	1.43	19,300

BIBLIOGRAPHY

1. Alden, G. I. "Operation of Grinding Wheels in Machine Grinding", Trans. ASME, Vol. 36, 1914, p. 451.

2. Guest, J. J. "Grinding Machinery", Arnold and Company (1915). See also: Proc. Inst. of Mech. Engrs. (London) 1915, p. 543.

3. Chapman, W. H. "Cylindrical Grinding in 1920", Trans. ASME, Vol. 42, 1920.

4. Krug, C. Maschinenbau, September 1925, p. 875 and Zeit, V. D. I., August 1927. See also: A. Hoffman; Maschinenbau, January 1933.

5. Heinz, W. B. "Metal Cutting with Abrasive Wheels", Trans. ASME, Vol. 65, 1943, p. 21.

6. Backer, W. R., Marshall, E. R. and Shaw, M. C. "The Size Effect in Metal Cutting", Trans. ASME, Vol. 76, 1952, p. 61.

7. Kalpakcioglu, S. "Geometrical Analysis of Grinding", M.I.T. S.M. Thesis (Mechanical), January 1953.

8. Taylor, G. F. Physics Review, Vol. 23, 1924, p. 655.

9. Herring and Galt "Elastic and Plastic Properties of Very Small Specimens", Physics Review, Vol. 85, 1952.

10. Brenner, S. S. "The Tensile Strength of Whiskers", General Electric Research Laboratory, June 1956, Report No. 56-RL-1565.

11. Roscoe. Phil. Mag., Vol. 21, 1936, p. 399.

12. Cottrell and Gibbons. Nature, Vol. 162, 1948, p. 488.

13. Makin. See Andrade, E. M.; da C Inst. of Metals, Mono No. 13, 1953, p. 138.

14. Walker, D. R. "Size Effect", S.D. Thesis (Mechanical), 1954.

15. Reichenbach, G. S., Shaw, M. C., Mayer, J. E., and Kalpakcioglu, S. "The Role of Chip Thickness in Grinding", Trans. ASME, September 1955, p. 824.

16. Merchant, M. E. "Mechanics of the Metal Cutting Process", Journal of Applied Physics, Vol. 16, 1945, pp. 267 and 318.

17. Shaw, M. C. and Finnie, I. "The Shear Stress in Metal Cutting", Trans. ASME, Vol. 77, 1955, p. 115.

18. Thompson, E. G., Lapsley, J. T., and Grassi, R. C. "Deformation Work Absorbed by the Workpiece During Metal Cutting", Trans. ASME, Vol. 75, 1953, p. 591.

19. Walker, D. R. "Factors Affecting the Role of Metal Removal in Grinding", S.M. Thesis (Mechanical), May 1951.

BIBLIOGRAPHY (CONTD)

20. Reichenbach, G. S. "Forces in Internal Grinding", S.M. Thesis (Mechanical) August, 1952.

21. Letner, H. R. "A Modern Perspective of the Grinding Process", ASME Paper No. 54-F-4 (September 1954)

22. McKee, R. E., Moore, R. S., and Boston, O. W. "Experimental Study of Cylindrical Grinding", Trans. ASME, Vol. 69, 1947, p. 891. See also: Trans. ASME, Vol. 69, 1947, p. 125; and Trans. ASME, Vol. 70, 1948, p. 893.

23. Reid, R. "Single Grain Studies", M.I.T. Machine Tool Laboratory, July 1954.

24. Cole, J. M. "Wear Studies of Single Aluminum Oxide Grains During Grinding", M.I.T. S.M. Thesis (Mechanical), August 1955.

25. Distel, J. W. "Wear Studies of Abrasive Particles", M.I.T. S.M. Thesis (Mechanical) May 1956.

26. Hayman, H. "Individual Grain Abrasive Studies", M.I.T. Machine Tool Laboratory, August 1956.

27. Wagner. "New Concepts of Abrasive Properties as Affecting Grinding Performance", Mechanical Engineering, Vol. 72, 1950, p. 225.

28. Coes, L. "Knowledge of the Scientific Principles of Grinding is Basis of Recent Progress in Abrasives", Industrial and Engineering Chemistry, December 1955, p. 2493.

29. Marshall, E. R. "The Mechanics of Dry Surface Grinding", M.I.T. S.M. Thesis (Metallurgy) May 1949.

30. Marshall, E. R. and Shaw, M. C. "Forces in Dry Surface Grinding", Trans. ASME, January 1952, p. 51.

31. Shaw and Yang. "Inorganic Grinding Fluids for Titanium Alloys", Trans. ASME, May 1956, p. 861.

32. Woxen, R. ""Wheel Wear in Cylindrical Grinding", The Royal Swedish Institute for Engineering Research, Proceedings No. 124, 1933.

33. Outwater, J. O. and Shaw, M. C. "Surface Temperatures in Grinding", Trans. ASME, January 1952, p. 73.

34. Loewen, E. G. and Shaw, M. C. "On the Analysis of Cutting Tool Temperatures", Trans. ASME, February 1954, p. 217.

35. Jaeger, J. C. "Moving Sources of Heat and Temperature of Sliding Contacts", Proc. Royal Society N.S.W., Australia, Vol. 76, 1942, p. 204.

36. A.S.M. Metals Handbook, 1948, p. 314.

BIBLIOGRAPHY (CONTD)

38. Cottrell. "Dislocations and Plastic Flow in Crystals", Oxford at the Clarendon Press (1953), p. 9.

39. Colding, B. N. "Critical Evaluation and Correlation of Tool-Life Data", M.I.T. S.M. Thesis, May 1957, Mechanical.

40. Shaw, M. C. and Dirke, O. "On the Wear of Cutting Tools", Microtecnic, No. 4, Vol. X, 1956.

42. Backer, W. R. and Merchant, M. E. "On the Basic Mechanics of the Grinding Process", ASME Paper No. 56-A-43.

43. Mayer, J. E. "Temperature Measurements in the Grinding Process", M.I.T. S.M. Thesis, 1954, Mechanical.

44. Cole, J. M. "Wear Studies of Single Aluminum Oxide Grains During Grinding", M.I.T. S.M. Thesis, August 1955, Mechanical.

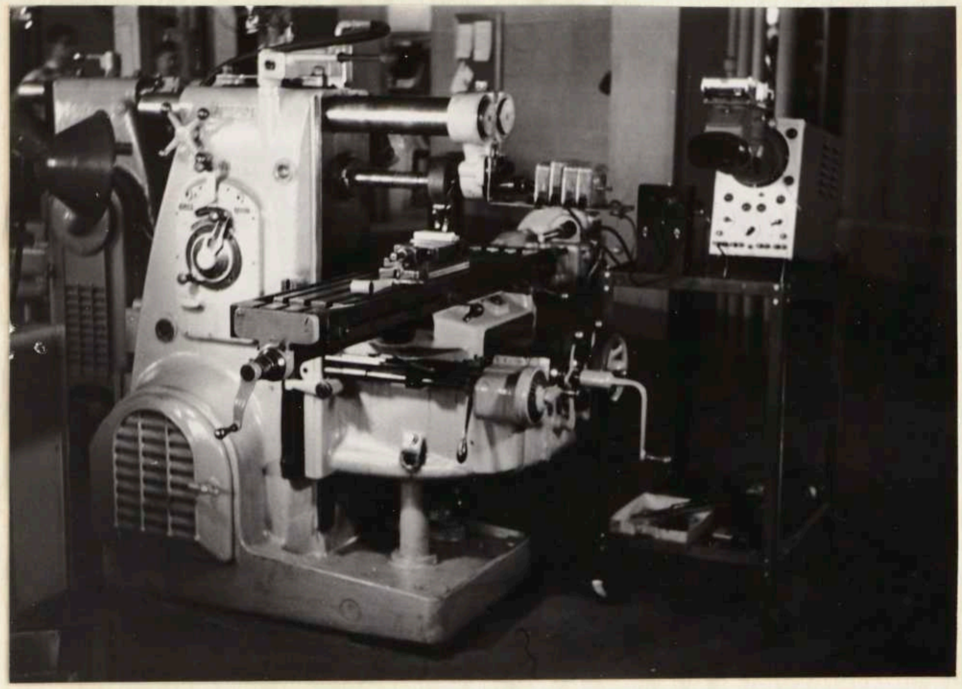


Figure 1 General View of the Apparatus

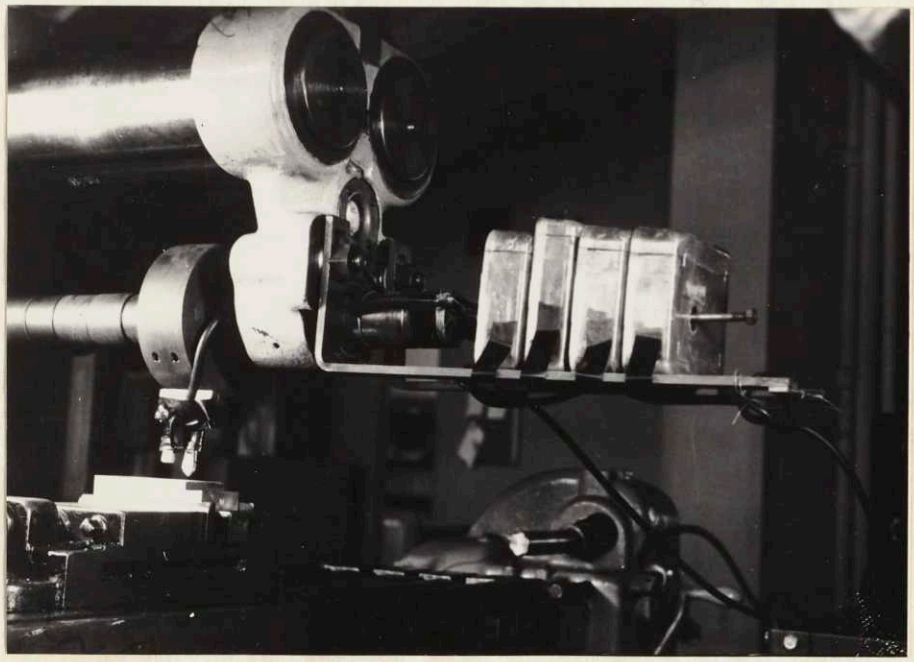


Figure 2 The Fly Cutter and Mercury Cummutator

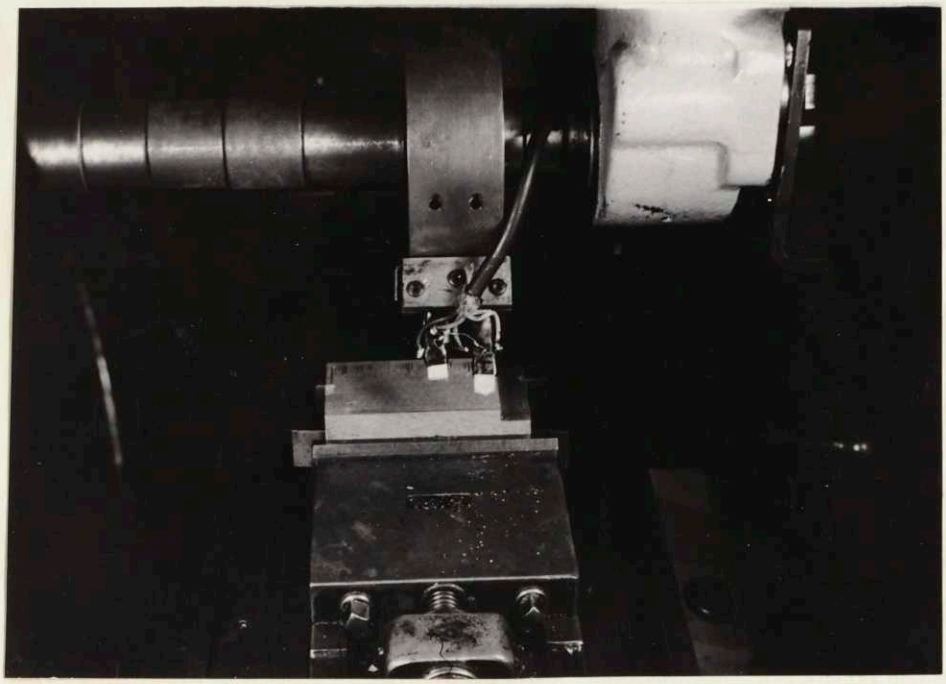


Figure 3 Strain Gauge Connections

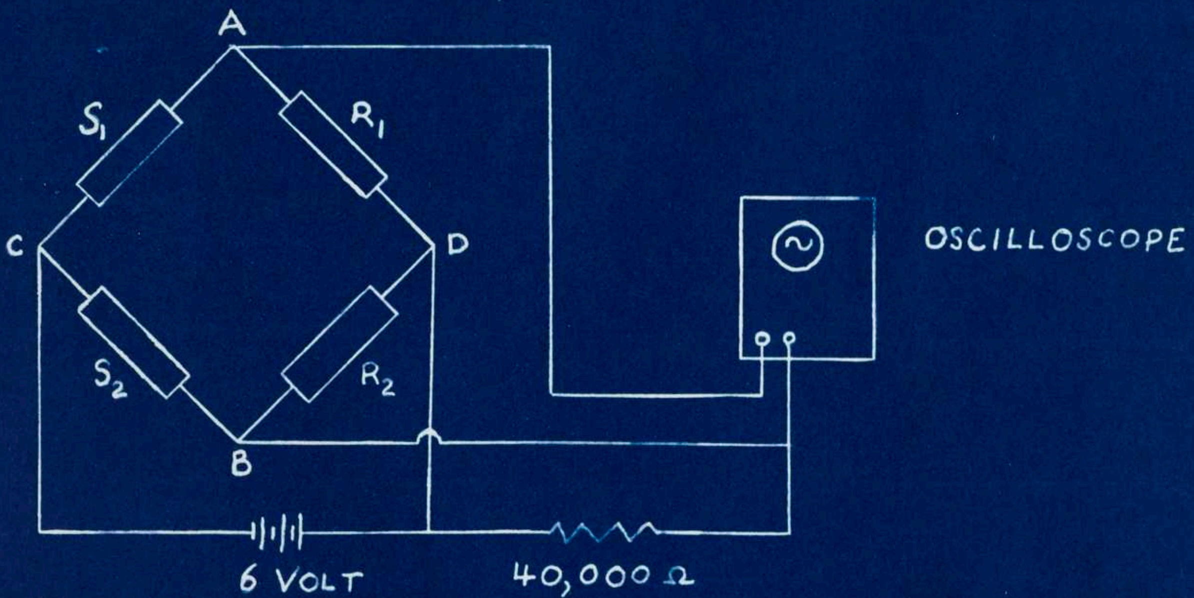


FIGURE 4

STRAIN GAGE CIRCUIT - S_1 and S_2 ACTIVE GAGES

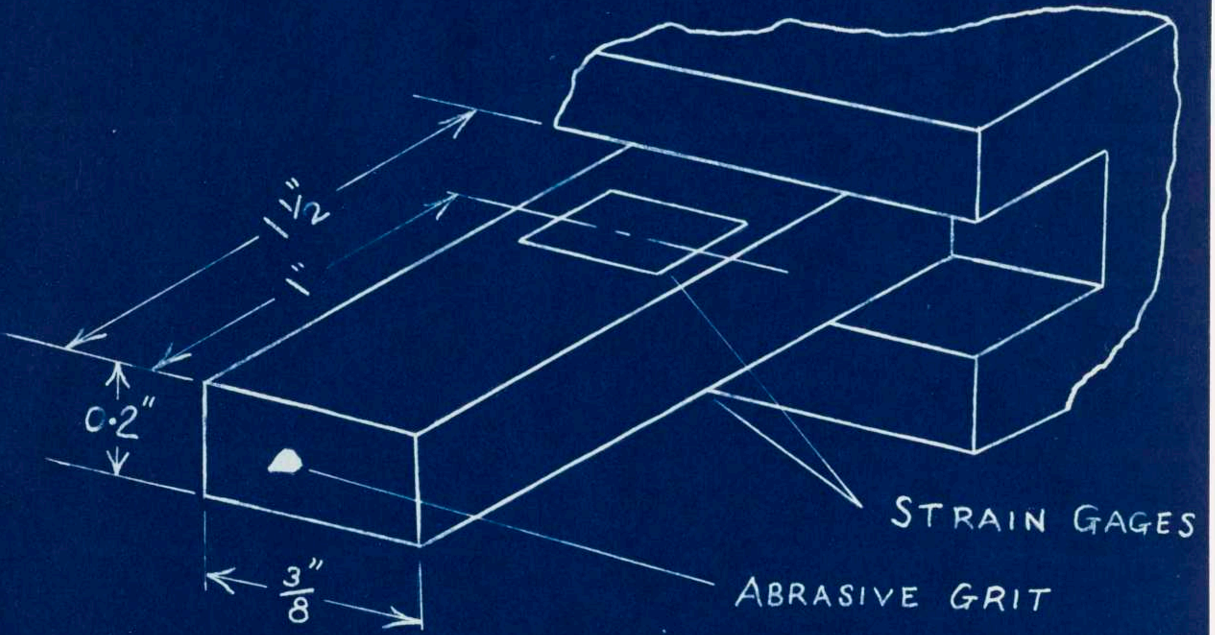


FIGURE 5

FORCE MEASURING CANTILEVER

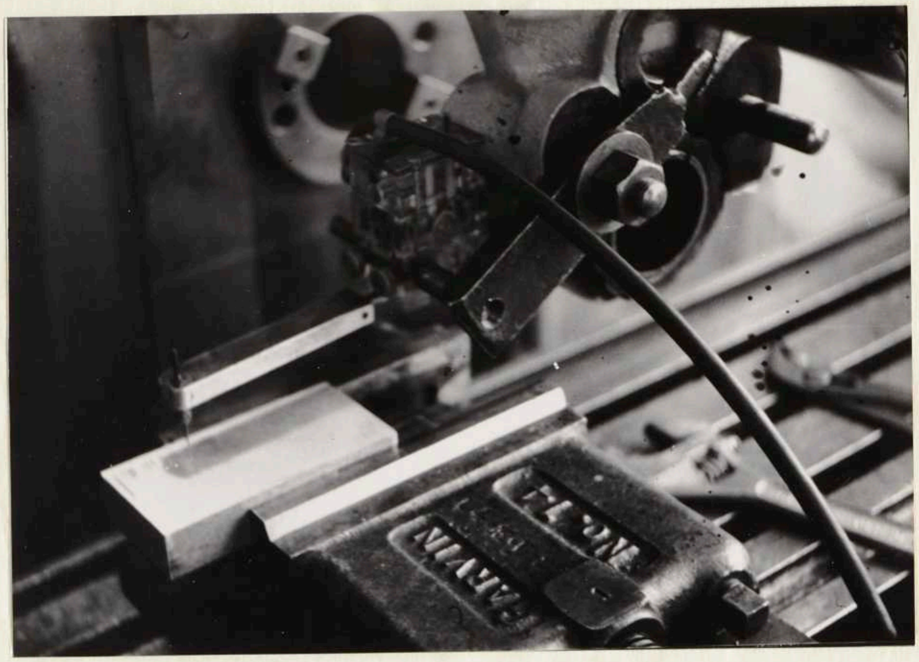


Figure 6 Surface Measuring Head

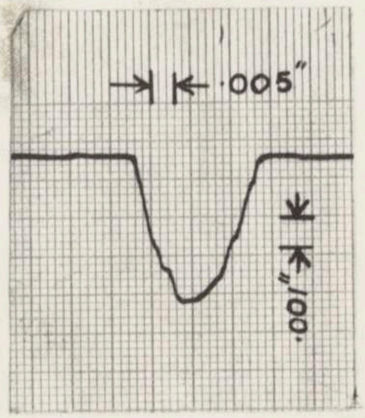


Figure 7 A Scratch Profile

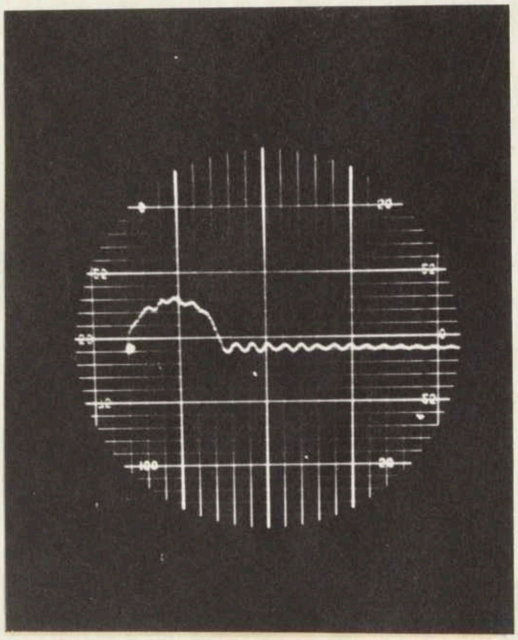


Figure 8 Typical Picture of Oscilloscope Deflection

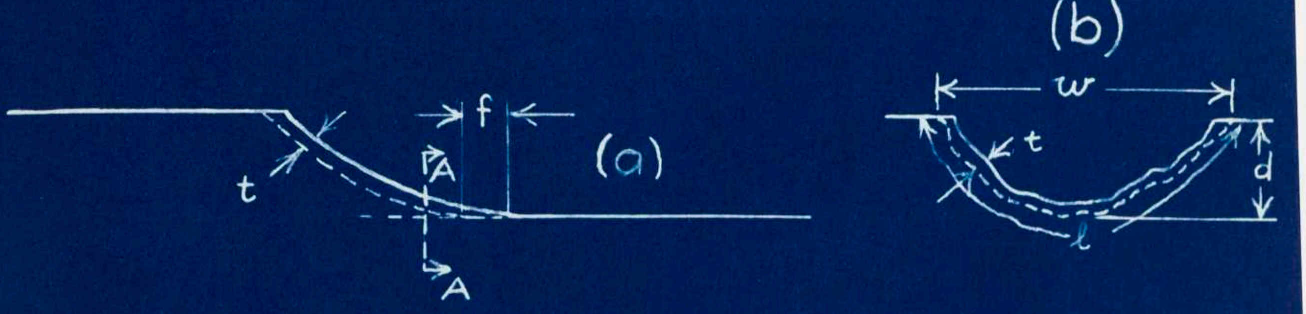


FIGURE 9

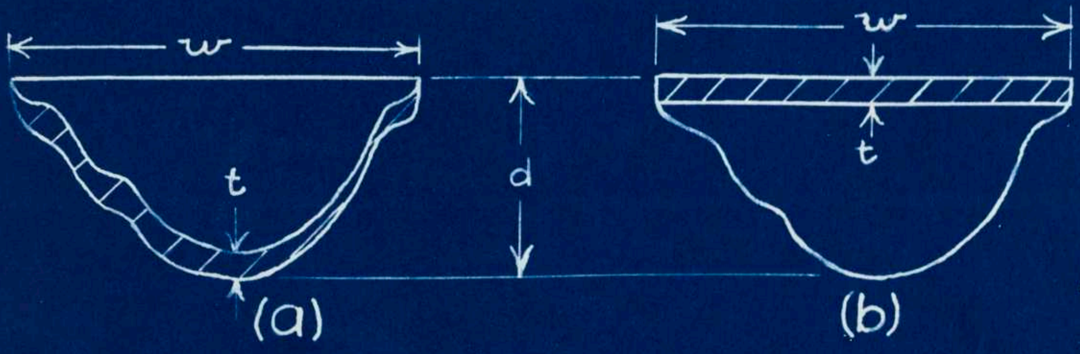


FIGURE 10

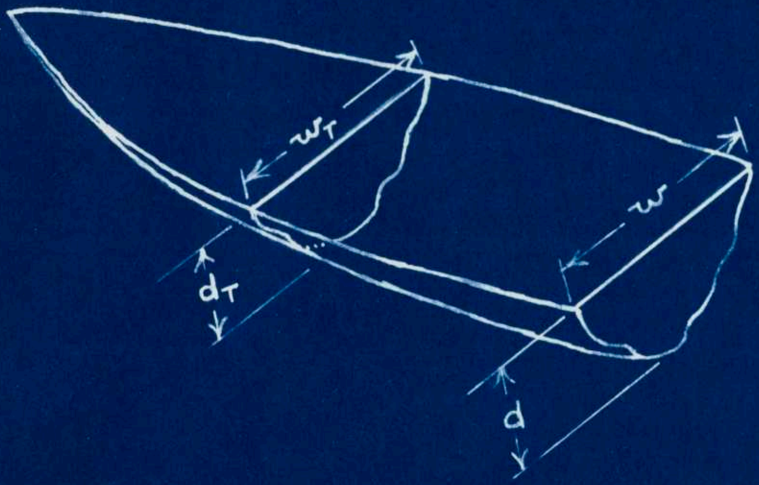


FIGURE 11

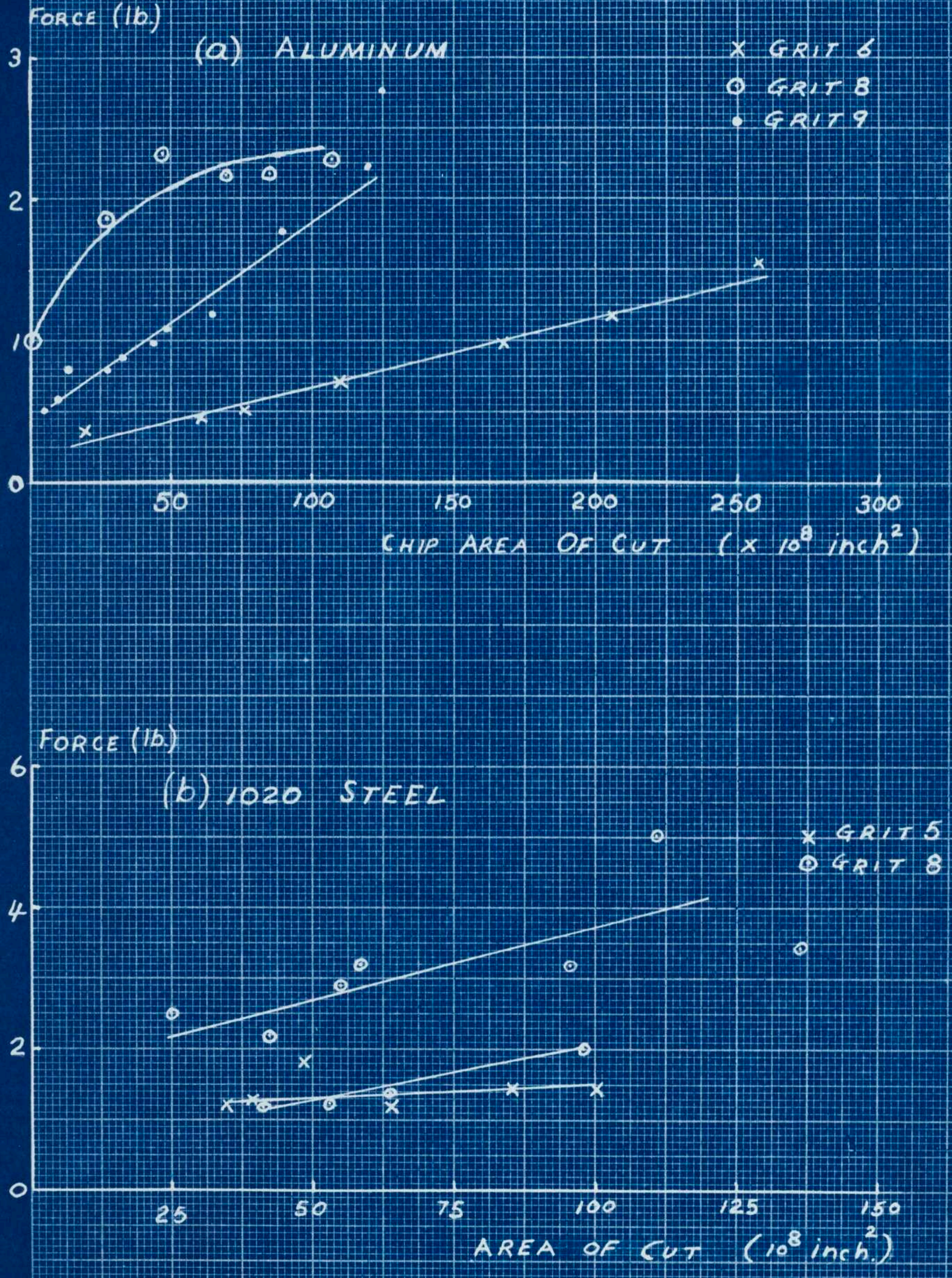
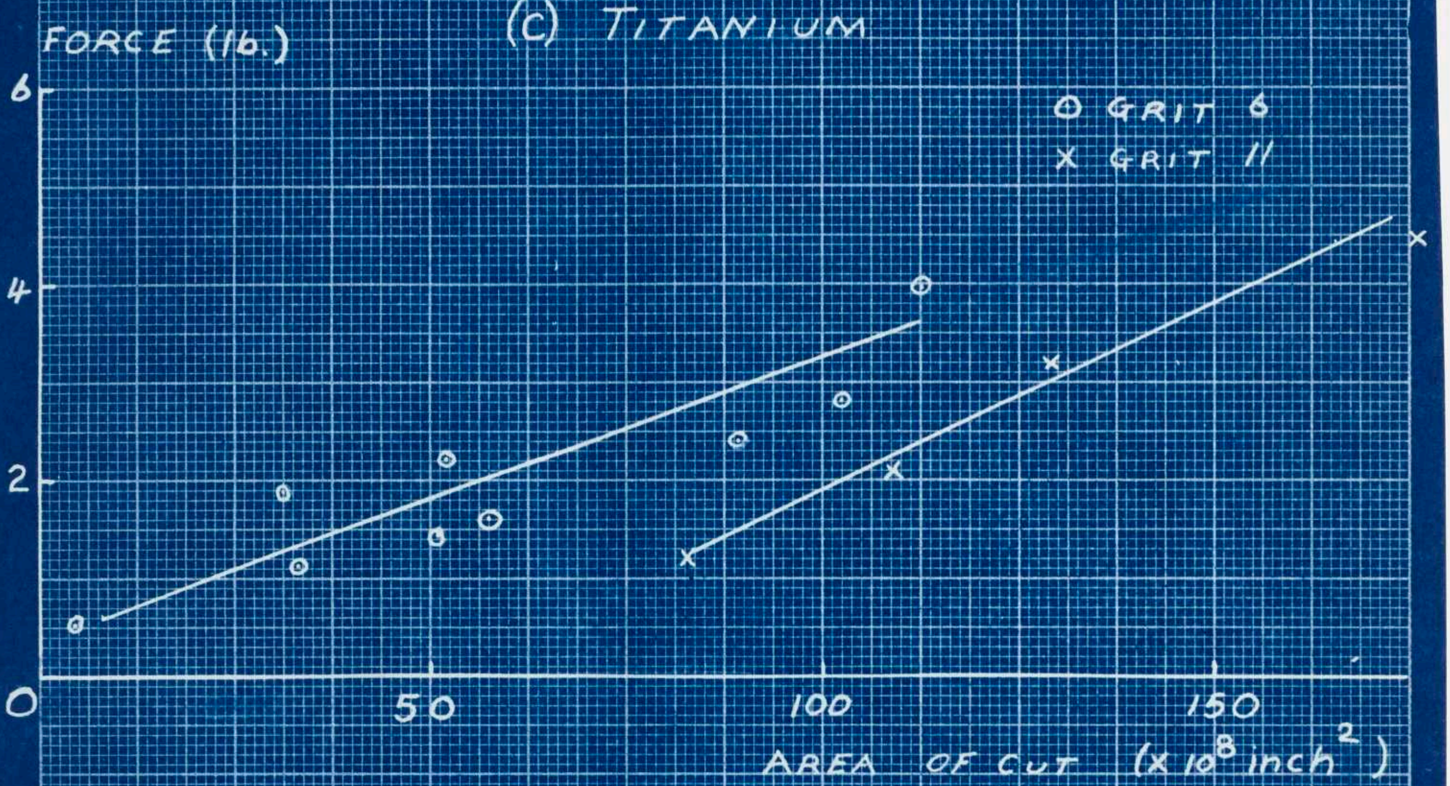


Figure 12 Aluminum oxide
250 f.p.m.
½ i.p.m.



(C) TITANIUM

FIGURE 12

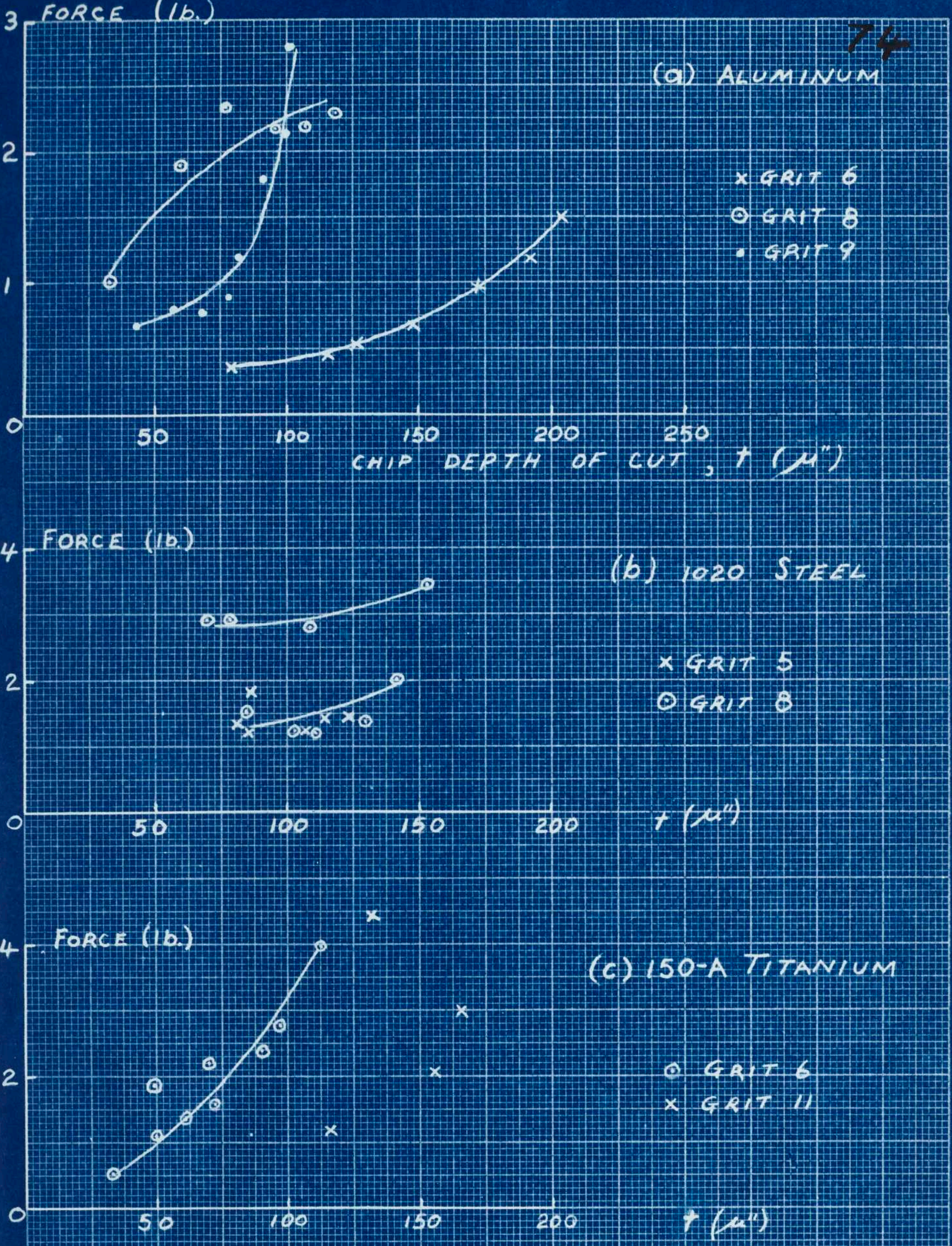


FIGURE 13

ALUMINUM OXIDE
250 f.p.m.
½ i.p.m.

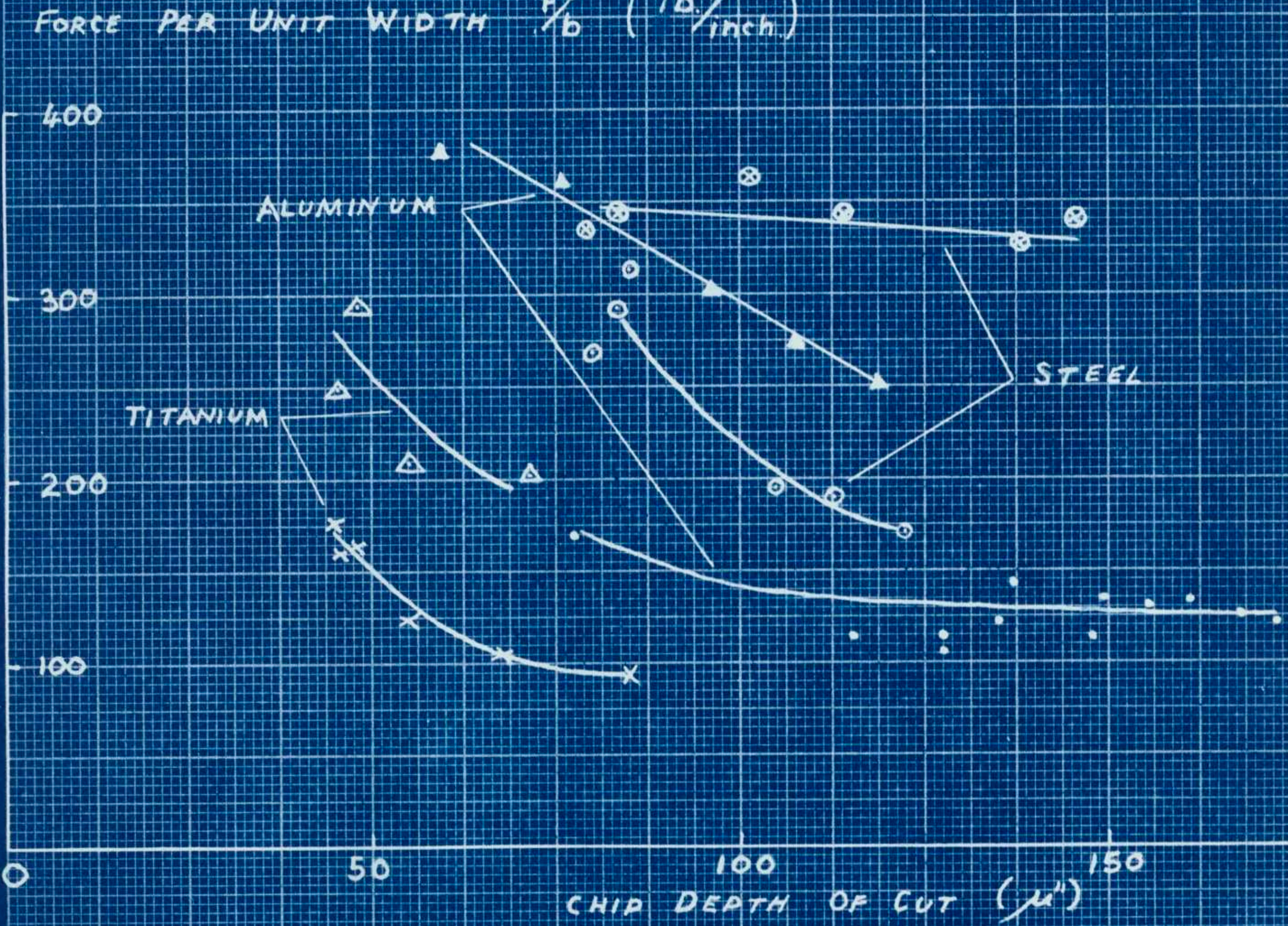


FIGURE 14

ALUMINUM OXIDE
250 f.p.m.
½ i.p.m.

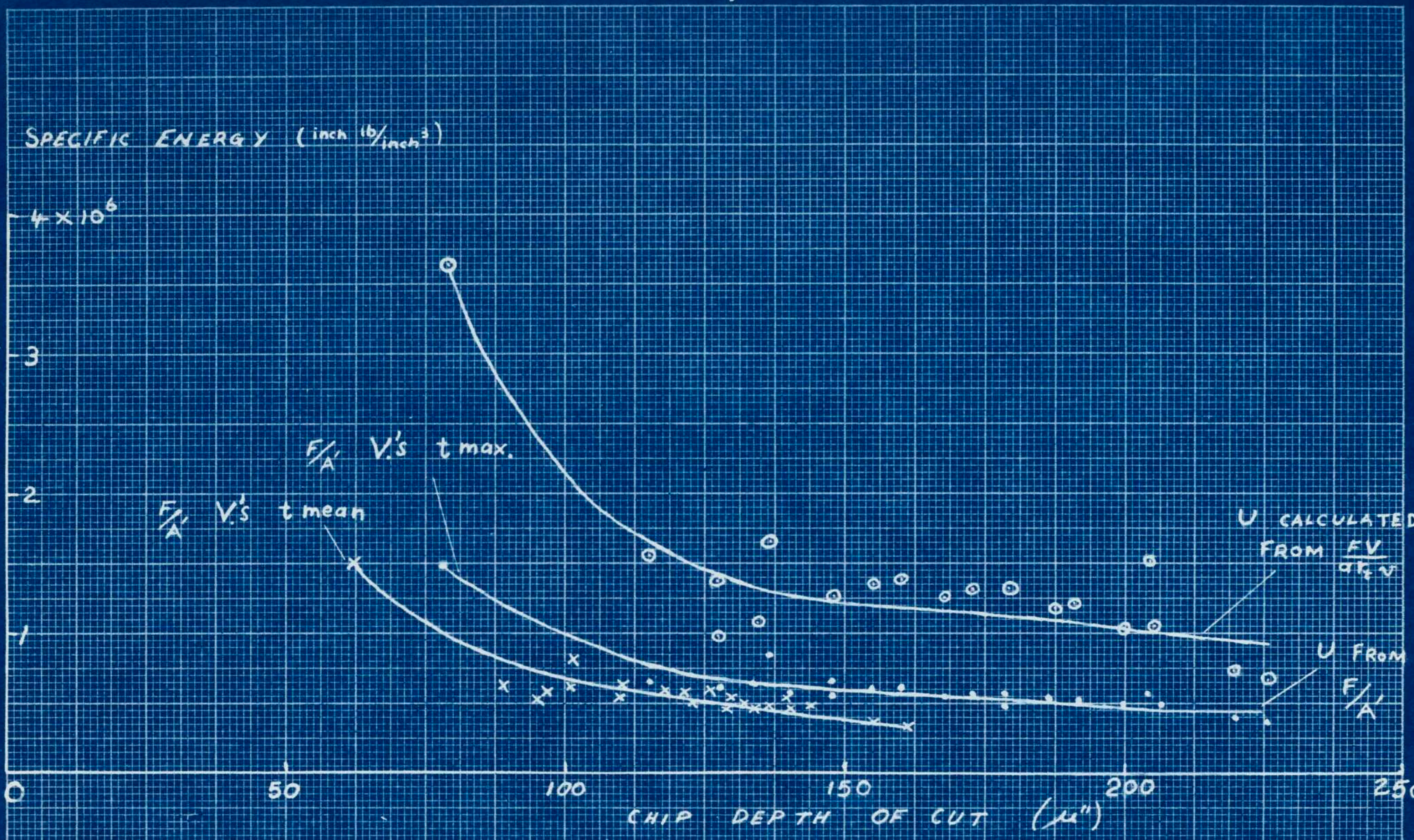


FIGURE 15

ALUMINUM WORK; ALUMINUM OXIDE GRIT; 250 fpm SPEED; ½ ipm FEED

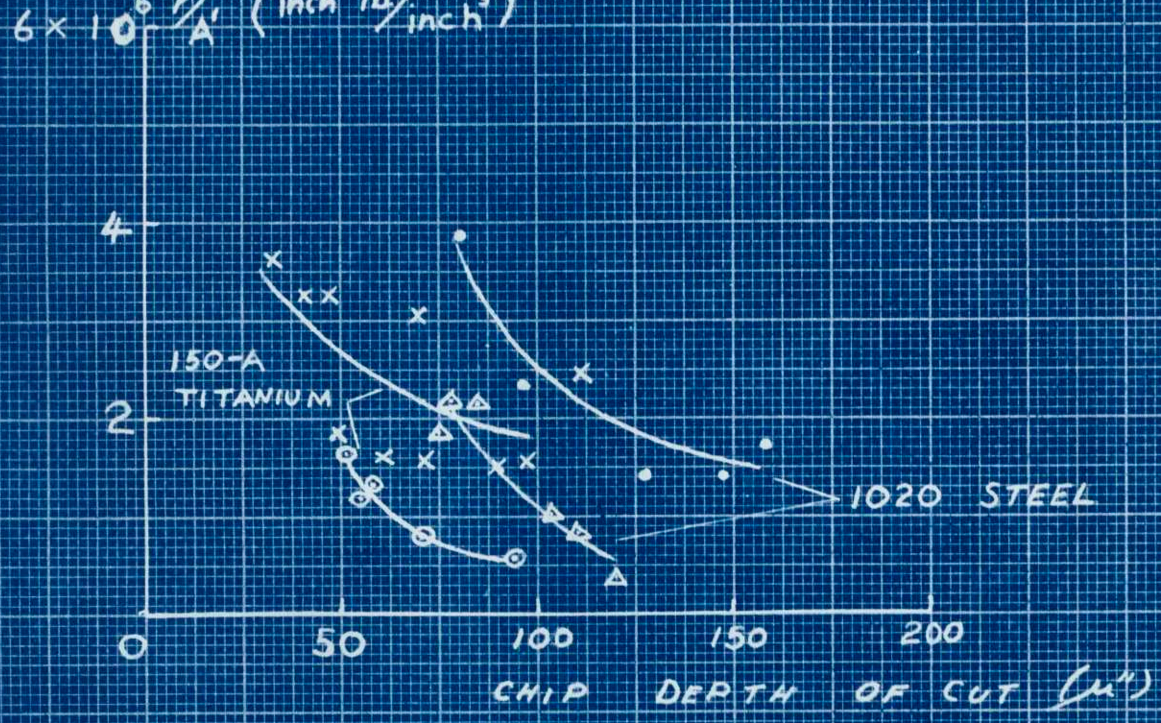


FIGURE 16

ALUMINUM OXIDE GRIT
250 f.p.m.
½ i.p.m.

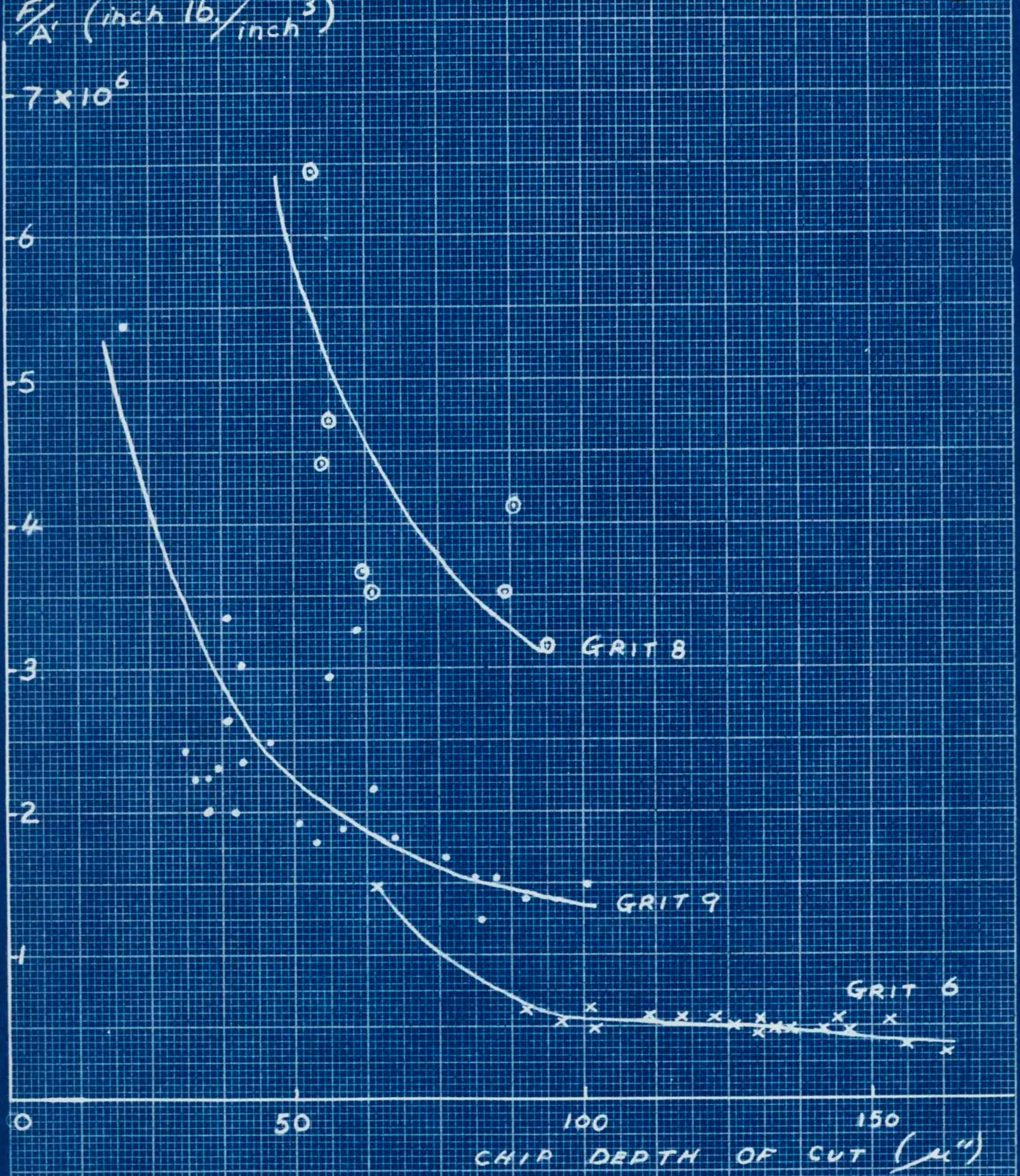


FIGURE 17

ALUMINUM WORK ; ALUMINUM OXIDE GRIT ; 250 f.p.m.
½ i.p.m.

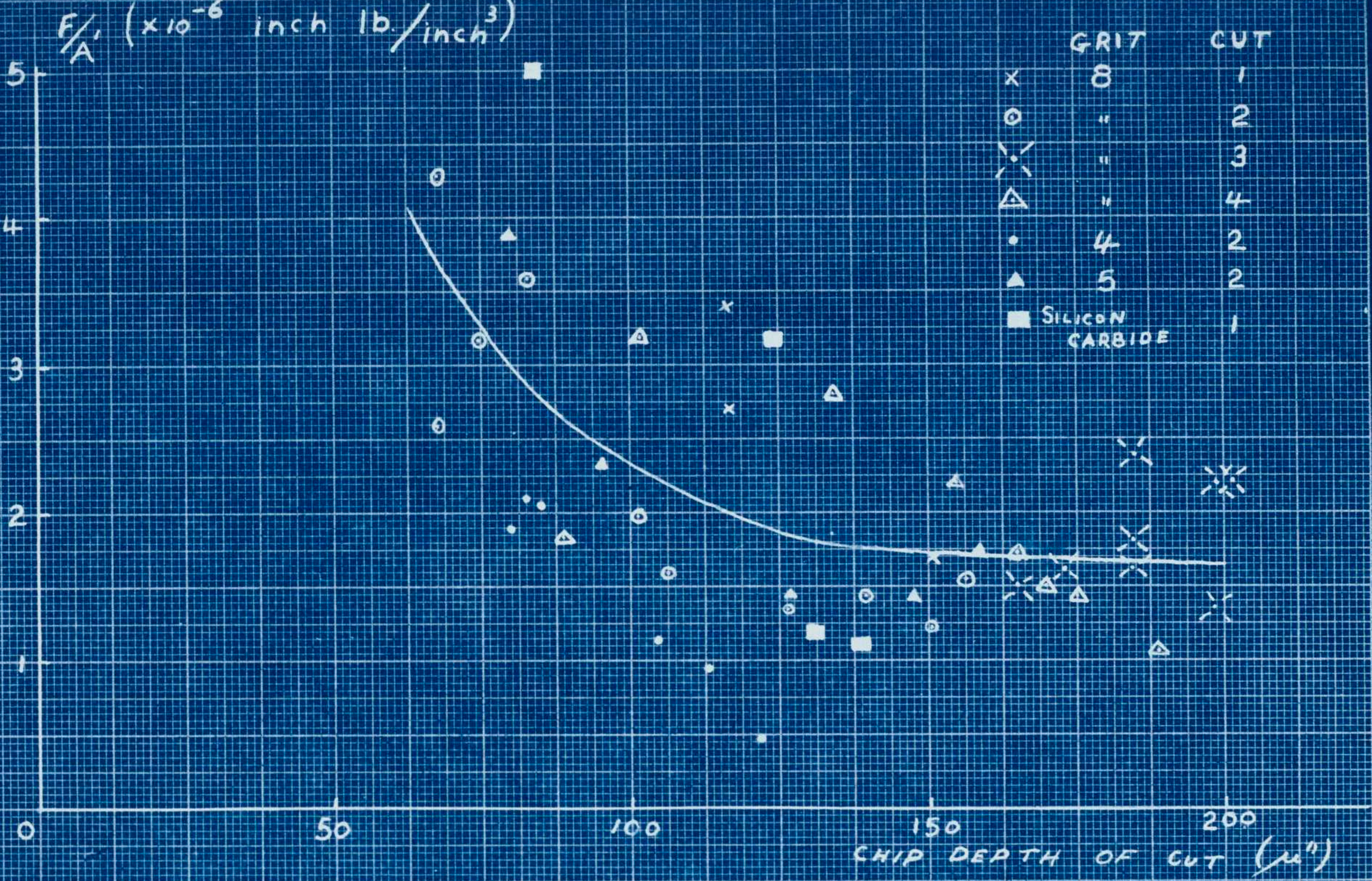


FIGURE 18

1020 STEEL WORK ; ALUMINUM OXIDE GRIT ; 250 fpm ; ½ ipm

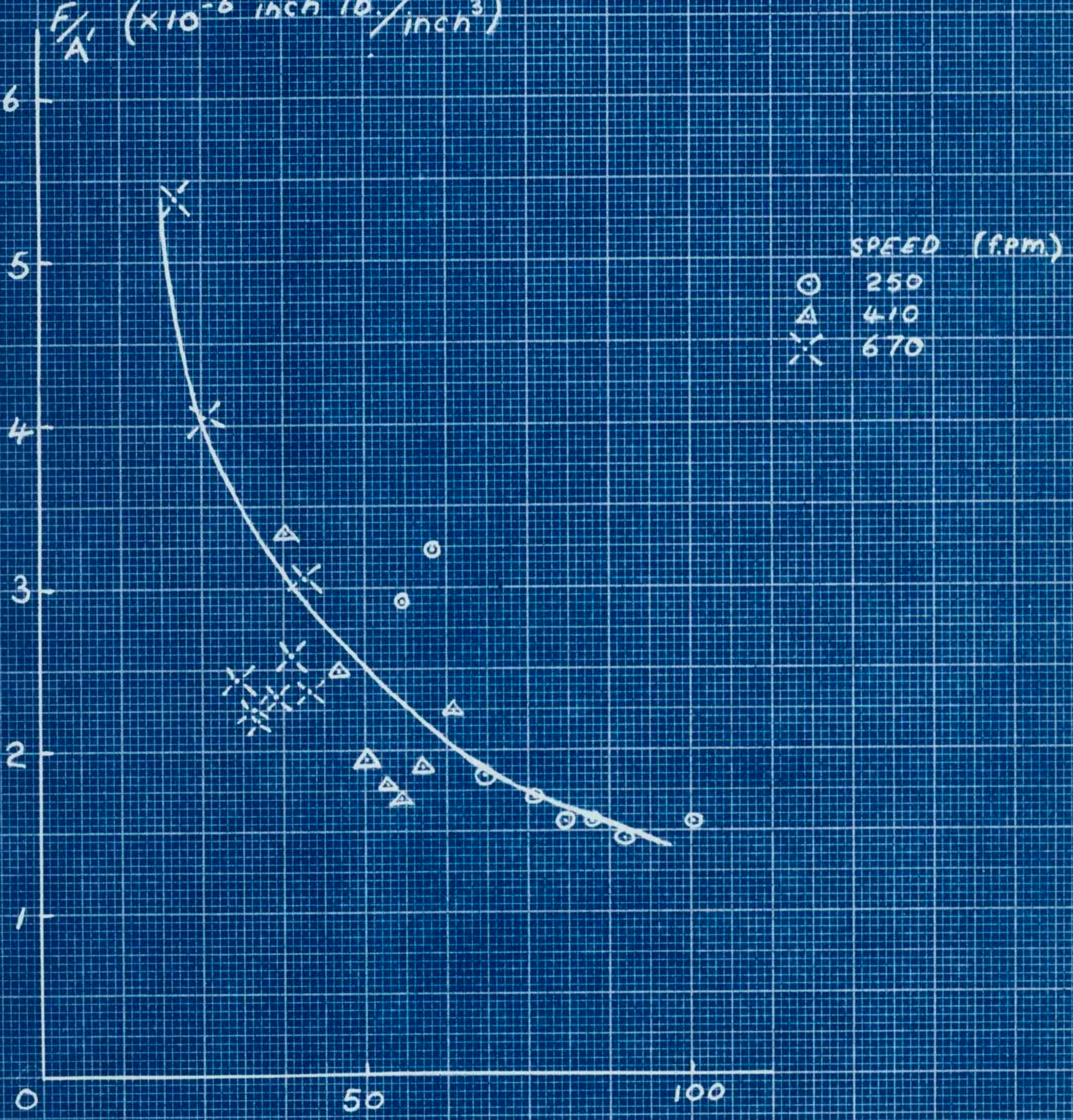


FIGURE 19

ALUMINUM WORK ; ALUMINUM OXIDE GRIT ; ½ i.p.m FEED.

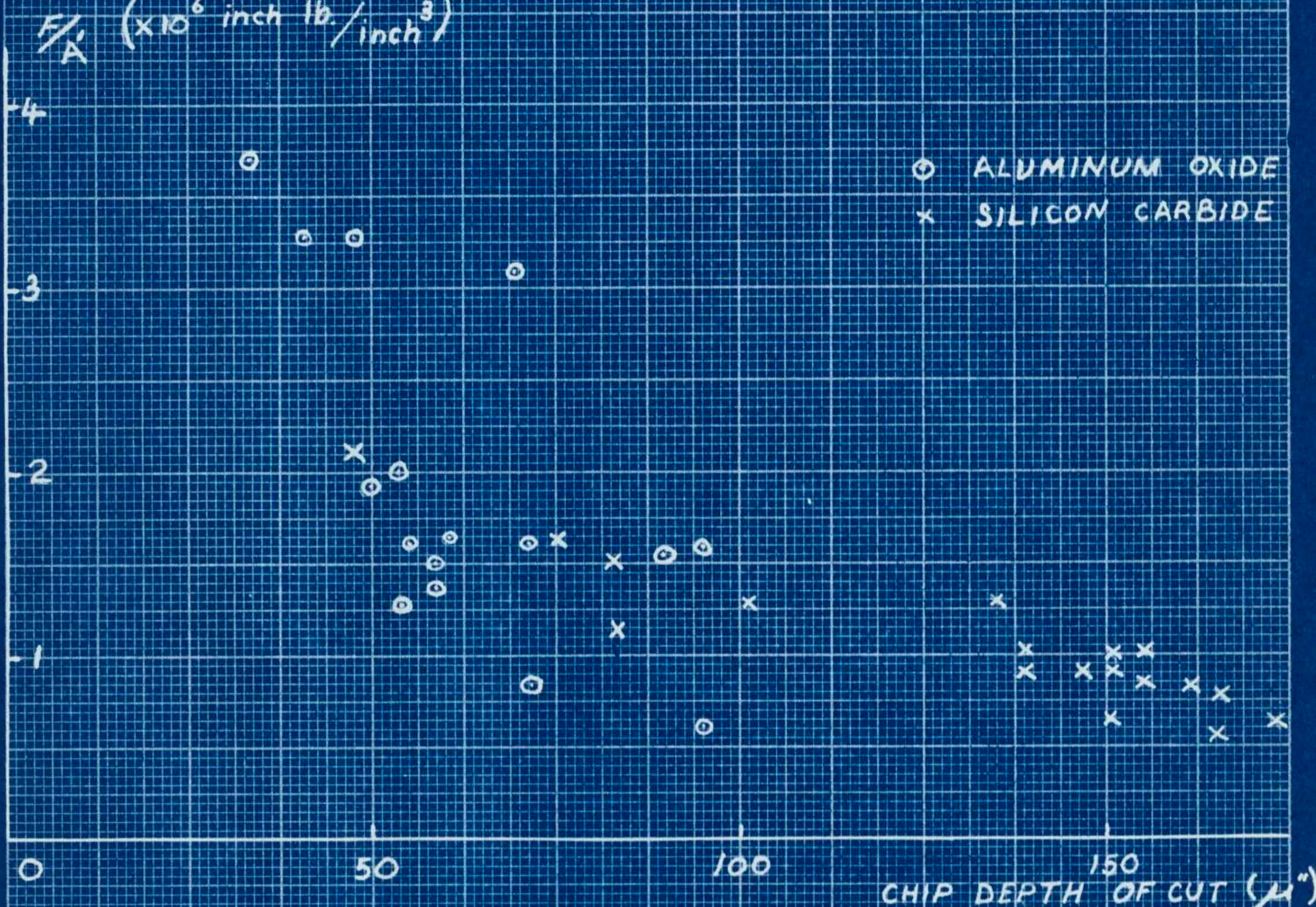


FIGURE 20

150-A TITANIUM WORK; 250 f.p.m; ½ i.p.m.

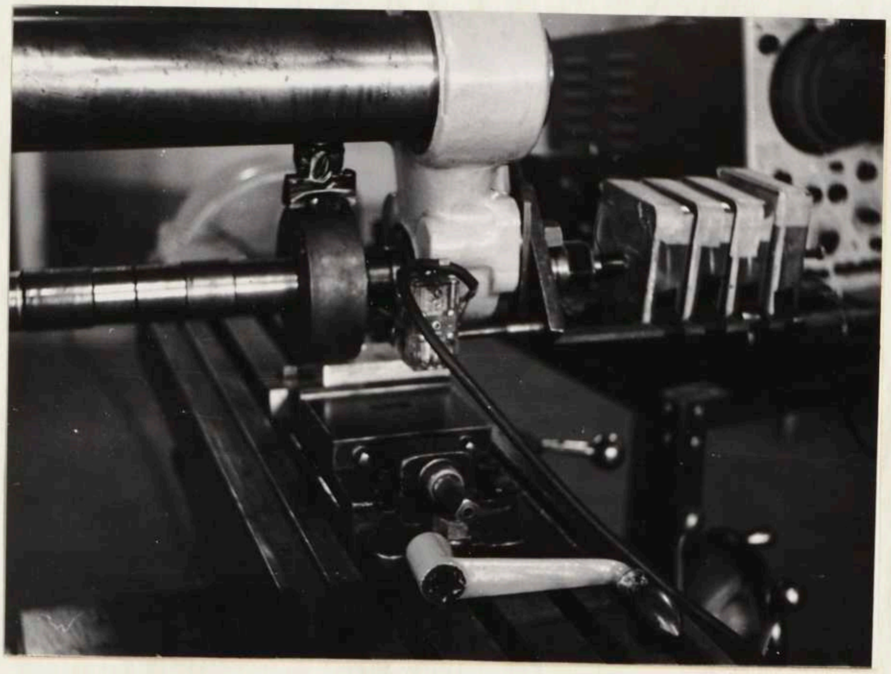


Figure 21 Longitudinal Surface Trace Measurement

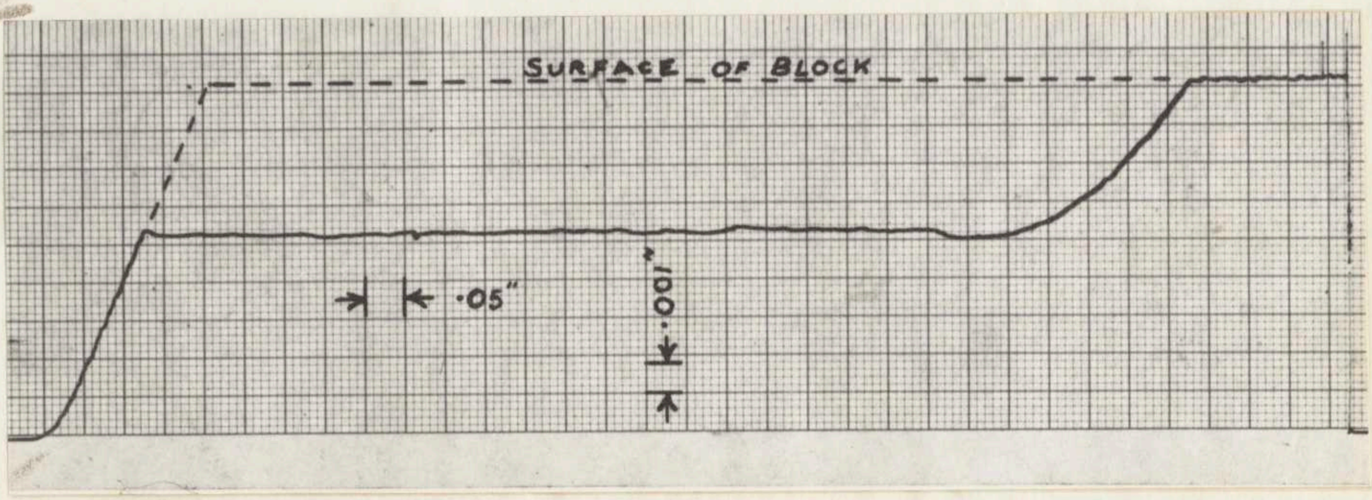


Figure 22 A Sample Longitudinal Surface Trace (Material: Aluminum)

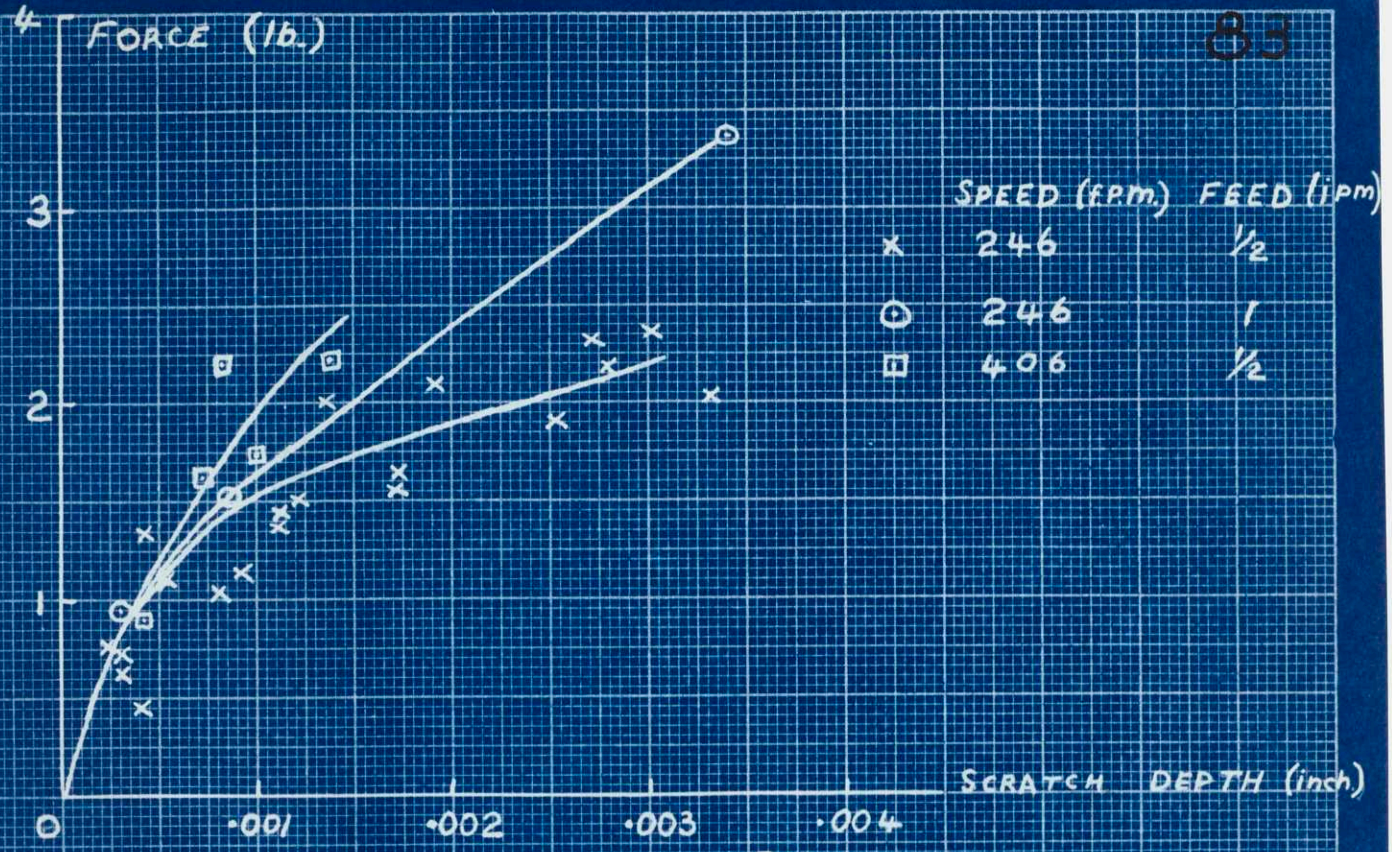


FIGURE 23

ALUMINUM WORK ; CERAMIC TOOL ; −15° RAKE

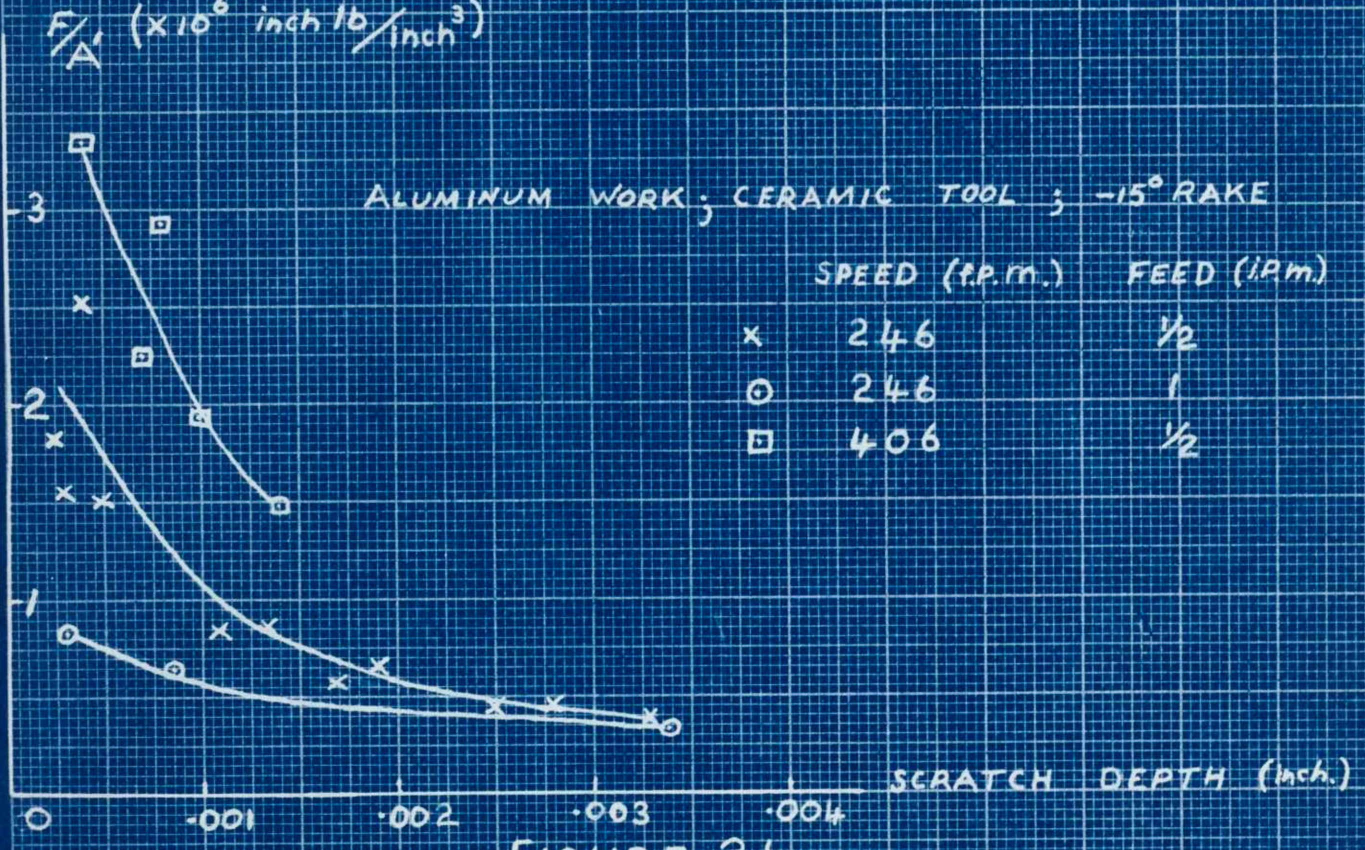


FIGURE 24

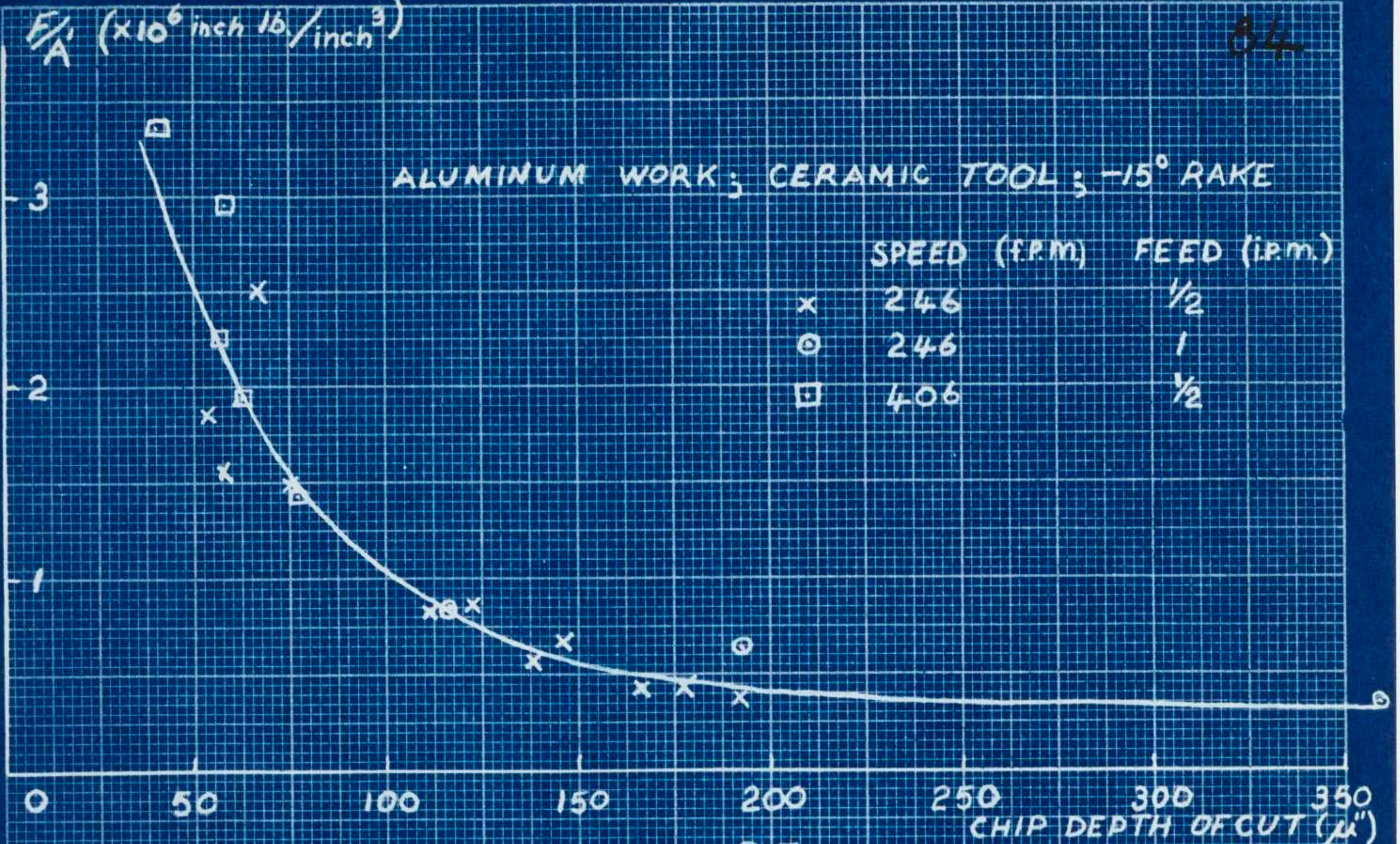


FIGURE 25

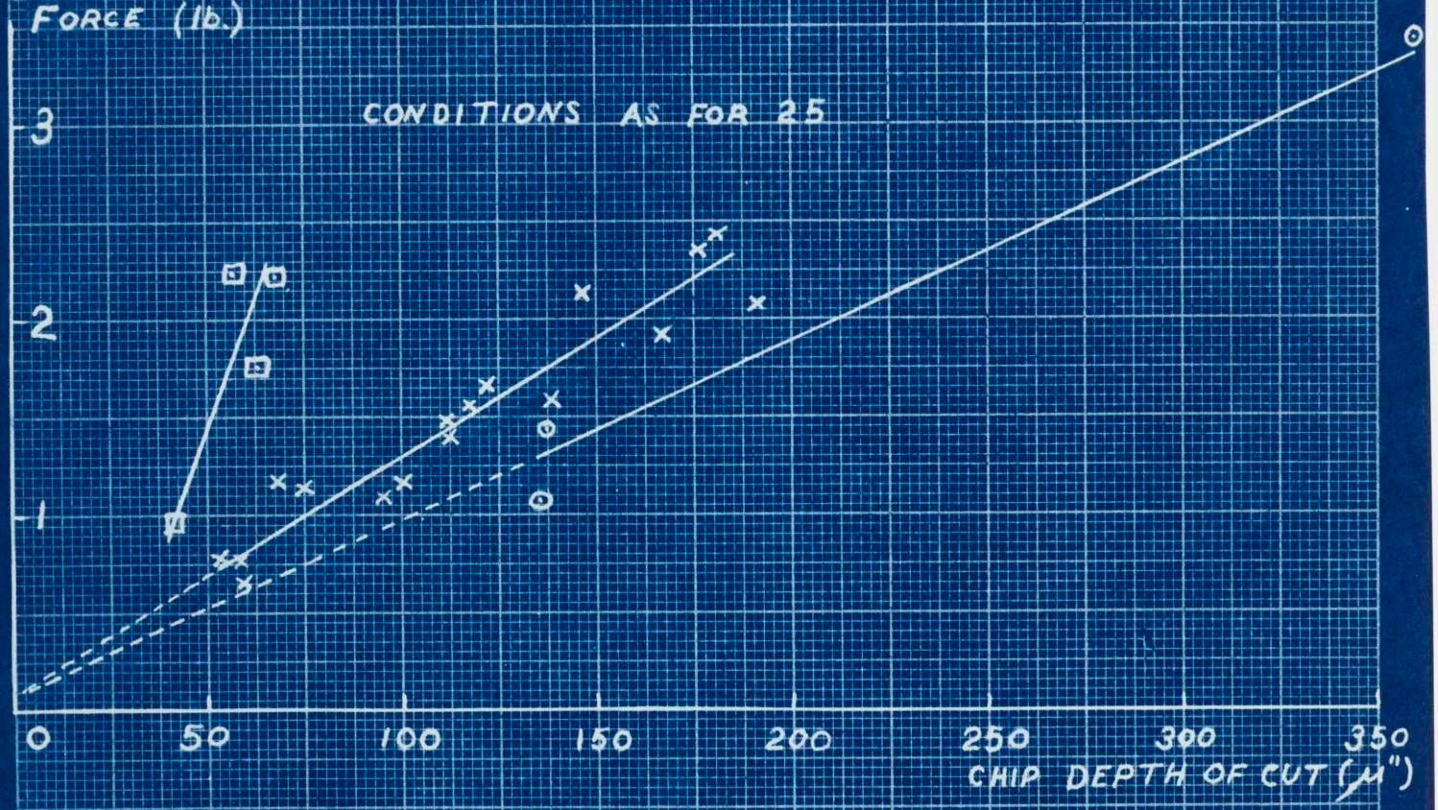


FIGURE 26

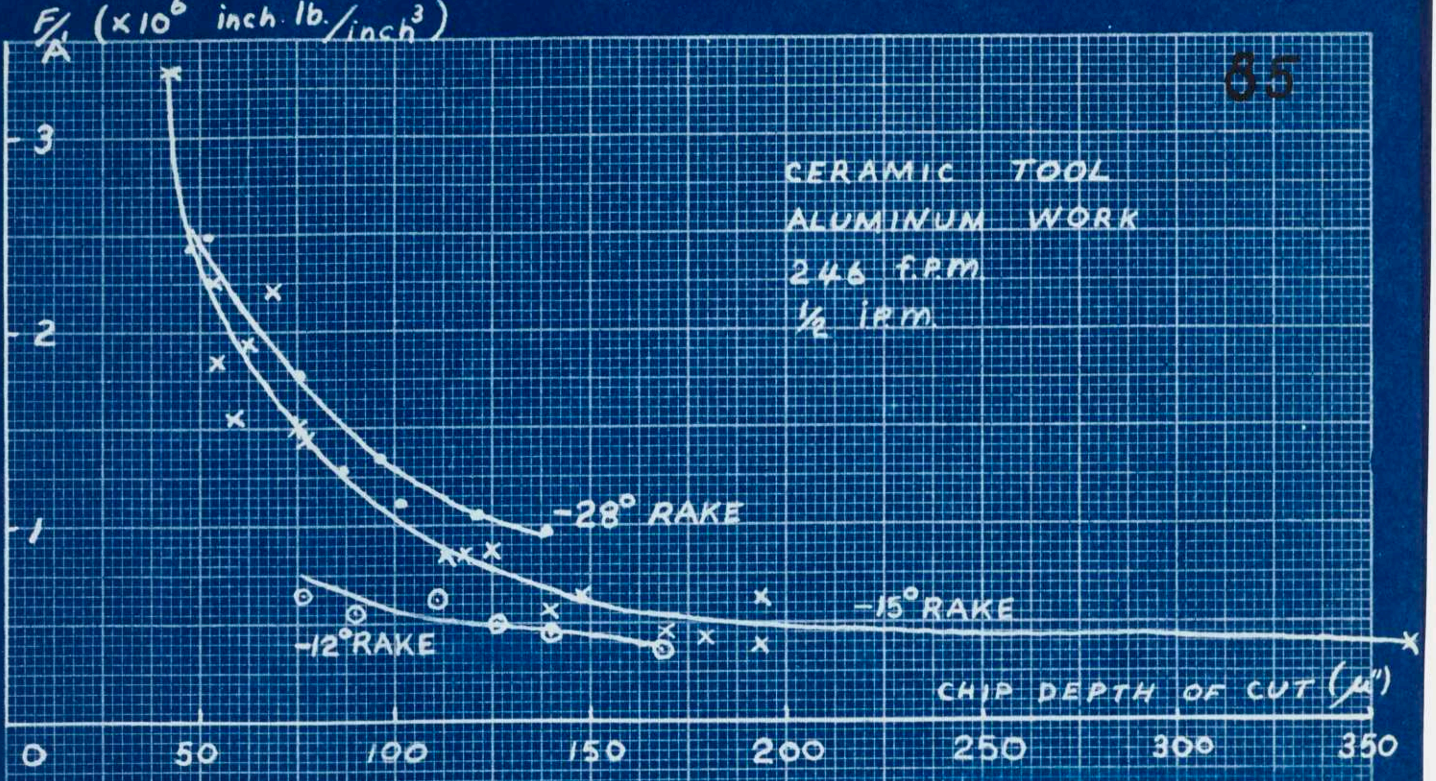


FIGURE 27 - DIFFERENT GRIT FOR EACH RAKE

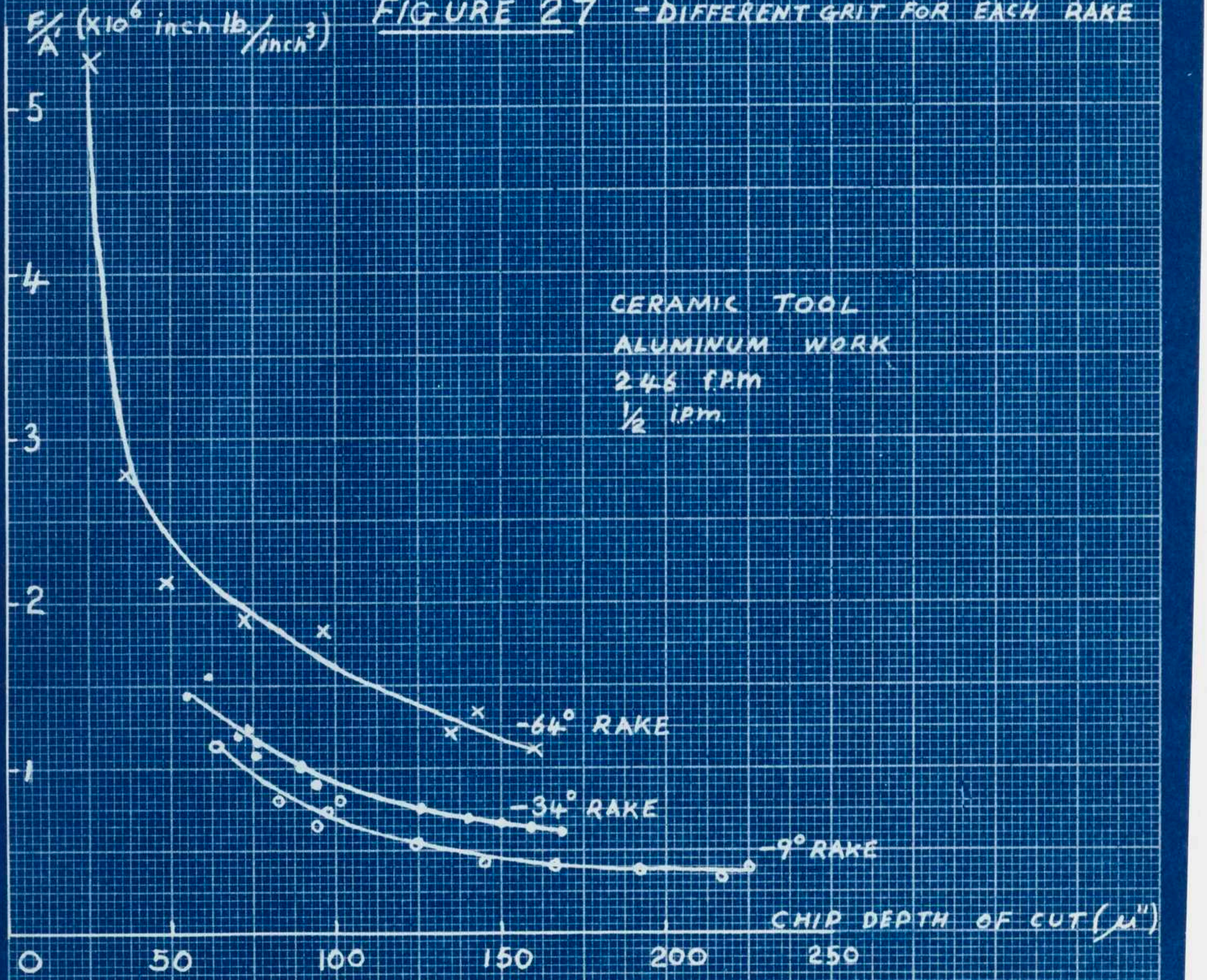


FIGURE 28 - THE SAME GRIT FOR EACH RAKE

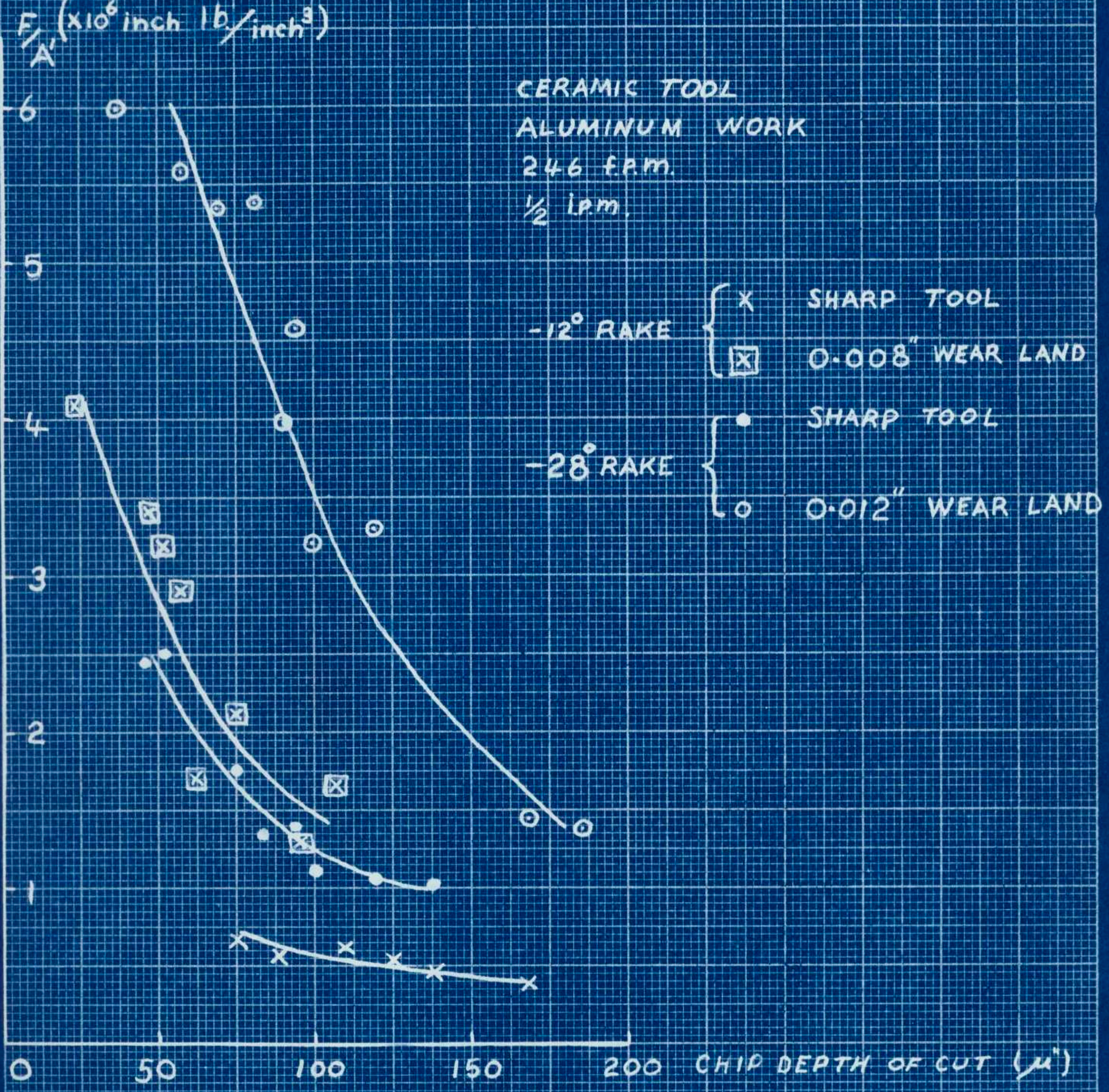

F/A' (x10^6 inch lb/inch^3)
6
5
4
3
2
1
0
50
100
150
200
CHIP DEPTH OF CUT (μ")
CERAMIC TOOL
ALUMINUM WORK
246 f.p.m.
½ i.p.m.
-12° RAKE
x SHARP TOOL
☒ 0·008" WEAR LAND
-28° RAKE
● SHARP TOOL
○ 0·012" WEAR LAND

FIGURE 29

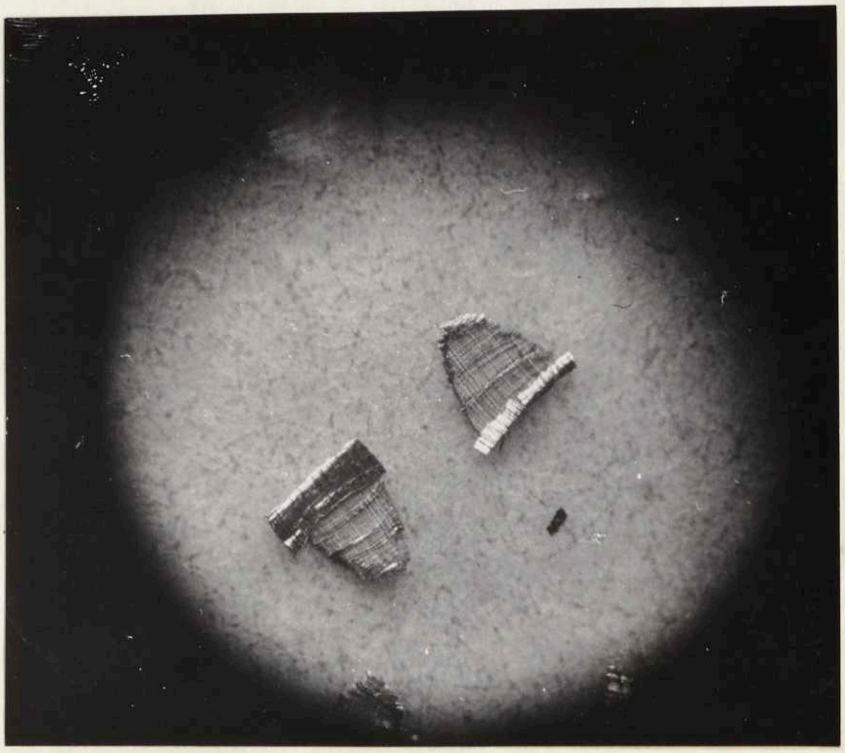


Figure 30 Chips Formed by Ceramic Tool. Magnification X24 (approx.)
Aluminum workpiece: 246 fpm; 1/2 ipm; Scratch depth 0.003 inches.

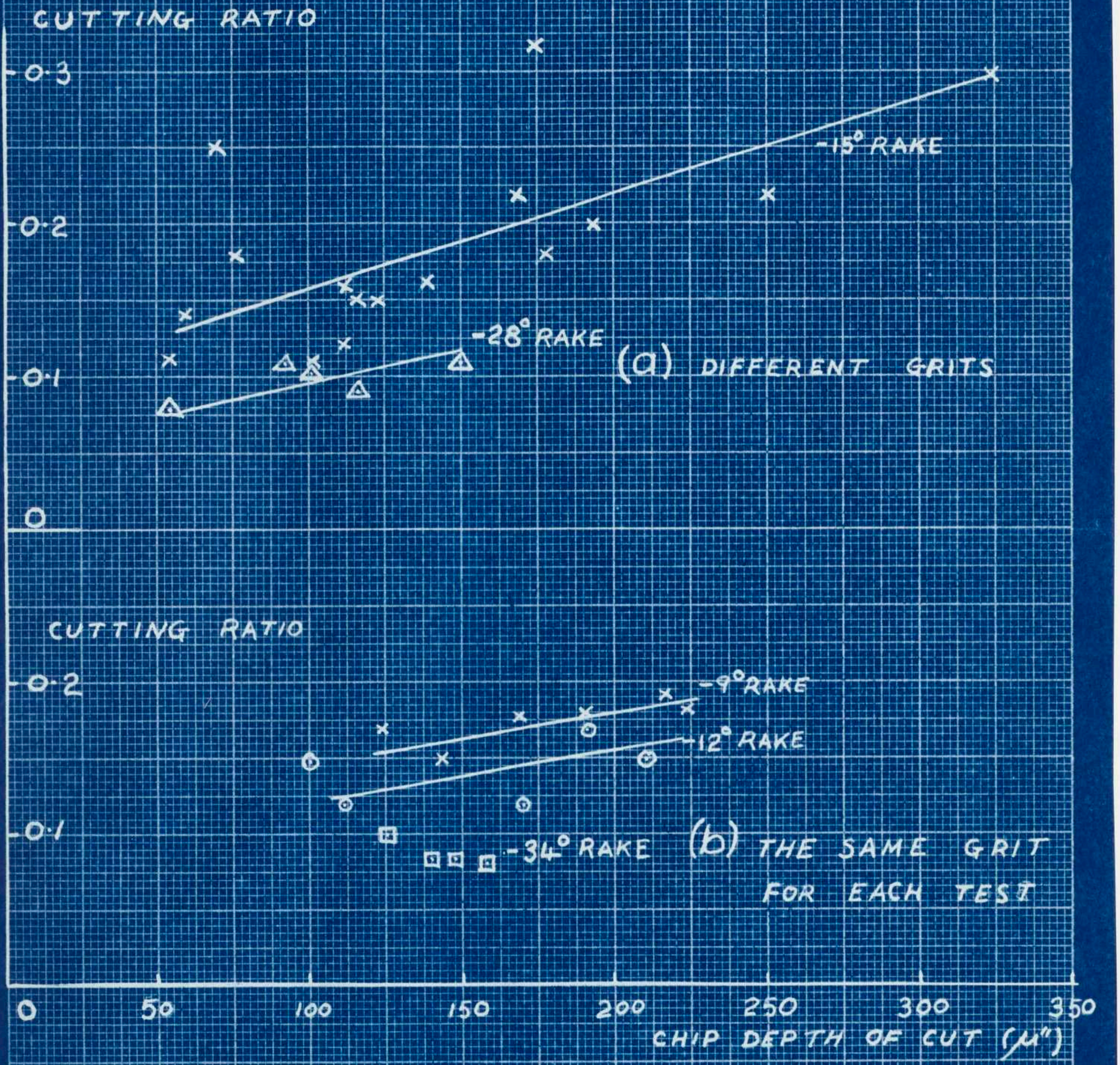


FIGURE 31

CERAMIC TOOL ; ALUMINIUM WORK ; 246 fpm ; ½ i.p.m.

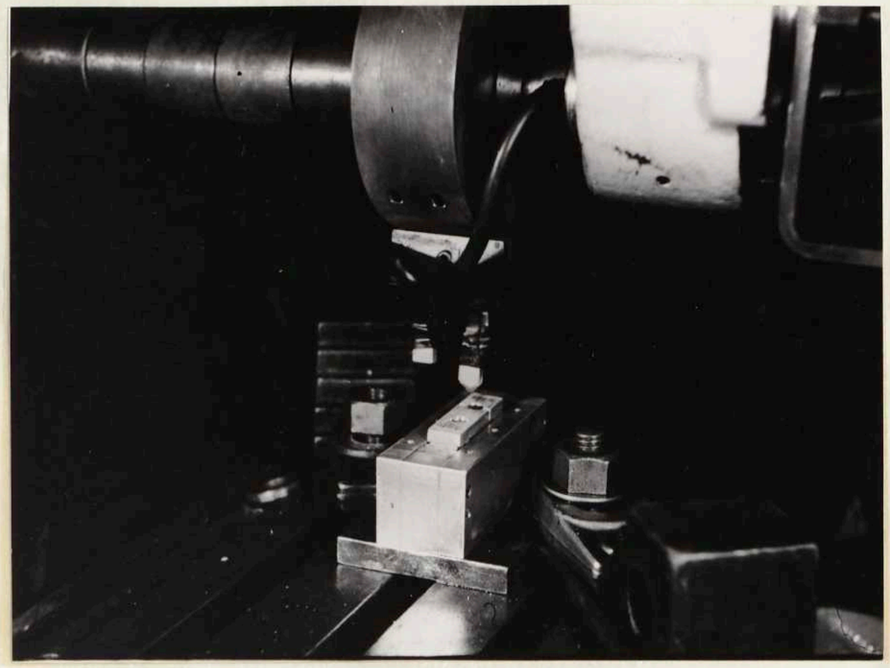


Figure 32 Two Component Dynamometer

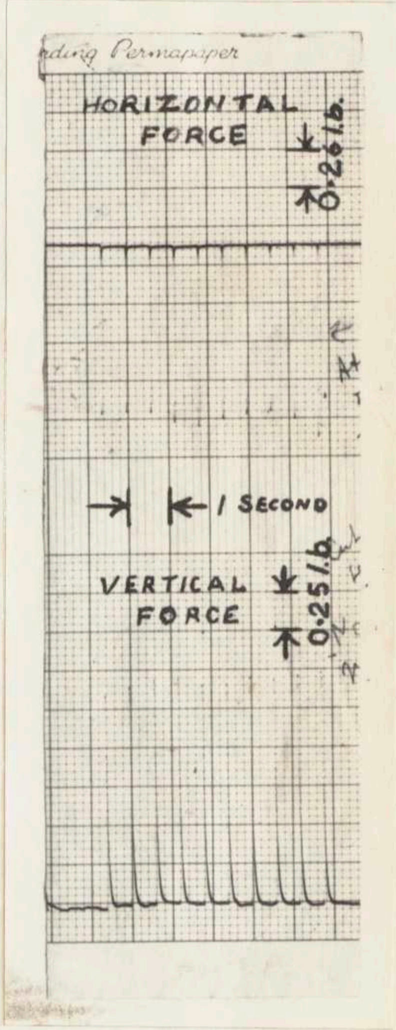


Figure 33 Two Component Force Record

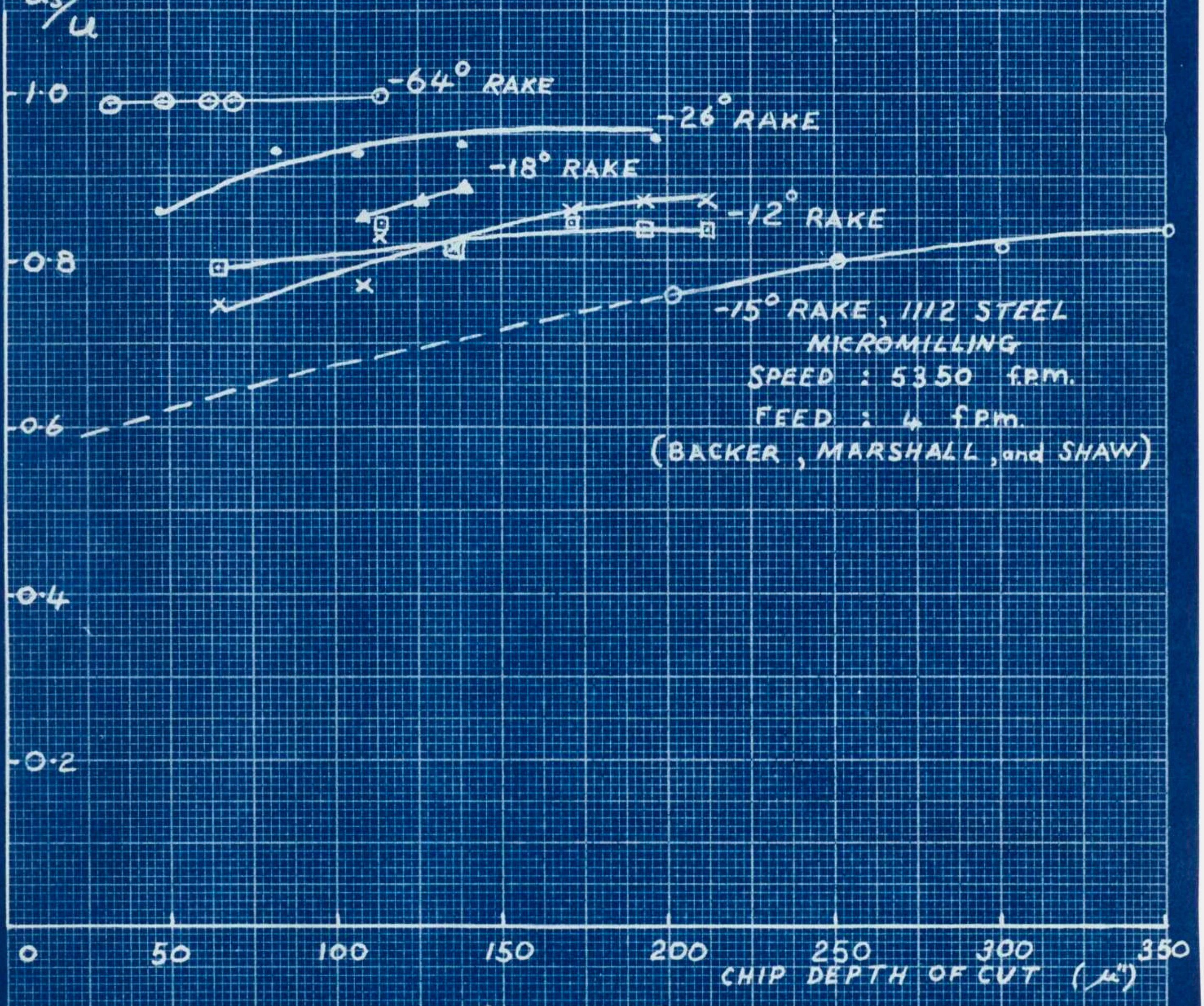


FIGURE 34

CERAMIC TOOL ; ALUMINUM WORK ; 246 f.p.m ; ½ ipm

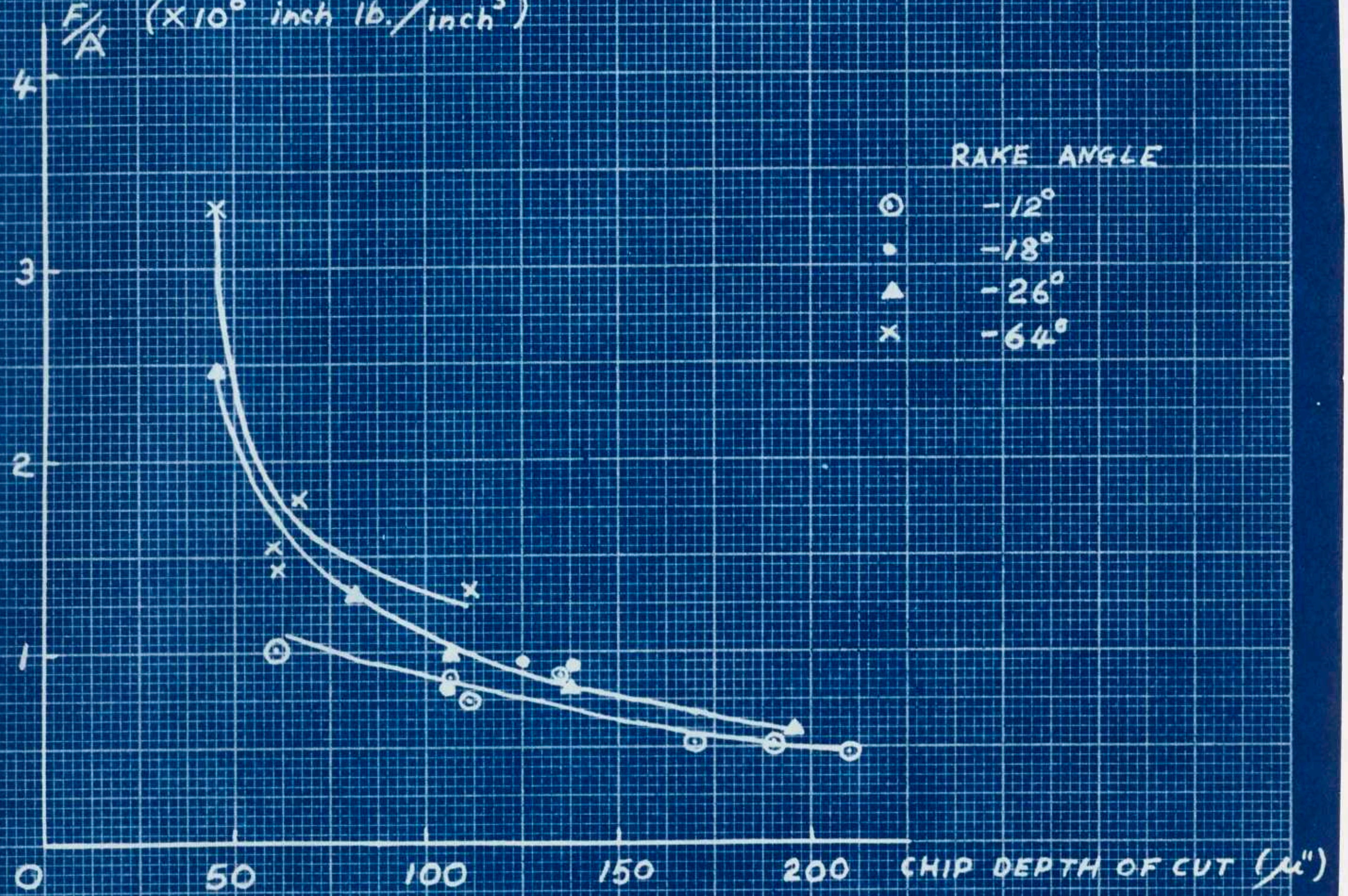


FIGURE 35

CERAMIC TOOL ; ALUMINUM WORK ; 246 fpm ; ½ ipm.

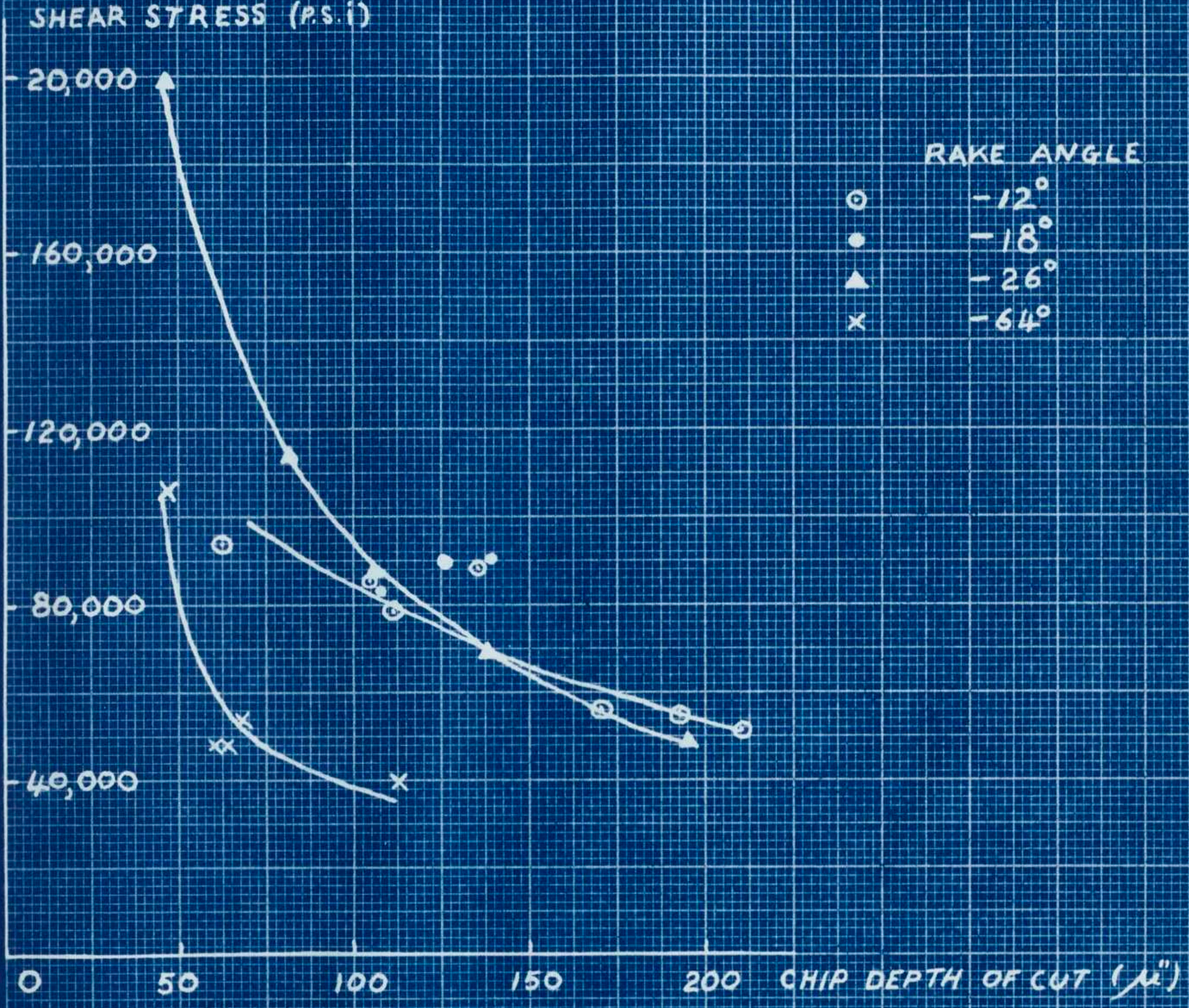


FIGURE 36

CERAMIC TOOL ; ALUMINUM WORK ; 246 f.p.m. ; ½ i.p.m.

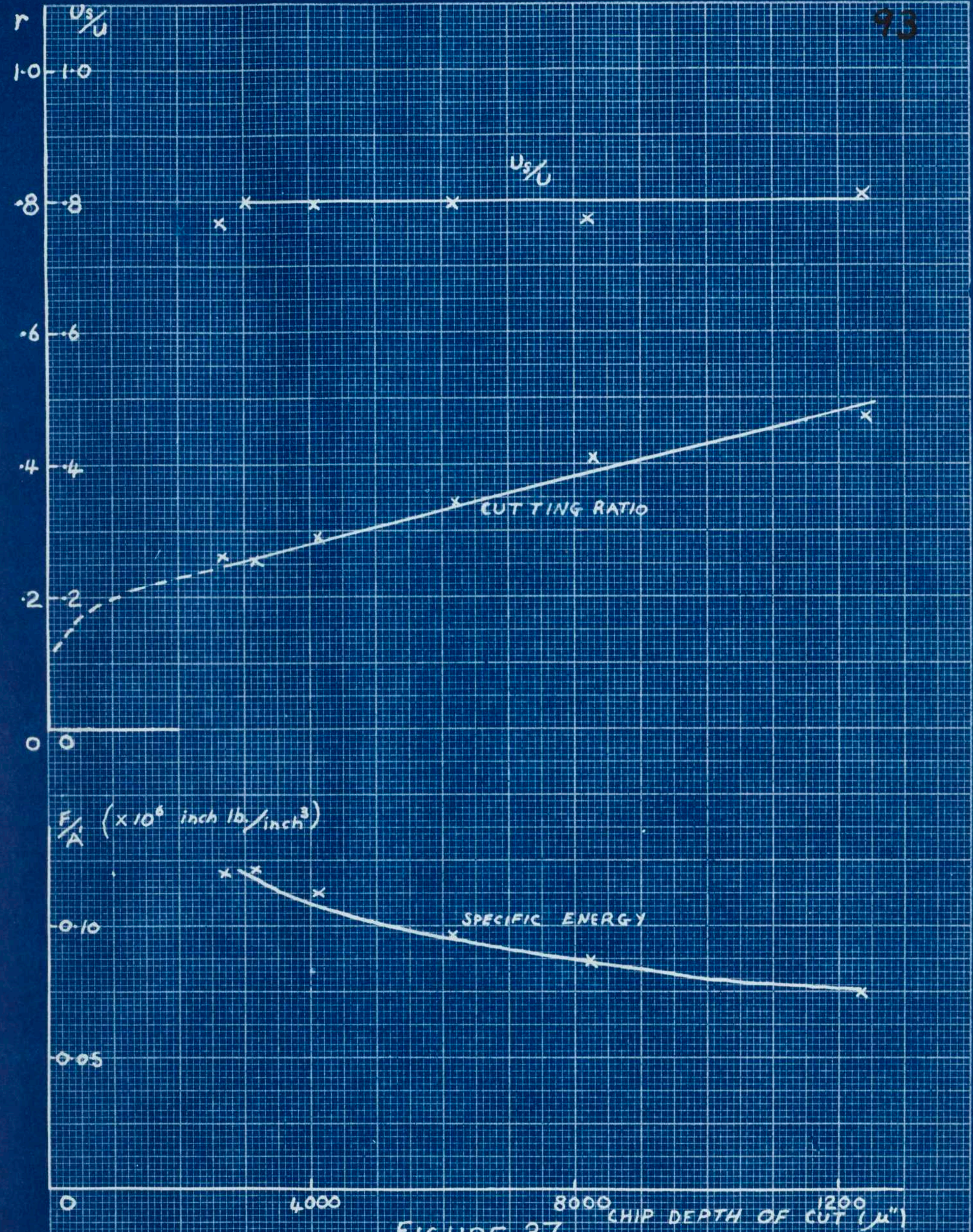


FIGURE 37

TURNING TESTS : CERAMIC TOOL ; ALUMINUM WORK ; 240 sfpm SPEED.

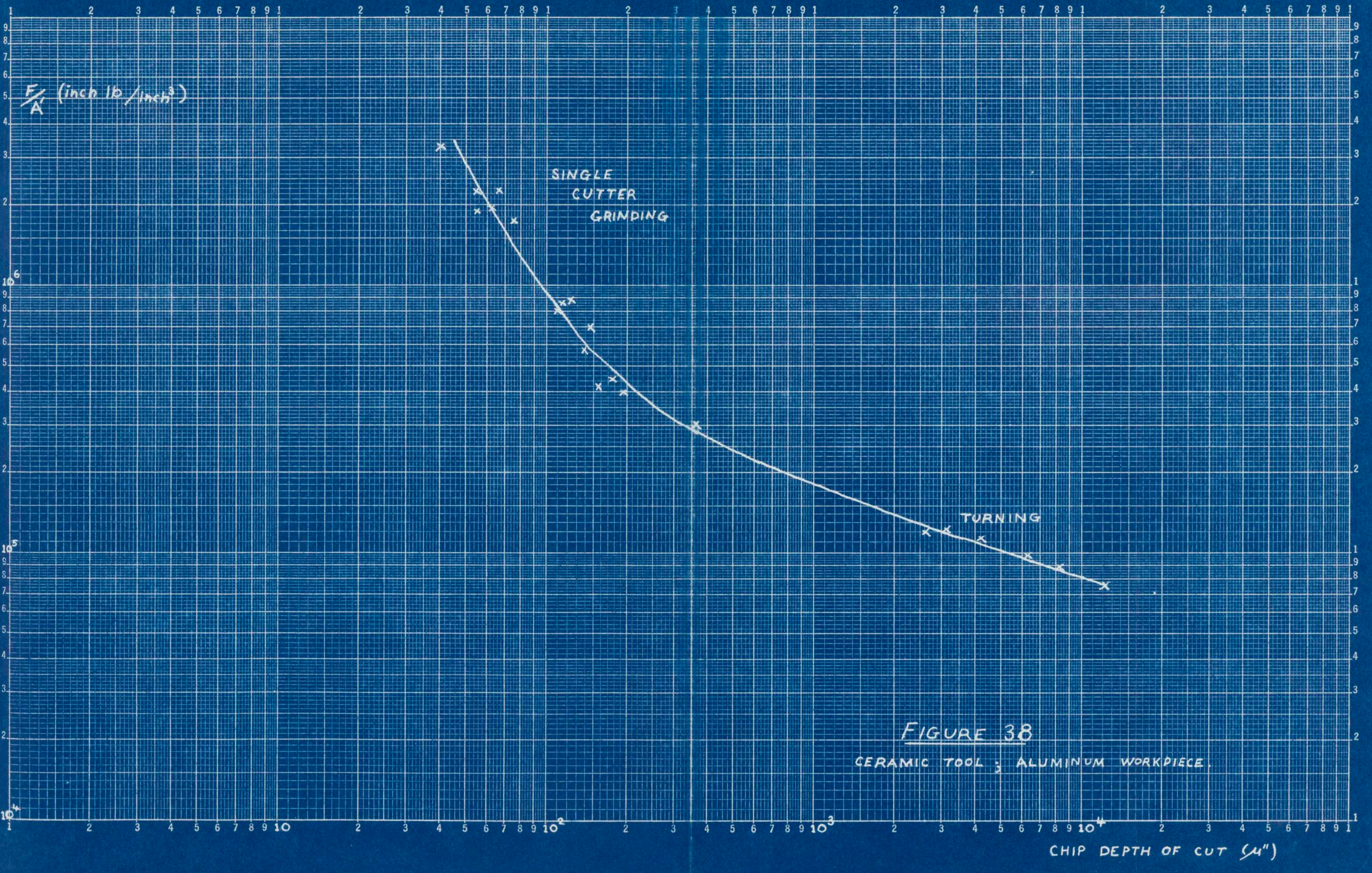


FIGURE 38

CERAMIC TOOL ; ALUMINUM WORKPIECE.

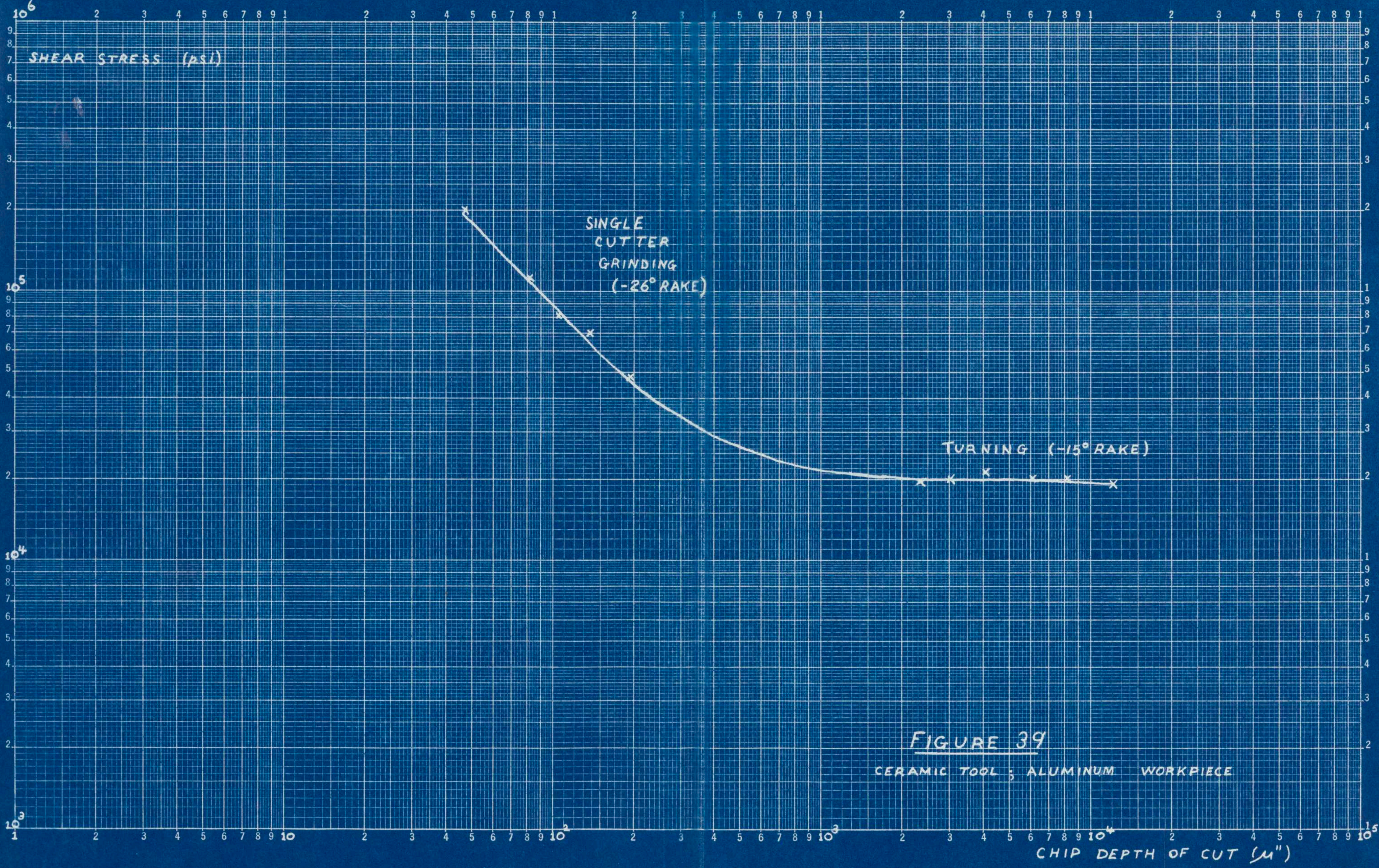


FIGURE 39

CERAMIC TOOL ; ALUMINUM WORKPIECE

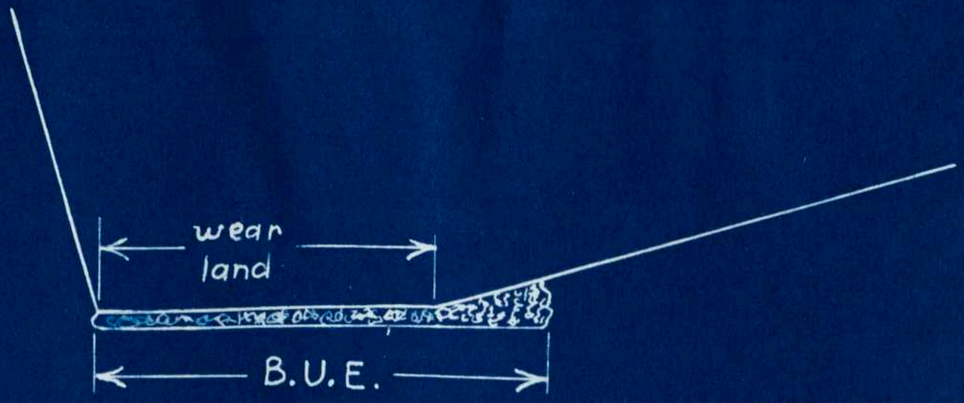


FIGURE 40

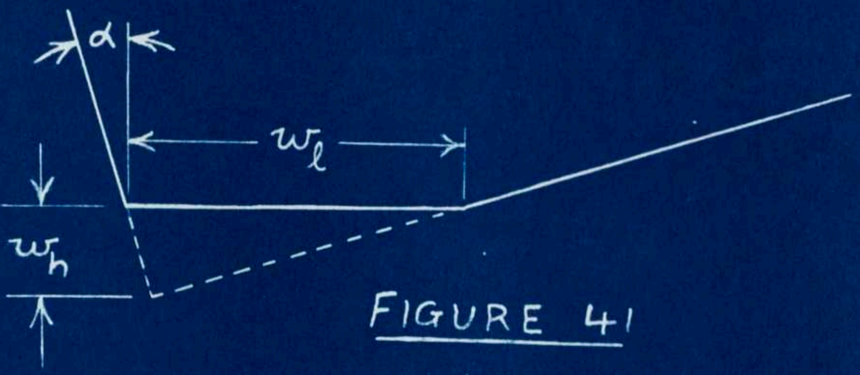


FIGURE 41

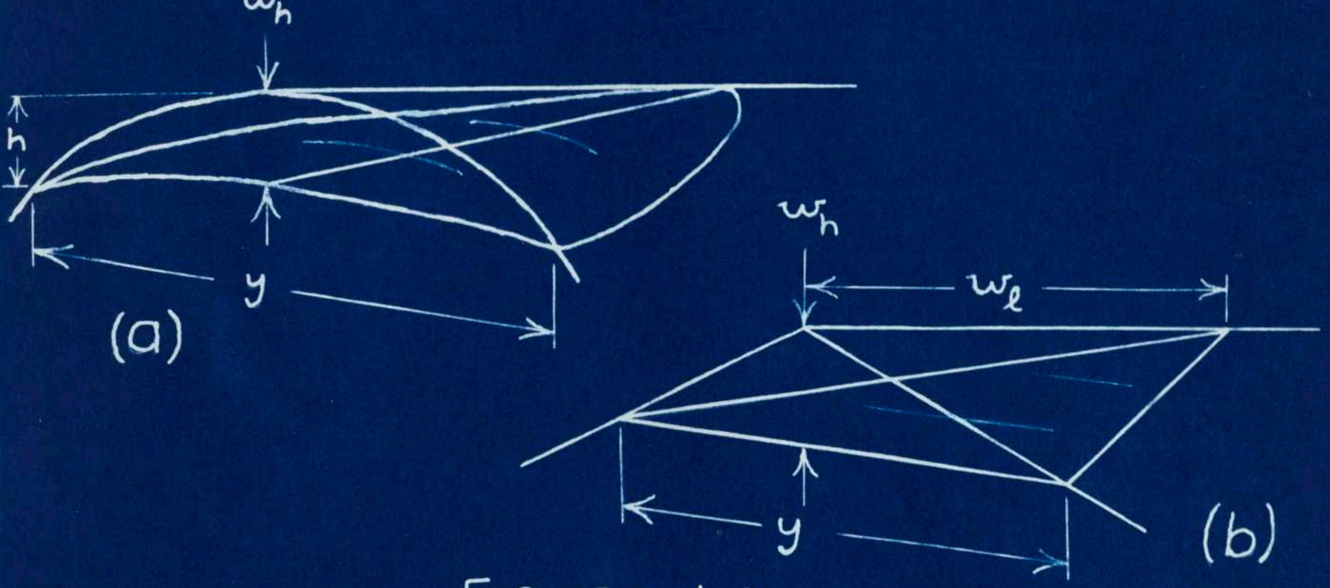


FIGURE 43

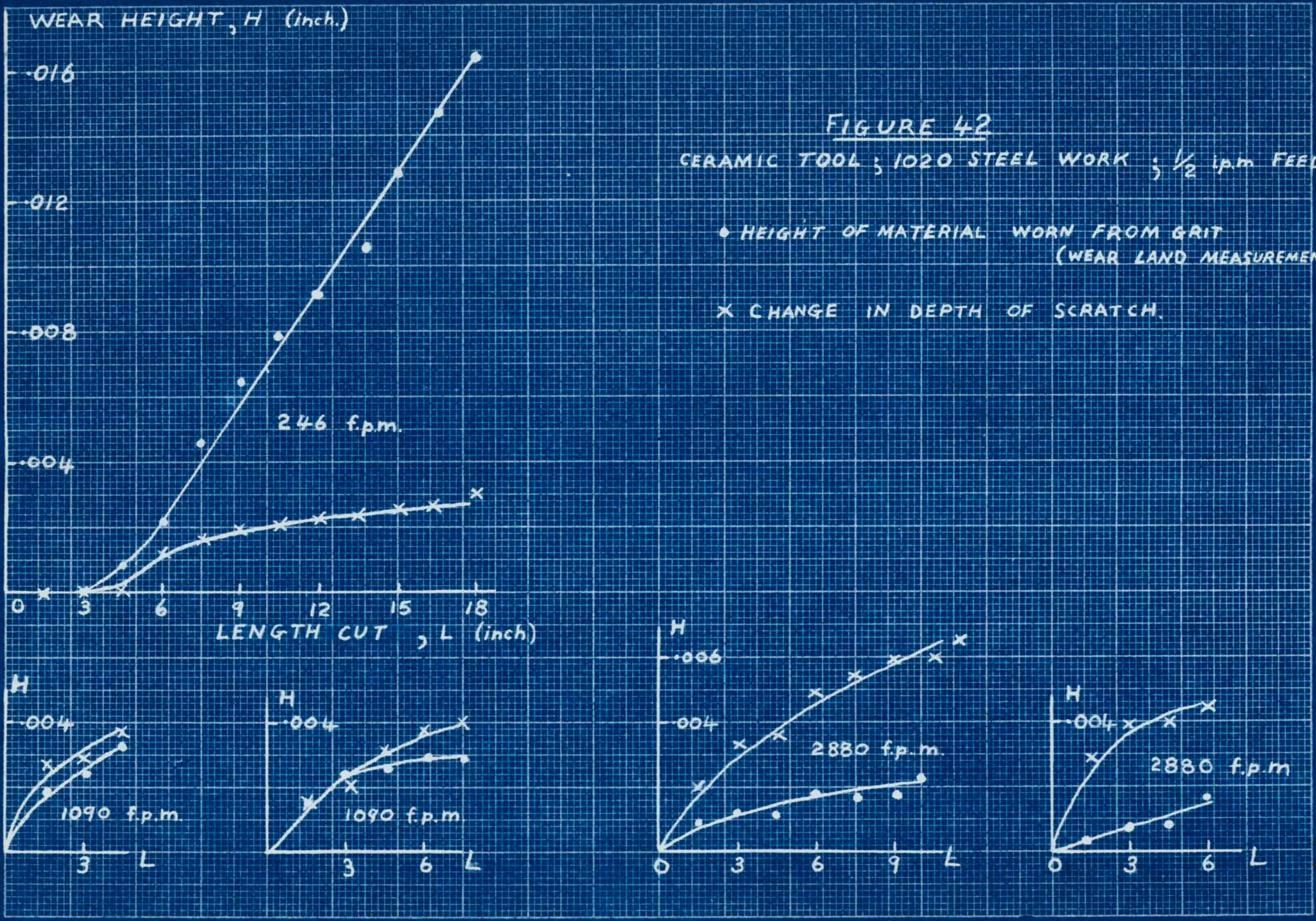


FIGURE 42

CERAMIC TOOL ; 1020 STEEL WORK ; 1/2 i.p.m FEED