CRITICAL EVALUATION AND CORRELATION OF TOOL-LIFE DATA

by

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ABSTRACT

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The machining characteristics of clamped carbide tools when machining the titanium alloy C 130AM and AISI 4340 steel are presented and compared. The radioactive β-technique was used in connection with a limited number of conventional tool-life data to establish tool-life curves for three different feeds. The procedure in correlating radioactive and conventional data is described. The variation of tool-life with a change in side cutting edge angle is discussed theoretically and compared with radioactive wear rates. When machining AISI 4340 the optimum tool-life was found to occur for a SCEA of 5° while for a SCEA of 15° for Ti C130AM.

The constancy of the wear rate in cutting is discussed on basis of pure diffusion being the cause of wear. The arguments lead to a constant wear rate provided temperature at the interface is constant throughout a tool-life test. By assuming temperature is responsible for the wear on the clearance face the variation of the friction force on the clearance during a test is discussed.

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CHAPTER I

RADIOACTIVITY

Introduction

The use of a radioactive tool is a convenient method of determining the change in relative rate of tool wear when a single cutting variable is adjusted. The method offers some saving in time, but an even larger saving in the amount of work material required. This latter item is particularly important in the case of titanium alloys where the cost of the workpiece material is unusually great. Radioactive carbide tools were used in this investigation to study the relative rate of tool wear when the feed was altered and when the side cutting edge angle was changed. However, before describing these tests and the results obtained, a discussion of the radioactive method of tool wear testing will be presented.

Use of the radioactive method for studying tool wear was first described in 1951 by Merchant and Krabacker[1] and in Stockholm in 1952 by Colding and Erwall.[2] Two different types of radiation were used in these investigations. In the first, the γ radiation from isotopes Co 60 and Ta 182 was used while in the second the β radiation from isotope W187 was used. The principal difference between the two techniques lies in the fact that isotopes Co 60 and Ta 182 have a long half life while isotope W187 has a short half life. The significance of this statement will be discussed later after we have defined half life and other pertinent terms. Recent Russian papers[3,4] describe results using the γ and β radiation methods respectively, while Hake[5] has applied the γ radiation technique in some interesting tool wear studies conducted in the Institute for Machine Tool Research at Technischen Hochschule Aachen.

Atomic Structure

The atom is the smallest particle into which a material may be subdivided without losing its chemical identity, and consists of a relatively small nucleus where essentially all of its mass is concentrated and a number of orbital electrons. The electron is a particle that is practically without mass, but which carries a negative charge of one unit. The nucleus consists of particles that have appreciable mass and which may or may not have a positive charge of plus one unit. If such a nuclear particle has a charge of plus one it is called a proton and if it has no charge it is called a neutron. The nucleus then consists of a number of protons (Z) and a number of neutrons (M-Z). Since the planetary electrons are essentially massless, the total mass of the atom will be $Z + (M-Z) = M$ units.

All atoms are electrically neutral, and hence the number of planetary electrons (each of which has a unit negative charge) must just equal the number of protons in the nucleus Z (each of which has a unit positive charge). The electrons move in several orbits or shells about the nucleus planet-wise, and the number of electrons in the outer shell are primarily responsible for the chemical properties of the atom. The size of the atom may be taken as the diameter of the outer shell, but it should be kept in mind that this diameter mostly consists of empty space. The nucleus is small and the size of each planetary electron is small compared with the diameter of its orbital path.

An ordinary atom has associated with it an atomic weight (which is the weight of the atom in arbitrary units such that oxygen has a weight of 16 units) as well as an atomic number (Z). The atomic number (Z) is always the same for a given atom, and all atoms in a specimen have the same number of planetary electrons (Z), the same number of electrons in the outermost shell, and hence the same chemical properties. The atomic number is always an integer, and all particles having the same number of protons and electrons are said to be atoms of the same species which is assigned a name and symbol such as cobalt (Co) or iron (Fe).

If all atoms in a specimen had the same mass then their atomic weights would also be integers. However, a material with particular chemical properties may have a different number of neutrons in its nucleus and hence different values of mass. Particles having the same atomic number (Z) but different numbers of neutrons (M-Z) are assigned the same chemical name and symbol but are said to be isotopes of each other. Thus, if A represents the chemical symbol of any atom we may represent several isotopes of this material as follows:

$$A_Z^{M_1} \quad , \quad A_Z^{M_2} \quad , \quad A_Z^{M_3}$$

where M_1, M_2 and M_3 represent three integral multiples of the basic unit mass (1/16 that of the oxygen atom) and Z is the fixed integral number of protons and neutrons associated with the chemical species A.

In nature, we normally find a mixture of isotopes of a given atom rather than a single isotope. Thus, we might find x, y and z percentages of the above three isotopes to be the naturally occurring configuration of element A. The atomic weight of this material would then be the weighted mean atomic weights of its isotopes or

$$\text{Atomic Weight} = \frac{xM_1 + yM_2 + zM_3}{x + y + z} \tag{1}$$

This of course need not be an integral number of the basic mass unit and in fact normally is not.

Neutron Induced Isotopes

If a specimen is placed in a high speed stream of neutrons, such as that encountered in an atomic pile, its atoms will take on neutrons. This reaction may be represented as follows:

$$A_Z^M + n \longrightarrow A_Z^{M+1} \qquad (2)$$

Atoms A are then said to be in an excited state and will undergo disintegration to a more stable configuration with the emission of a ray (consisting of particles without mass) or stream of particles (items having mass) in several different ways as follows:

1. by reemission of a neutron stream

2. by emission of γ rays (a γ ray is a stream of high speed electrons without charge. The items constituting a γ ray are, therefore, essentially without mass)

3. by emission of a proton stream

4. by emission of a stream of α particles (an α particle is a nucleus of helium)

5. by emission of β rays (a β ray is a stream of high speed negatively or positively charged electrons. A positively charged electron is called a positron).

A β ray may be generated as follows depending on whether it consists of negatively or positively charged massless particles:

$$A_Z^M \longrightarrow A_{Z+1}^M + \beta^- \qquad (3)$$

$$A_Z^M \longrightarrow A_{Z-1}^M + \beta^+ \qquad (4)$$

A specific example is given in the following reactions:

$$Fe_{26}^{59} \longrightarrow Co_{27}^{59} + \beta^{-} \qquad (5)$$

$$Fe_{26}^{52} \longrightarrow Mn_{25}^{52} + \beta^{+} \qquad (6)$$

The simultaneous emittance of the two types of β rays is often associated with the formation of γ rays as follows:

$$\beta^{+} + \beta^{-} \longrightarrow 2\gamma \qquad (7)$$

The details of just how the nucleus is changed by bombardment and precisely what happens when unstable, artificially generated isotopes disintegrate are not yet completely understood by Physicists, and if they were, such considerations would be beyond the scope of the present discussion. For our purposes here it is sufficient to understand that atoms can be artificially activated by bombardment in a high speed stream of neutrons, and that these artificially generated isotopes then disintegrate with the emission of a stream of particles each having a characteristic mass and change. The name assigned to the particular radiation depends on the charge and mass of the individual particles. The rate of disintegration is a characteristic of each particular isotope and will be considered next.

Radioactive Decay

For a specimen containing n activated atoms at a certain time, a probability $(\frac{dn}{n})$ exists that n atoms will have changed. This probability is found to be proportional to the time elapsed, and therefore, if we let (-dn) be the number of activated atoms disintegrating due to the radioactive process in a time (dt), we have for the probability:

$$-\frac{dn}{n} = \lambda\, dt \qquad (8)$$

where λ is the proportionality constant.

Upon integration equation 8 may be written:

$$n = n_o e^{-\lambda t} \quad (9)$$

where n_o is the integration constant (the number of atoms present at zero time).

The number of activated atoms present is not easily measured but their presence may be detected by measuring the radiation emitted. The intensity of radiation is called the activity (I). Since this activity is directly proportional to the number of atoms present we may write from equation 9

$$I = I_o e^{-\lambda t} \quad (10)$$

If $T_{1/2}$ is used to denote the time required for I to change from I_o to $1/2\ I_o$ (the half life of the isotope) then we have

$$I = I_o e^{-.693 \frac{t}{T_{1/2}}} \quad (11)$$

for the intensity of radiation at any time t. The half life $T_{1/2}$ is a very important quantity since it determines the time available for radioactive experiments.

Neutron Bombardment

When a tool tip is subjected to neutron bombardment, two rates of change are involved. The number of activated atoms increases uniformly with time and the atoms already activated decay. At the end of an infinite period of time the material will be saturated with regard to activation and the activity may be represented by I_∞. For any time of bombardment less than infinity, the activity pertaining will be (making use of equation 11 for the decay component)

$$I = I_\infty (1 - e^{-.693 \frac{t}{T_{1/2}}}) \quad (12)^*$$

* This expression is most easily obtained by counting time backward from infinity rather than forward from the true zero value of time.

It is customary to express activity in terms of the curie, c, (1 curie equals a source of strength such that 3.7×10^{10} atoms disintegrate per second) or the millicurie (Mc), which is 1/1,000 part of a curie.

Specific activity (S) is the activity per gram of material. When a gram of substance has been saturated with regard to activity its specific activity S_∞ may be expressed as follows:

$$S_\infty = \frac{0.6F\sigma}{3.7(10^{10})M} \tag{13}$$

where F is the neutron beam intensity in neutrons/cm.^{2}sec.

σ is the cross sectional area of the nucleus of a single atom in barns (where one barn is 10^{-24}cm.^{2}).

M is the atomic weight of the element.

The specific activity (S) after irradiation for a finite time (t) may be expressed as follows from equations 12 and 13:

$$S = S_\infty \left(1 - e^{-\frac{.693t}{T_{1/2}}}\right) \tag{14}$$

$$= \frac{0.6F}{3.7(10^{10})M}\left(1 - e^{\frac{.693t}{T_{1/2}}}\right) \text{ c/gm.}$$

For example, we might consider a carbide cutting tool with a nominal chemical composition of 80% WC, 10% Co, 8% TiC and 2% TaC. The resulting isotopes produced after irradiation are: W187, W185, Co 60, Ta 182. Table 1 shows the half life, and type and intensity of each type of radiation produced. The intensity is given in millions of electron volts (MeV).

Table 1

Isotope	Half-Life	β-energy MeV	-energy MeV
Co 60	5.3 years	0.306	1.17,1.33
Ta 182	115 days	0.5	1.13,1.22
W185	73 days	0.68,0.48	—
W187	24.1 hours	1.33,0.63	0.78,0.686,0.552 0.48,0.134,0.072

Bombardment in a neutron flux of 10^{12} n/cm.^{2} sec. for 1 hour and 1 week duration respectively yielded the specific activities shown in Table 2. The total activities in MC per gram of tool material are also presented. Equation 11 was used in these calculations and the values of the cross section of this nucleus (δ) were taken from the literature.

Table 2

Isotope	1 hour S mC/g	1 hour Tot.A. mC	1 week S mC/g	1 week Tot.A. mC
Co 60	0.4	0.04	14.5	1.45
Ta 182	1.5	0.03	52	1.04
W185	0.075	0.06	2.7	2.2
W187	25.0	20.0	900	720
Total		20.13		724.51

Experience has shown that a specific activity of from 5 to 25 mC/g is available in work with radioactive cutting tools.

When a carbide specimen is irradiated for 1 week the intensity of the W187 isotope will be initially too intense for safe handling. If, however, the irradiated specimen is set aside for from one week to ten days the intensity of irradiation from the W187 isotope will have decreased to a negligible value and the Co 60, Ta 182 and W185 isotopes will be available for making β measurements and the Co 60 and Ta 182 isotopes for γ measurements. If γ measurements are made for a few days, the intensity of radiation may be considered constant during this period due to the long half life of these isotopes.

When a specimen is irradiated for but one hour, all but the W187 isotope will have a negligible intensity of radiation. However, due to the short half-life of this isotope it is necessary to make all measurements quickly and to correct for the continuous change in intensity of radiation. The intensity will fall to essentially zero in a period of about 10 days in this case, which is a distinct advantage from the safety point of view. By waiting this length of time all chips may be handled and disposed of in the ordinary manner. When Co 60 is used as the tracer on the other hand, it is not safe to handle chips in the usual manner for a period of years.

Radiation Energy

Most nuclear particles can possess a rather wide range of energy (i.e., from about 0.05 to 5 MeV). β rays which are rays of particles having the negligible mass of the electron are easily stopped. The range of penetration of such rays into a material (t) depends on their energy and upon the density of the material (ρ). An approximate empirical expression for β ray penetration is the following:

$$t \rho = 0.54 E_M - 0.16 \tag{15}$$

where t is in cm.

ρ is in gm/cm^3.

E_M is the maximum energy of any particle in the β ray in MeV.

For example, to stop a 1 MeV β ray would require 1.5 mm. (.060 inch) of aluminum or 0.25 mm. (.010 inch) of gold.

Gamma ray absorption follows the law

$$I = I_o e^{-\mu t} \tag{16}$$

where μ = the absorption coefficient of the material absorbing the ray, which in turn is proportional to density (ρ)

t = the thickness of the absorbing material.

The uncharged particles of a γ ray are not counted directly in a Geiger-Muller tube but they ionize the air in the tube and the secondary electrons thus emitted are detected. Since the degree of ionization in a detecting tube increases inversely with the speed of the γ particles, it is advantageous to use relatively thicker windows in such tubes than would be used for β ray detection.

Safety Precuations

The following information issued by the Radiological Safety Office at M.I.T. will serve as a guide in work with radioactive cutting tools.

As a preventive for accidents it is recommended that all persons working with radioactive materials abide by the following safety rules:

1. Survey hands carefully for contamination after radiochemical operations and especially before eating, smoking, or leaving work.

2. Refrain from smoking during experimental work.

3. Do not eat at laboratory areas where radioactive materials are used, and do not store food in laboratory refrigerators.

4. Wash rubber gloves before removing them.

5. Do not pipette radioactive solutions by mouth.

6. Before performing glass blowing in laboratories using radioactive materials be certain that the mouth piece is not contaminated and that there is no possibility of inhaling significant active material from the glassware system.

7. Use a fume hood when evaporating radioactive solutions or when transferring powdered radioactive material.

IF SPLASHED WITH A RADIOACTIVE SOLUTION:

1. Begin decontamination procedure as soon as possible. Attempt to reduce skin contamination to less than 1 mrem/hr. Call Radiological Safety Lab., Ext. 2360, if help or advice is wanted.

2. If decontamination is unsuccessful with soap and water or other hamless laboratory solvents, use a Decontamination Kit.

3. If a decontamination kit or radiation survey instruments are not immediately available, wash the affected parts with soap or detergent and water and report to the infirmary.

Persons cut by glassware, injured by hypodermic needles, splinters, etc., containing radioactive materials:

1. Immediately wash the wound under a strong stream of water.

2. Report to the infirmary as soon as possible, specifically informing the medical personnel the character of the radioactive material involved.

Acute exposures producing biological effects

Exposure	Part Exposed	Biological Effects
50 r*	whole body	Slight, transient reduction in white cell blood count.
350 r	whole body	Fatal exposure for approximately 50%
600 r	whole body	Fatal exposure for approximately 100%
600 r	gonads	Sterilization(male): Temporary for 60% of cases.
600 r	eyes	Cataract production: 100-200 KV x-rays.
2000 r	skin	Skin erythema dose for radium gamma rays.

Maximum permissible exposures

A. External radiation:

1. Whole body exposure—

a. X-ray and gamma radiation (up to 3 Mev):

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r* = roentgen (1r is that amount of radiation which will produce one electrostatic unit of charge as ions in 1 cc of air at 0°C and 760 mm pressure).

0.3 r/week to blood forming organs which are assumed to be at a depth of 5 cm below the surface. This dose corresponds to 0.5 r/week measured at the surface of the body, or to 0.3 r/week measured in free air.

b. Beta rays:

1.5 roentgens equivalent per week measured at the basil layer of the epidermis, which is take to lie at a depth of 7 mg/cm^2 below the surface of the skin.

c. Neutrons:

one-tenth of the energy absorption permitted for gamma rays, or in terms of incident neutron flux:

2.0-20	Mev	30 n/cm^2 per second	For a 40 hour week
0.5-2	Mev	50 n/cm^2 per second	
Thermal		1200 n/cm^2 per second	

2. Partial body exposure--

X-rays, gamma rays, beta rays: If limited to hand and forearms, 1.5 r (or its energy equivalent) per week at the basil layer of the epidermis.

3. For operating purposes, it is permissible that in any one week twice the weekly figures given above may be taken provided that the average over three months does not exceed the weekly limits.

B. Internal Radiation:

Maximum permissible amounts of radioisotopes in total body:

Radioisotope	Where concentrated	Permissible amount in total body
Ra^{226}	bone	0.1 microcuries
$Sr^{90} + Y^{90}$	bone	1.0 microcuries
Co^{60}	liver	3.0 microcuries
P^{32}	bone	10.0 microcuries
Ca^{45}	bone	65.0 microcuries
$Cs^{137} + Ba^{137}$	muscle	90.0 microcuries

General Considerations

Conditions for the successful use of radioactive methods in studying the relative mertis of tool materials, work materials, cutting fluids, etc., include the following:

1. The isotope used should be formed in sufficient quantity during irradiation.

2. The isotope used must emit a radiation that is conveniently detected.

3. The isotope used must have a half life that is long enough to allow for transportation from atomic pile to the testing laboratory and so that the activity of the tracer does not change too rapidly during the tests.

4. It is convenient that the half life be as short as possible in the interest of ease of disposal of waste products (chips and used tools), and a low cost of irradiation.

Either the method involving γ radiation detection or that for β ray detection will satisfy these requirements. The γ method involves a longer time of irradiation and hence greater cost, greater delay in getting tools ready for use, and greater inconvenience in handling due to the larger half life involved. However, the fact that the activity of the isotope used remains constant throughout a test provides a distinct advantage in the use of the γ method.

Either method may be used to determine the relative rates of face and flank wear. When a carbide tool wears it has been found experimentally that essentially all of the tool particles become attached to either the face of the chip that rubs on the rake face of the tool, or to the newly developed surface. Thus, in Fig. A the particles coming from the rake face of the tool become attached to surface A of the chip while those particles that leave the clearance face of the tool are welded to surface B. Upon making a second cut, it is evident that the chips produced will have tool wear particles attached to both the shiny and dull surfaces. Those particles attached to the shiny surface are associated with tool face wear while those found on the dull surface are due to flank wear. By flattening such chips and arranging them into a standard pattern, the β radiation from either surface of the chips may be measured by placing them either face up or face down. The β rays are so easily stopped that only those coming from the upper surface have any influence on the Geiger-Muller tube.

Gamma rays on the other hand have much greater penetrating power and the γ method cannot be used in this way. Instead, the total radiation from both surfaces may be conveniently measured by placing a number of chips into an annular arrangement (known as a Marinelli beaker) as shown in Fig. B and placing the detecting tube in the central space. The penetration of γ rays is such that particles from both chip surfaces and from chips far and close to the detecting tube are effective. In order to determine the relative amounts of flank and face wear by the γ method, Hake[5] has used two tools spaced 1/2 the feed distance axially along the bar as shown in Fig. C. The tool at A is radioactive while the one at B is not. This method provides chips that have radioactive wear particles only on the shiny faces. The flank wear is then obtained by difference.

The β method was adopted in this investigation due to the greater ease of handling. The irradiation period was from 22 to 33 minutes and W187 was the only radioactive isotope present in any measurable amount.

Use of radioactive tool wear methods depends upon an assumed linear relationship between tool wear and the amount of material machined. While this is frequently the case, a nonlinear region is sometimes experienced at the beginning and end of a conventional tool life test, and also jogs in the curve may occur in some cases.[7] Due to this uncertainty it is advisable that a minimum number of conventional tool life tests be made and compared with the corresponding radioactive results. The radioactive method may then be used to interperpolate between the few conventional test results that are produced.

Representative radioactive tool wear results taken over a long period of time by the β radiation method are shown in Fig. D. Here the rate of wear is seen to be linear after the first 15 minutes of cutting.[6] Jogs in the curve were found in this case only during the break in period of 15 minutes. This test was made starting with a sharp tool. It has been found that the 15 minute break-in period, before the wear curve becomes linear, may be shortened by grinding a flat on the clearance surface of the tool. Jogs in the curve in a direction parallel to the cutting velocity due to chipping were similarly prevented from occurring by storing the cutting edge so as to produce a very small surface having a negative rake angle of 45 degrees.[6,7] The conventional tool wear tests in which the size of the wear land is plotted against the cutting time, provide the necessary information to determine the size of the initial flat that should be provided on the tool to shorten the break-in period.

CHAPTER II

RADIOACTIVE TOOL WEAR TECHNIQUE

General Procedure

The tools used in this investigation (K2S clamped carbide tips measuring 3/8 x 3/8 by 1 1/2") had the following tool angles: back rake angle, -7°; side rake angle, -7°; end relief angle, 7°; side relief angle, 7°; end-cutting edge angle, 15°; side-cutting edge angle, 15°; nose radius, 1/32 inch; cutting fluid was tap water. Before being irradiated, a flat 0.012 to 0.014 inch was ground on the clearance face of each of the eight cutting edges. These flats were inclined at 8.5 degrees to the clearance faces since the resulting surface will then be approximately parallel to the velocity vector when clamped in the tool holder used.*

All specimens to be irradiated were sent to Brookhaven National Laboratory, Upton, Long Island, New York. To some specimens a small particle (30 to 40 milligrams) of carbide was afixed by means of plastic tape. By irradiating tool and particle simultaneously both obtained the same specific activity. The chip was then used for estimating the absolute wear rates, by a procedure to be described later.

Each tool was subjected to a neutron flux of 2.6×10^{12} n/cm.^{2}sec. for either 22 minutes or $1.65 \cdot 10^{12}$ n/cm.^{2}sec. for 33 minutes. The tools arrived at M.I.T. one day after irradiation was completed. The specific activity of these specimens was about 24 mC/gram immediately after irradiation, but upon arrival at M.I.T. was about 10 mC/grams.

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* The angle at which this flat should be ground is slightly larger than the relief angle measured normal to the cutting edge. This is $\tan^{-1}\left(\frac{\tan R_S}{\cos C_S}\right)$ where R_S is the side relief angle (7°) and C_S is the side cutting edge angle (15°). The value of $\tan^{-1}\left(\frac{\tan R_S}{\cos C_S}\right)$ for this case is 8° 8'.

The tests were carried out in a special room where other people were not allowed to go. The first tests were for AISI steel cut at different speeds at a feed of 0.0104 ipr. Before chips were collected, the tools were run-in for from 1 to 5 minutes (longer times for conditions of longer tool life). Chips were then collected for 1/2 minute of cutting. After each cut the tool was unclamped and turned through 90° to provide a new cutting edge for the next test. Fig. E shows a close-up view of the tool and holder, while Fig. F is a view of the lathe used showing the lead protective shield. A flexible exhaust tube mounted above the cutting tool is used in conjunction with a fan of 200 to 300 ft.^{3}/min. capacity to discharge air from the vicinity of the tool onto the roof of the building. This is a precaution against the penetration of any air-borne radioactive dust into the room. The air in the room was monitored as a safety precaution and the lathe operator was supplied with a film badge and wore rubber gloves and goggles at all times.

When tests at the 0.0104 ipr feed rate were compared with conventional data and found to be in good agreement, tests on other feeds were undertaken. It was found that two or three successive tests could be made on the same cutting edge without any influence on the results obtained. It is not possible, however, to get consistent results at different speeds if the tool has developed an appreciable crater, for the shape of the crater that develops is a function of speed.

The chips collected for each tests were broken into small pieces and representative samples placed in position with tweezers to cover a paper disc. A photograph of a chip sample is shown in Fig. G and the sample in place under the end window Geiger Mueller tube is shown in Fig. H. By counting for two or three minutes, the average number of counts per minute (cpm) may be established. The background count (No.) determined with no specimen present, other than air, was then determined and subtracted. The background count normally amounted to from 20 to 22 cpm.

The data of Table 3 illustrate the procedure followed, where 5 independent determinations on 5 different samples of a given test are recorded.

Table 3

Time	Counts	Counting Time, Min.	I cpm	$I-N_o$ cpm	I_A cpm
13.00	1008	4	252	232	464
13.05		4	305	285	570
13.10	1120	4	280	260	525
13.15	1152	4	288	268	544
13.20	1180	4	295	275	562
				$\bar{I}_A$ =	533

The background count (no.) was in this case 20 cpm over the entire period of time. The values I_A are for the activity of the specimen referred to a standard time and are obtained by projecting the measured values of I backward in time to a standard time, by use of a curve of activity versus time. The time of measuring (4 minutes in this case) is determined such that the variation due to statistical fluctuation of β radiation is less than $\pm$ 5% for the entire determination. Since the fluctuation in β emission satisfies a Poisson distribution, the uncertainty may be found by dividing the square root of the number of counts by the measuring time. Thus, for the first value of Table 3, the uncertainty will be $\frac{\sqrt{1008}}{4} = \pm 8$ cpm, which is $\frac{\pm 8}{252}$ or $\pm$ 3%. If this had been larger than 5%, then a longer counting time would have been used. The background measurement should be determined over a period of about an hour (for a background count of about .20 cpm) as may be seen from the following calculation.

$$No = 20 \pm \frac{\sqrt{1200}}{60} = 20 \pm .6 \text{ cpm}$$

This corresponds to an uncertainty of $\pm$ 3%.

The plot to be used in making the corrections to I_A is prepared by use of the equation below which follows directly from equation

$$I_A = (I-N_o)\, e^{-\frac{.693t}{T_{1/2}}} \qquad (17)$$

The value to be substituted for $T_{1/2}$ here is that for W187 which is 24.1 hr. (1446 min.). When equation 29 is plotted, Fig. I results. For the data of Table 3 standard time was 24 hrs. before the first value. Hence, for the first point of Table 3 the value of $(\frac{I_A}{I-N_o})$ is found to be 0.5 opposite t = 24 hrs. and hence, I_A is (232) $(\frac{1}{0.5})$ or 464 as given in the table.

The best method of selecting a representative chip sample has been found to be to break all chips collected, place in a box and shake, and then select at random a number of chips sufficient to cover the standard area.

Determination of Absolute Wear Rate

The specific activity (S) may be computed from equation 14, but the value obtained in this way will not be accurate for two reasons. First, the intensity of the neutron flux in the pile may vary with time and yield a variation of $\pm$ 10% in the activity of the irradiated specimen and secondly, the efficiency of a counter is not 100%. It is best to take care of both of these uncertainties by a calibration procedure in which a small piece that has been irradiated is weighed, and an actual count made. When this measured count is compared with the activity computed from equation 14, an overall efficiency of counting is established.

The efficiency of counting is not found to be sensitive to specimen area* but is very sensitive to specimen distance. In carrying out the calibration,

* within 200-400 mm^2 chip area

the small weighed particle of carbide that was irradiated with the tool is dissolved in molten sodium nitrate and the resulting tungstate is dissolved in water. One 2000th part of this solution is placed on an iron disc of the same size and shape as the chip specimen and evaporated to dryness. The activity of this reference source may then be measured at different distances from the end window of the tube with the result shown in Fig. J. The value of I corresponding to the standard distance between window and chips may be taken from this curve, connected to standard time and then converted to a specific value i_{ref} per microgram (μg) as follows.

$$i_{ref} = \frac{2000}{m} (I) (10^{-3}) \text{ cpm}/\mu g \qquad (18)$$

where m is the weight of the carbide particle in milligrams.

The efficiency was found to be 25% for the standard distance (1/8 inch). From Fig. J it is evident that the efficiency of the counter changes by about 10% when the distance between counter and specimen varies by but 1/16 inch at the distance used. It is, therefore, important that the distance between the surface of the chips and the end of the tube be accurately maintained. All measured values were corrected with the aid of equation 17 in conjunction with a counting efficiency of 25%.

The following quantities are associated with the determination of the rate of wear by the radioactive method.

Z = time required to yield one mg. of tool material on rake face of chip (Z_R) or on back of chip (Z_C), min./mg.

M = weight of carbide on either side of chip, mg.

T = cutting time for (M) mg. to be deposited on chip, min.

I_A = activity of chip sample at standard time, cpm.

L_r = reference activity, cpm/μg.

W = weight of chip, mgs.

ρ = density of chip mg/mm.^{3}

V = cutting speed, fpm

t = feed, ipr

b = depth of cut, in.

It is immediately evident that

$$Z = \frac{T}{M} \text{ min./mg.} \qquad (19)$$

and

$$M = \frac{I_A}{i_r} \times 10^{-3} \text{ mg.} \qquad (20)$$

therefore,

$$Z = \frac{T\, i_r}{I_A} \times 10^{3} \text{ min./mg.} \qquad (21)$$

From continuity considerations

$$W = 197\, \rho\, VtbT \text{ gms.} \qquad (22)$$

Eliminating T between this equation and equation 21 have

$$Z = 5.07 \frac{i_r}{I_A} \frac{W}{Vtb\rho} \text{ min./mg.} \qquad (23)$$

In applying this equation i_r is determined as previously described, while W and I_A are the average values for each test series.

The value of Z is the tool life in minutes to produce one milligram of wear particle and a curve of Z versus cutting speed (V) on log-log coordinates should look just like a Taylor plot. Two types of Z curves may be distinquished — that associated with wear on the clearance face (Z_C) and that associated with wear on the rake face (Z_R).

Radioactive Results

In Fig. K values of Z_C and Z_R are shown plotted against cutting speed (V) for AISI 4340 steel for three values of feed. The conventional tool wear data [redacted] for the middle value of feed (0.0104 ipr) is also shown in Fig. Kc. Both the Z_C and Z_R curves are seen to be similar in appearance to the conventional wear land curve. The dotted curve marked 1 in Fig. Kc was originally drawn as shown, but in view of the radioactive curve in Fig. Kb for t = 0.0104 for Z_R it now appears that this dotted curve might better have been estimated as shown by 2 in Fig. Kc. The Z_R curve should be expected to best approximate the total destruction curve while the Z_C curve should better approximate the wear land curves. There is some indication that this is so in Fig. K.

An interesting tendency for the Z_R curves to bend upward again at very low speeds (below about 30 fpm) after first decreasing with decrease in speed is to be seen in Fig. Kb. A similar tendency is also evident for the intermediate feed (0.0104 ipr) curve of Fig. Ka. The radioactive data of Fig. K indicates that the tool life should have a maximum value at somewhere between 70 and 140 fpm depending on the feed, and a minimum value at about 30 fpm. The built-up edge (BUE) is known to have a maximum size in the region of speed corresponding to that for which the tool life is a minimum (about 30 fpm in this case), and it would appear that the entire nonlinear region of the wear curves (i.e., for speeds below about 200 fpm here) is primarily due to the presence of a BUE.

Fig. L gives similar data for titanium alloy Ti C 310AM. Here the curves for Z_C and Z_R are seen to be linear except at the highest speeds (speeds above 120 fpm for t = .0150 ipr, above 135 fpm for t = 0.0104 ipr and above about 175 fpm for t = .0052 ipr). These limiting values of speed undoubtedly correspond to the values at which the wear land curve for a value of about 0.030 inch intersects the line of total destruction. The slopes of the Z_C vs. V lines correspond closely with the slope of the W = 0.030 inch line of Fig. Lc. However, the slopes of the Z_R lines are different from the conventional wear land curves, again indicating a closer resemblence of the Z_C vs. V curves to the conventional constant wear land curves than to either the conventional total destruction lines or to the Z_R vs. V curves.

A comparison of the relative rates of wear for the clearance (Z_C) and rake (Z_R) faces is given in Fig. N. Here it is seen that in practically all cases the rate of clearance wear is less than the rate of rake wear i.e., $Z_C/Z_R > 1$). The same general pattern of (Z_C/Z_R) vs. V seems to hold for both AISI 4340 and Ti 130 AM. However, the practical machining speed for titanium (about 100 to 150 fpm) curves at a region of the curve where Z_C/Z_R is decreasing with increased speed, while just the reverse is true for Ti 130 AM. From this observation we should expect AISI 4340 to encounter difficulty due to cratering at high speeds but not the titanium alloy. This is actually found to be the case. AISI 4340 fails by cratering at high speeds while titanium alloys succumb to nose failure at high speeds.

Similar Z_C/Z_R curves are shown in Fig. N for other steels cut at different rate of feed. These results are seen to follow the same general pattern as the curves of Fig. **M**. For example, consider the Cr-Ni steel results of Fig. N (solid lines). It would appear that the 0.012 ipr curve is for region BC (see the lower part of Fig. Ma of the general curve), while the 0.020 ipr and 0.040 ipr curves are for the BCD and CD regions respectively/ The AISI 1060 and 1045 data of Fig. N also satisfy the general ABCD type of curve, and again it would appear that minimum point C occurs at a lower speed as the feed is increased.

General Tool Life Equation for Ti C 130AM

In Fig. Oa the curves of Figs. Ka La are shown plotted with a change of vertical scale such that the radioactive curves for t = .0104 ipr of Figs. Ka and La correspond with the conventional 0.030 inch wear land curves of Figs. Kc and Lc respectively. All three of the titanium curves are parallel straight lines for which the Taylor exponent is 0.34, and thus

$$VT^{.34} = C \tag{24}$$

Fig. Ob is a cross plot of the data of Fig. Oa with t as the independent variable (abscissa) instead of V. As is usually the case, the T vs. t curves for the titanium alloy are not quite straight but are concave downward suggesting the following relation instead of a Taylor type equation:

$$T = T_o e^{-\lambda t} \tag{25}$$

where T_o is the value of T when the feed (t) is zero

λ is a constant.

The titanium data of Fig. Ob are shown plotted on semilog arithmetic coordinates in Fig. P where straight lines are obtained, thus substantiating equation 25. The quantity λ corresponds to the decay constant in the radioactive intensity equation and its average value may be most conveniently evaluated as follows.

Let $t_{1/2}$ be the value of t corresponding to $T = T_o/2$. Then, from equation 25

$$\frac{T_o}{2} = T_o e^{-\lambda t_{1/2}} \tag{26}$$

or

$$e^{\lambda t_{1/2}} = Z \tag{27}$$

and

$$\lambda t_{1/2} = \ln Z = 0.6932 \tag{28}$$

The values of $t_{1/2}$ (i.e., t for which $T = T_o/2$) may be read from Fig. P with the following results:

V, fpm	100	75	50	
$t_{1/2}$, ipr	.0030	.0029	.00305	Av = 0.003

From equation 28

$$\lambda = \frac{0.6932}{.003} = 231 \tag{29}$$

For t = 0 equation 24 may be written

$$VT_o^{\,n} = C_o \tag{30}$$

Combining equations 25 and 30:

$$T = \left(\frac{C_o}{V}\right)^{1/n} e^{-\lambda t} \tag{31}$$

or

$$VT^n = C_o e^{-n\lambda t} \tag{32}$$

Substituting n = .34, and $\lambda = 231$, C_o may be evaluated from any combination of t, T and V such as

$$\left.\begin{aligned} t &= 0.0104 \text{ ipr} \\ T &= 100 \text{ min.} \\ V &= 72 \text{ fpm} \end{aligned}\right) \qquad C_o = 781$$

Thus, equation 32 becomes

$$VT^{.34} = 781\ e^{-78.6t} \tag{33}$$

From this equation the value of T (0.030 inch wear land) for any combination of V and t may be found for titanium alloy Ti C 130AM.

CHAPTER III

INFLUENCE OF SIDE CUTTING EDGE ANGLE ON TOOL-LIFE

Theory

An alteration of the side cutting edge angle of a lathe tool is illustrated in Fig. Qa,b. The two parallelograms ABCD and A'B'C'D' are equal in the present case where depth of cut (b), feed (t) and nose radius (r) are kept constant, the side cutting edge angles being C_S and C_S' respectively. These parallelograms are approximately equal to the area of cut before the removal of a chip. Therefore,

$$ABCD = A'B'C'D' \simeq b\,t \qquad (1)$$

The approximation made neglecting the influence of (r) and (t) on the calculation of the area of cut is easily realized to be of minor importance. As the ratio $\frac{b}{t}$ is of the order 10 in practical cases then the relatively complicated cutting process around the nose radius may be neglected and the present problem may be simulated by orthogonal cutting. In doing so the problem in Fig. Qa,b is equivalent to two orthogonal cuts with depths of cut AB and A'B' and feeds S and S' respectively. The dependence of C_S, b, t on AB and S is

$$AB = a = \frac{b}{\cos C_S} \qquad (2)$$

$$S = t \cos C_S \qquad (3)$$

We also have

$$b\,t \cong a\,S \qquad (4)$$

which means that the power put into the tool should be approximately the same in the two cases.

A general tool-life equation which is approximately valid within certain limits of feed and depth of cut can be written

$$Vt^{\alpha}\ b^{\beta}\ T^{n} \cong C \qquad (5)$$

In the above relation the exponent (n) is set to be a constant, although it sometimes varies considerably with (t) and (b) (compare materials AISI 4340 and Ti C 130AM, Chapter 2). The influence of the side cutting edge angle variation on tool-life will now be studied on basis of above tool-life equation and Eqs. 2 and 3. In the present orthogonal cutting process (b) and (t) have to be replaced by (a) and (S) in Eq. 5. Furthermore, (a) and (S) should be expressed as function of (C_S) from Eqs. 2, 1 and 3. Then

$$V(t \cos C_S)^{\alpha} \left(\frac{b}{\cos C_S}\right)^{\beta} T^{n} \cong C$$

or

$$T^{n} \sim (\cos C_S)^{(\beta-\alpha)} \qquad (6)$$

as (t) and (b) are constant.

From Eq. 6 it is readily seen that T is continuously increasing with ($\cos C_S$) provided $\beta > \alpha$ and is continuously decreasing for $\beta < \alpha$. In other words T has a minimum for $C_S = 0°$ and increases continuously with larger side cutting edge angle provided $\alpha > \beta$. The opposite is true when $\alpha < \beta$.

In practical cases $\frac{\alpha}{\beta}$ is of the order of magnitude 2 to 4. Therefore, above theory suggests the use of a big side cutting edge angle to prolong tool-life. In practice, it is observed that values of C_S greater than about 60-70° introduces vibrations. This is probably due to the increased cutting force which is associated with the larger cutting edge length resulting when (C_S) increases, but also the relatively larger radial component of the resultant force gives rise to increased radial force on the workpiece causing instability. Above theory agrees with practical experience. For example, all tool-life testing in turning seems to be made at $C_S = 45°$ in Germany.

It would be of interest to repeat above procedure on basis of the tool-life equation suggested for TiC 130AM (Eq. 32, Chapter 2).

$$VT^n = C_o e^{-n\lambda t}$$

However, the depth of cut is not taken into account in above equation. Assuming the b-term has the same general form as the t-term, we can write

$$VT^n = C_o \, e^{-n\lambda S} \, e^{-n\mu a} \tag{7}$$

where (a) and (S) are defined by Eqs. 2 and 3. Therefore

$$T \sim e^{\left(-\lambda t \cos C_S - \frac{\mu b}{\cos C_S}\right)}$$

or

$$\log T \sim -\lambda t \cos C_S - \frac{\mu b}{\cos C_S} \tag{8}$$

Investigating extreme values of Eq. 8 yields

$$\frac{d \log T}{dC_S} = 0 = \sin C_S \,(\lambda t \cos^2 C_S - \mu b)$$

$$\frac{d^2 (\log T)}{dC_S^2} = \cos C_S \left(-2\lambda t - \mu b + 3\lambda t \cos^2 C_S\right)$$

It is easily shown that

1) $\sin C_S = 0$: has minimum, if $\lambda t > \mu b$

has maximum, if $\lambda t < \mu b$

2) $\cos^2 C_S = \frac{2\lambda t + \mu b}{3\lambda t}$:

has maximum, if $\lambda t > \mu b$

minimum, if $\lambda t < \mu b$

The value of λ for Ti C 130AM was 231. Taking b = .10", t = .0104" we get

$$\frac{\lambda t}{b} \gtrless 24 \mu$$

This is the limiting value of μ which might indicate the variation of tool-life for this alloy.

It is interesting to note the different possibilities arising when using the two approximate tool-life relations above, Eqs. 5 and 7. The former equation yields the commonly observed influence of C_S in practical tool-life testing, while the latter indicates a more complex behavior.

Test Results

The radioactive β technique was used and the activity of both sides of the chips was measured. One C-5 grade carbide tool with the same tool geometry as in the other radioactive tests was used. The eight edges were preground to give .016" to .018" wear land. Four different side cutting edge angles were investigated:

$$C_S = 5°, 15°, 30°, 45°.$$

The cutting speeds were choosen to yield tool-lives in the region of economic life: 60-120 minutes. Presented below is the cutting data used in this test:

Material:	4340	Ti C130AM
V:	230	80
t:	0.0104	0.0104
b:	0.100	0.100
Fluid:	tap water	tap water

The tool edges were run-in for one or two minutes. Due to the spring back primarly in the tool holder at $C_S = 30°$ and 45° the depth of cut could not be maintained. It is known that depth of cut influences tool-life, although to a smaller extent than feed. This variation should be taken into account for reasons given below.

Tool-life in radioactive testing is expressed as the time to wear off a predetermined volume (Vol.) of tool-material from clearance or rake face while a predetermined wear land (W) is the criterion in conventional testing.

The relation between Vol and W is

$$\text{Vol} \simeq \frac{1}{2} \tan \varphi \, W^2 L \qquad (9)$$

where L is the engaged cutting edge length, Fig. Q and φ = the clearance angle (measured perpendicular to the edge) Fig. R. From Fig. Q it is seen that L depends on the b, t, C_S and nose radius r. In particular, an approximate expression of L is:

$$L \simeq L_1 + L_2 + L_3 = \frac{b - r(1 - \sin C_S)}{\cos C_S} + \frac{\pi r(90 - C_S)}{180} + \frac{t}{2} \qquad (10)$$

The approximation can be shown to be less than 2 or 3% in most practical cases. Introducing the length L* corresponding to $C_S = 15°$ as a standard cutting edge length it is readily shown that the relative tool-life (T) for any other length L is

$$T = T^* \frac{I_A^*}{I_A} \frac{L}{L^*} \cdot \frac{b^*}{b} \qquad (11)$$

where the L-ratio comes from the volume ratio of Eq. 22 and the I_Ab-ratio from Eq. 23.

Table 4 gives some necessary quantities to calculate relative tool-lives: n = number of chip samples measured for each side cutting edge angle, b = measured depth of cut, L = calculated edge length, total and average weight of chip samples. Also the chip thickness (h) and the chip thickness ratio (r_C) are given in Table 4.

Table 4

C_S^o	n	b in	L in	h in	r_C	Total weight of chips gram	Average weight per sample
			4340				
5	4	.102	.125	.027	.38	5.7	1.43
15	4	.111	.137	.027	.37	5.5	1.38
30	4	.111	.147	.026	.37	5.9	1.48
45	4	.109	.171	.022	.33	4.9	1.23
			Ti C130AM				
5	5	.119	.142	.017	.61	1.55	.31
15	3	.116	.142	.017	.59	1.0	.33
30	3	.106	.148	.015	.60	1.0	.33
45	4	.079	.129	.0145	.51	.95	.24

Table 5 shows the activity values recorded and the time within which the measurements were made. By subtracting the background counts (20-21 cpm), taking the average activities and dividing by the average weight of the chip samples and then extrapolate these values to the reference time 12:00 A.M., January 31, the values are ready to be put into Equation 11. Fig. S shows the relative tool-lives obtained for rake and clearance as function of side cutting edge angle. For 4340 steel tool-life is seen to have a minimum at $C_S \simeq 15°$ as to clearance and rake wear, while Ti C130AM has a maximum tool-life for $C_S \simeq 15°$ regarding clearance face. Tool-life for the rake face is seen to increase with increasing side cutting edge angle. In Fig. T the ratio of rake to clearance wear is plotted against side cutting edge angle. The results obtained indicate a behavior of the two work materials and the K2S carbide tool corresponding to the theory on p. 28: both maximum and minimum of relative tool-life occur. It should also be observed that the tool-lives obtained by radioactive tests correspond to the portion of constant wear rate of a wear curve. The region of catastrophic wear may be reached at a rather early stage for one particular SCEA (C_S) while this does not happen for the other angles.

Table 5

	4340			Ti C130AM		
C_S	I_C cpm	I_R cpm	Date	I_C cpm	I_R cpm	Date
	106	226	Feb. 1	338	641	Jan. 31
	99	235	5^{21}-5^{50}pm	476	960	3^{00}-3^{50}pm
5°	112	238		353	564	
	102	244		290	633	
	105	236		501	1185	
				392	797	
	163	334	Feb. 1	100	256	Jan. 31
	149	293	5^{55}-6^{15}pm	118	237	3^{57}-4^{25}pm
15°	215	421		168	287	
	134	255		129	260	
	163	326				
	136	262	Feb. 1	176	248	Jan. 31
	137	241	6^{20}-6^{35}pm	173	175	4^{20}-5^{00}pm
30°	98	283		173	218	
	156	220		174	214	
	129	252				
	143	238	Feb. 1	163	158	Jan. 31
	182	275	6^{40}-7^{00}pm	129	127	5^{05}-5^{30}pm
45°	170	297		144	145	
	162	290		134	125	
	164	275		143	139	

CHAPTER IV

ON THE CONSTANCY OF THE WEAR RATE

Metal Transfer and Wear Between Sliders

Mechanical wear involves many factors both mechanical and chemical. Whenever one metal slides over another the surfaces make contact only at the asperities to form a junction. A certain fraction of these junctions mold together to be broken after a small amount of sliding has taken place, material is transferred from one surface to the other or a loose wear particle is formed. Due to the plastic deformation of the asperities the normal load (N) will be related to the real area of contact (A_R) as follows:

$$N = \gamma_m A_R \qquad (1)$$

where (γ_m) is the mean flow pressure of a surface asperity

The first attempt to provide a quantitative theory of wear is due to Holm[9] who considers wear as a process involving the removal of (Z) atoms per atomic encounter. He obtains the result

$$\frac{W}{\ell} = Z \frac{N}{\gamma_m} \qquad (2)$$

where (W) is the worn weight or volume, (N) is the normal load, (ℓ) is the sliding distance and (γ_m) the flow pressure of the softer material.

Burwell and Strang[10] obtained an empirical law similar to that of Holm

$$\frac{W}{\ell} = K \frac{N}{\gamma_m} \qquad (3)$$

where (K) is regarded as the fraction of the real areas of contact resulting in a wear particle. This law was found to hold for normal stresses ($\frac{N}{A}$) below (γ_m). When yielding occurs in the softer material wear increases rapidly in connection with the increase of the real area of contact. Combining Eqs. 1 and 3 one obtains

$$\frac{W}{\ell} = K^1 A_R \qquad (4)$$

Although Holm's result was based on an atomic micro-transfer type of wear, Burwell and Strang suggested that their law would still be valid if the removal of particles larger than atoms was considered. Archard[11] then proceeded to show that Eq. 3 could be deduced independently of any assumptions about the size or distribution of the local contact areas. Later Shaw[12] derived a similar expression to Eq. 4

$$\frac{W}{\ell} = K\ (nC)\ A_R \qquad (5)$$

where (n) is the mean number of junctions per linear distance, (C) is the mean height of a wear particle, (K) the probability that a contact will result in a wear particle. If (b) represents the mean spring of asperities, then (b) will equal (1/n). The mean contact diameter of a junction (a) Shaw relates to the apparent area of contact (A), real area (A_R) and the mean spring (n)

$$a \sim \frac{1}{n} \sqrt{\frac{A_R}{A}} \qquad (6)$$

The mean volume of a wear particle (ΔW) is then

$$\Delta W \sim a^2 C = \left(\frac{A_R}{An^2}\right) C \qquad (7)$$

The importance of Eqs. 5, 6 and 7 lies in the more detailed account taken by showing that (n) and (C) are important. From Eq. 1 it is seen that upon an increase in load (A_R) increases which will result in more wear. However, the variation of (K) and (n_C) should also be considered. According to Bruwell and Strang's experiments (KnC) should remain constant.

It is evident that (n) increases with load. However, the probability (K) is considered constant by above authors. If this is accepted, then according to Eq. 5 (C) should decrease inversely proportional to (n). Shaw assumes this is due to a size effect involving the probability of finding an imperfection within the wear specimen changing its strength. As (a) increases upon an increase in load Shaw suggests (C) should decrease due to the greater probability of finding an imperfection at a given distance from the interface. On the other hand, it could be argued that in the size range considered the probability of finding an imperfection would be very small. By assuming dislocations are responsible for the reduction of the strength of the asperities the strength reduction might be due to the greater probability of the existence of dislocations when (a) increases. As the wear is directly proportional to the load, (C) should, therefore, decrease to make (nC) constant for a constant combination of materials. It is interesting to note that above wear formulas are independent of the speeds used in the experiments in question. However, Bowden and Tabor[13] used small cylinders of different metals sliding at different speeds on a steel surface and measured the thermoelectric potential. Their results indicated that the maximum temperatures reached as the asperities increased with speed until the melting point of the metal was reached. Thereafter temperature was independent of the speed. Comparing these tests with the wear results reviewed above naturally suggests that these were performed at the melting point of one or the other of the sliders used. On the other hand, in metal cutting where sliding conditions are probably extremely severe, it is found that temperature varies with cutting speed and the wear rate (tool-life) is extremely sensible to temperature. The wear process on the two faces of a cutting tool may, therefore, be quite different from that of ordinary sliders. One important observation common to the two types of wear mentioned is the constancy of the wear rate with respect to time of sliding or cutting.

However, in the theories mentioned above none really deals with the basic cause of the wear process. The arguments leading to above relations yield essentially the same result. It is reasonable that a theory based on atomistic wear (Holm) gives the same result as one which is related to microscopic particles (Archard and Shaw). However, considering the wear process as a pure diffusion process would be a more fundamental problem.

Tool Wear on Basis of Pure Diffusion

Although the account of the wear process given above does not elaborate on different types of wear: adhesive, abrasive or plowing wear, the outcome of the results is an approximately constant wear rate when other facotrs are held constant.[1,3,4,7] In metal cutting the wear rate increases with time when the time of cutting approaches the time of failure. The difference between time of failure and the time when the constancy of the wear rate ends depends on several conditions. The important thing is, however, that, in most practical cases the region of constant wear rate is of primary importance.

Instead of regarding the wear mechanism from the point of view of welds involving a number of junctions and their size I assume in the present theory that the resulting wear is entirely due to a diffusion process. It is known from experiments by e.g. Dawihl[14] and Trent[15] that a fused layer of an alloy is formed between the steel cut and the tool material. By radioactive tests it is also pretty well established that (at least in practical speed ranges) between 95 and 100% of the wear of a tool is found as transfer products on the two sides of the chips.[1,7] In the case of a WC-Co-carbide tool Trent found that an alloy was formed between the work and the tool material causing large crater wear.. The addition of TiC reduced the amount of crater wear and only small traces of alloying was noticed. In the metallurgy field diffusion plays a tremendous roll and diffusion may take place extremely rapidly due to thermal activation. In a recent paper by Cohen et al[16] on the kinetics of tempering the authors applied with success the fundamental laws of diffusion of carbon atoms to explain that martensite decomposes into martensite with small tetragonality and ϵ-carbide.

According to Fick's law

$$\mathcal{J} = D \frac{\delta c}{\delta x} \tag{8}$$

where ($\mathcal{J}$) is the flux of atoms down the concentration gradient ($\frac{\delta c}{\delta x}$) per unit area and unit time, (D) is the diffusion coefficient.

Experimental data on (D) are obtained in the form

$$D = D_o \, e^{-\frac{u}{R\theta}} \tag{9}$$

where (u) is the activation energy (related to the melting point of the material: $u/\theta_m \simeq$ const. for each material), (R) is the gas constant and (θ) is the absolute temperature. According to Cohen et al

$$\frac{\delta c}{\delta x} \sim \frac{1}{\ell} \tag{10}$$

where (ℓ) is the maximum diffusion distance which in turn is related to the diffusion coefficient (D) and the time available (t)

$$\ell \sim (Dt)^{1/2} \tag{11}$$

Combining Eqs. 10 and 11

$$\frac{\delta c}{\delta x} = (Dt)^{-1/2} \tag{12}$$

Combining Eqs. 8, 9 and 12

$$\mathcal{J} \sim t^{-1/2} \, e^{-\frac{u}{R\theta}} \tag{13}$$

For a given arbitrary wear land (W) and an engaged cutting edge length (L) the total diffusion rate (Ω) is

$$\Omega \sim W \, L \, t^{-1/2} \, e^{-\frac{u}{R\theta}} \tag{14}$$

It is easily shown that the volume material (W) removed from the clearance face of a tool is Fig. *Rb*

$$W \sim \tan\varphi \; W^2 L \qquad (15)$$

provided φ attains the small values observed in metal cutting (φ is often approximately equal to the clearance angle perpendicular to the cutting edge). Due to the constancy of the wear rate, we have

$$\frac{dW}{dt} = \text{const} = 2 \tan\varphi \; L \; W \frac{dW}{dt}$$

Hence

$$t \sim \tan\varphi \; L \; W^2 \qquad (16)$$

Introducing this expression into Eq. 14

$$\Omega \sim \left(\frac{L}{\tan\varphi}\right)^{1/2} \cdot e^{-\frac{u}{R\theta}} \qquad (17)$$

Equation 17 is interesting due to the fact that it expresses a direct dependence of wear rate and temperature (θ). Numberous investigations in the field of metal cutting have shown this to be the case. However, the relation between tool-life (T) temperature (θ in °F or °C) is usually approximated by an equation of the type

$$T = A \; \theta^{-B} \qquad (18)$$

where B is of the order of magnitude 20. As

$\Omega = \frac{dW}{dt}$ or $\Omega T = W^* =$ constant, Eq. 17 can be written

$$T \sim \left(\frac{\tan\varphi^*}{L}\right)^{1/2} \cdot e^{\frac{u}{R\theta}} \qquad (19)$$

where φ^* is the angle on the clearance corresponding to a predetermined volume (W^*) as in radioactive testing. Eq. 19 suggests that tool-life is inversely proportional to the square root of (L) when temperature (θ) is constant. The relation derived means that the engaged cutting edge length is a variable which together with temperature determines tool-life. What is more important is the fact that Eq. 19 gives the condition that wear rate is constant only when temperature is constant in a tool-life test. However, at present the intention is not to derive a general expression between cutting variables determining temperature and tool-life, but to show that if wear on the clearance face is a diffusion process then tool-life is closely related to temperature. It has thus been shown that the temperature dependence of the wear rate is very strong. The considerations basing the equations between sliders on particle wear does not lead to any temperature dependence which shows the possible fallacy in applying them in the cutting process.

Quite recently Trigger and Chao[17] applied the theory of diffusion to the basic slider wear equation, by assuming the probability constant (K) contains a temperature dependence:

$$K \sim e^{-\frac{u}{RT}} \qquad (20)$$

Trigger and Chao were concerned with the crater wear of carbide tools. They managed to derive an approximate equation including the normal load (N) on the rake face. This equation was then tested under a variety of cutting conditions and was found to agree rather well with experimental data. Their main conclusion is the direct temperature dependence of the wear rate on the rake face. One of their important assumptions is the statement of the normal load being constant throughout the life of the tool. In fact, no one has been able to check this experimentally due to the fact that only the components of the resultant force on the tool can be studied as a function of time. In ordinary slider wear a constant load yields a constant wear rate, Eq. 3. Trigger and Chao's assumption of a constant (N) also leads to a constant wear rate on basis of their equation. In the next section the constancy of the normal load will be considered.

Another interesting treatment of the cutting process is due to Saibel and Ling [18] who applied a reaction theory by Eyring [19] forcreep and rupture to the cutting process. The rupture time (t_r)

$$t_r = \frac{h}{K\Theta} \quad e^{\frac{F}{R\Theta}} \tag{21}$$

where h = Planck's constant

K = Bolzmann's constant

R = gas constant

Θ = absolute temperature

F = activation energy

By considering $\frac{h}{K\Theta}$ constant, t_r as tool-life T they showed that the temperature-tool-life equation $T = A\ \Theta^{-B}$ is possible better approximated by the creep equation above.

It is thus seen that Eq. 19 derived by the present author agrees very well with those suggested by above mentioned investigators. The application of a creep equation to the cutting process is also interesting from the following observation. The relation between volume wear or wear land wear and cutting time is represented by a steep initial wear followed by a linear wear (in the case of volume wear) or parabolic wear $W^m \sim t$, where $1 \leq m \leq 2$ (in the case of wear land wear). Thereafter, follows a period of steadily increasing wear (catastrophic wear) until tool fails. Exactly the same general pattern is observed in creep tests, in particular for viscous creep, when shear strain is plotted against time.

The reason why above authors did not apply their equations to clearance wear is due to the observation that temperature is lower on the clearance face than on the rake face. Therefore, the chances of a diffusion process governing the behavior on the clearance face may seem relatively small. According to the writer's opinion this does not seem to be justified as we deal with a process where wear takes place at the highest spots of the mating surfaces. At these spots temperature approaches the melting point, so a diffusion process should not be disregarded on the clearance. It is especially striking to note that tool-life data based on clearance wear are often compared with temperature data corresponding to rake face temperatures or mean temperatures in the tool. The close dependence observed in these tests between (T) and (θ) may very well show that temperature is responsible for the wear on the clearance and not just rubbing wear which is frequently referred to.

<u>On the Variation of the Friction Force on the Clearance Face</u>

Experimentally using the tool-work-thermocouple method one finds the temperature to be approximately constant throughout the life of the tool independent of the size of wear land and crater. 20,7,21 This observation is in accord with the prediction of Eq. 17. The constancy of the temperature will constitute the basis for a rather idealized treatment of the heat flow through the clearance face. As we have a steady heat production at the interface of tool and work this process may be regarded as one where heat suddently flows in one direction through a thick wall the initial temperature of which is θ_o. In a period of time (t) the temperature of the surface of the wall is increased from θ_o to θ. When a small area on the workpiece at temperature (θ_o) makes contact with an equal area of the worn surface of the clearance a heat flow into the workpiece is provided by the temperature difference between tool-work interface and the temperature of the work ($\theta-\theta_o$). It is known that the work piece temperature increases slightly with time of cutting, but this can be neglected as a first approximation. Applying the heat flow equation in one dimension in the radial direction of the workpiece

$$\frac{\delta\theta}{\delta t} = \alpha \frac{\delta^2\theta}{\delta x^2} \qquad (22)$$

for the condition

$$\theta\ (x,0) = \theta_o, \quad \theta = \theta_o, \quad t = 0$$

$$\theta\ (0,t) = \theta\ , \quad \theta = \theta\ , \quad x = 0$$

$$\theta\ (\infty,t) = 0, \quad \theta = 0\ , \quad x = \infty$$

The equation for the heat flow during time (t) over an area (A) is given by (see Jacob: "Heat Transfer"[22]

$$g = -k\ A \frac{\delta\theta}{\delta x} = \frac{kA(\theta-\theta_o)\, e^{-\frac{x^2}{4\alpha t}}}{\sqrt{\pi\alpha t}}$$

At the interface (x = 0) we have

$$g_o = \frac{kA(\theta-\theta_o)}{\sqrt{\pi\alpha t}} \qquad (23)$$

Above equation was used by Woxén[20] in 1936 to obtain a relation between tool temperature and cutting variables, probably the first treatment of the balance of heat in cutting. His final result agrees with those obtained by later investigations on basis of Jaeger's solution of the problem of the moving heat source. A certain fraction (R) of (g_o) goes into the clearance face. As frictional heat also can be expressed as the product of the friction force (F) and the cutting speed (V) we can set Eq. 23 proportional to (FV)

$$R\,\frac{kA(\theta-\theta_o)}{\sqrt{\pi\alpha t}} \sim R\ FV$$

or

$$\theta-\theta_o \sim \frac{FVt^{1/2}}{A} \qquad (24)$$

The area A is simply the product of the instantaneous height of the wear land (W) and the engaged cutting edge length (L)

$$A = LW \qquad (25)$$

The time (t) during which the workpiece rubs (generates heat) against the clearance face of wear land (W) at a cutting speed (V) is

$$t = \frac{W}{V} \tag{26}$$

This time is the same as in Eq. 24, but not a time quantity having anything to do with the time variation of the wear land (W). Combining Eqs. 25 and 26 with Eq. 24 yields

$$\theta - \theta_o \sim \frac{F}{L} \left(\frac{V}{W}\right)^{1/2} \tag{27}$$

Equation 27 is interesting in itself as it expresses the commonly found approximate relation between tool-temperature (θ) and cutting speed (V). In practice it is found that the registered forces only vary slightly with cutting speed, so (F) could be set constant while (W) corresponds to a certain wear land. Then we get the common relation between (V) and (θ):

$$(\theta - \theta_o)^2 \sim V \tag{28}$$

This indicates that Eq. 27 is a reasonable relation for studying the variation of (F) with wear land or cutting time when (V) is held constant as in a tool-life test. As experience shows (θ) independent of wear land (compare also Eq. 17) we can write

$$\frac{\delta}{\delta W}\left[F W^{-1/2}\right] = 0$$

or

$$\frac{\delta F}{\delta W} W^{-1/2} = \frac{1}{2} F W^{-3/2}$$

$$F \sim W^{1/2} \tag{29a}$$

Combining Eq. 29 with Eq. 16:

$$F \sim t^{1/4} \tag{30a}$$

Naturally Eqs. 29a and b should be written

$$F - F_o \sim (W - W_o)^{1/2} \tag{29b}$$

$$F - F_o \sim (t - t_o)^{1/4} \tag{30b}$$

where F_o is the value of friction force when wear land has established itself at t_o, W_o.

Equation 29 suggests that the friction force rises with the square root of the size of the wear land. The variation of F with cutting time expressed by Eq. 30 needs some further comments. Equation 16, expressing $t \sim W^2$, is only true provided $\tan \varphi$ is constant during a test. This is not so, however. The writer studied the variation of (φ) and (W) with time and found (φ) increases with time while (W) did not in general follow $t \sim W^2$. The exponent $2 = m$ was found to be $1 \leq m \leq 2$ (7), so (W) rises less than is shown by Eq. 16. As (φ) increases we can still regard Eq. 16 as a correct expression when φ is regarded a constant in those cases where the wear rate is of primary interest.

Therefore, Eq. 30 is only correct in the case where (φ) is constant and $t \sim W^2$. However, Eq. 29 is derived independently of any considerations of the variation of (W) with cutting time. Introducing Eq. 29 into Eq. 27 yields

$$\theta - \theta_o \sim \frac{V^{1/2}}{L} \qquad (31)$$

This results indicates $(\theta - \theta_o)$ rises with the square root of cutting speed independently of the value of the friction force or the wear land. However, this is only true as long as the workpiece temperature (θ_o) does not increase appreciably. Equation 31 also indicates that for a constant cutting speed $(\theta - \theta_o)$ diminishes when L is increased. However, Eq. 31 says that temperature is independent of the friction force. This seems probable as the observed values of the cutting forces do not vary more than 10-20% within rather large speed ranges. Also the diffusion theory suggests that the influence of forces is relatively small. The variation of the measured cutting forces is to a certain extent due to geometrical changes of crater and wear land as well as to the built-up formation on the tool. Above theory indicates, however, that the friction force on the clearance face may vary according to Eq. 29 when temperature alone determines tool-life. As this may be the case to a greater extent than hitherto realized it seems rather doubtful to base tool-life on the rise e.g., the thrust force in turning, which is sometimes done as temperature according to Eq. 31 is independent of the friction force.

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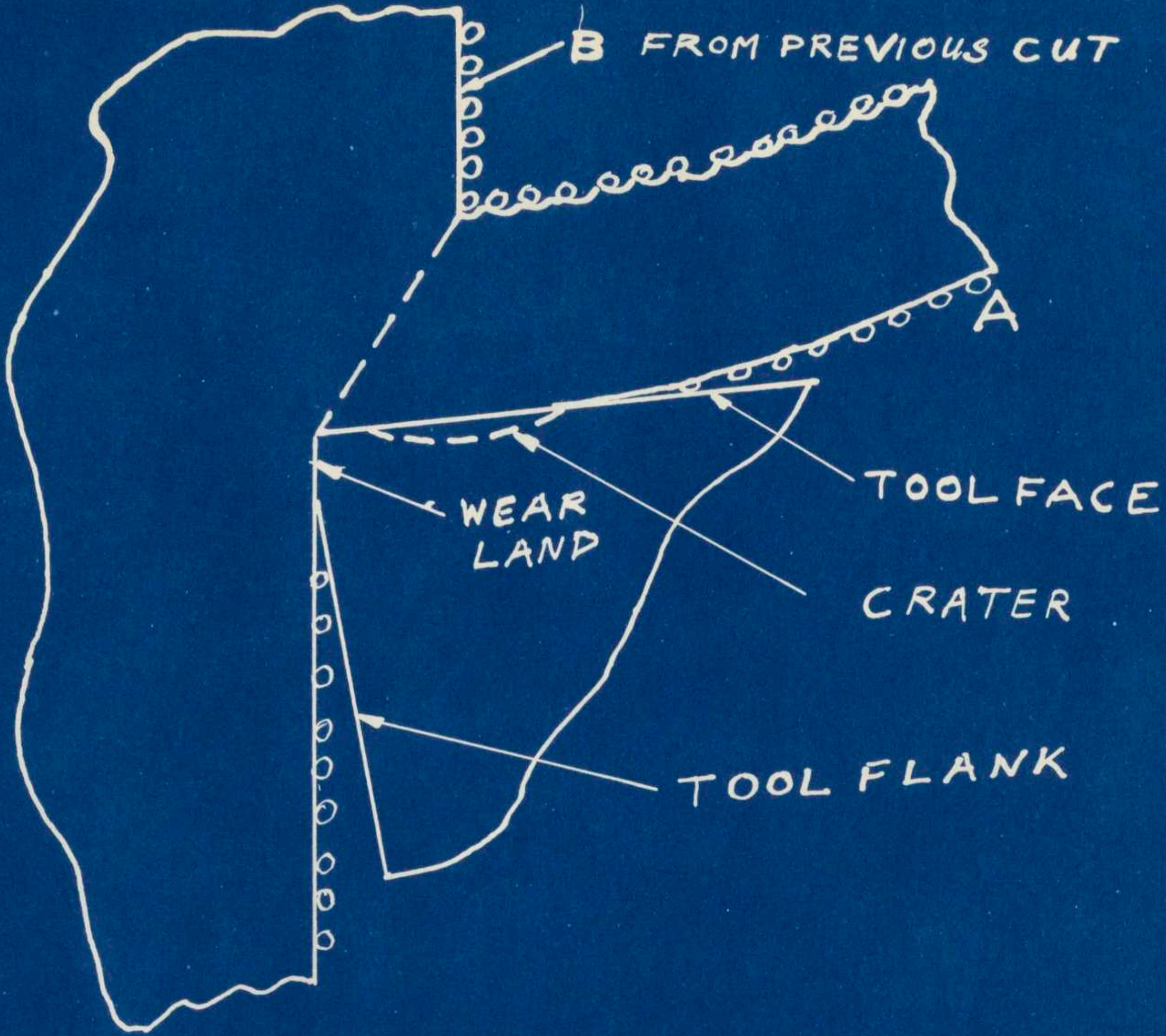


Fig. A TRANSFER OF WEAR PARTICLES FROM FLANK AND FACE OF TOOL

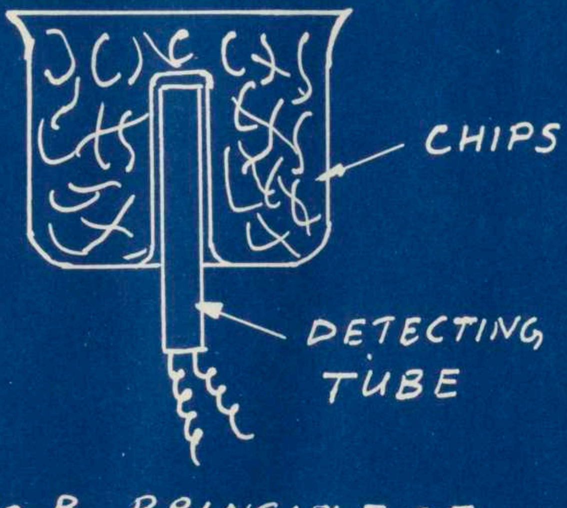


Fig. B. PRINCIPLE OF γ-MEASUREMENT

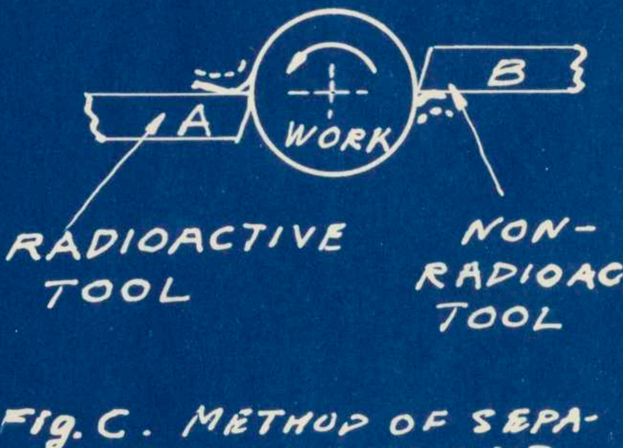


Fig. C. METHOD OF SEPARATING FLANK AND FACE WEAR (γ-method)

Fig D. Flank and face wear as functions of time

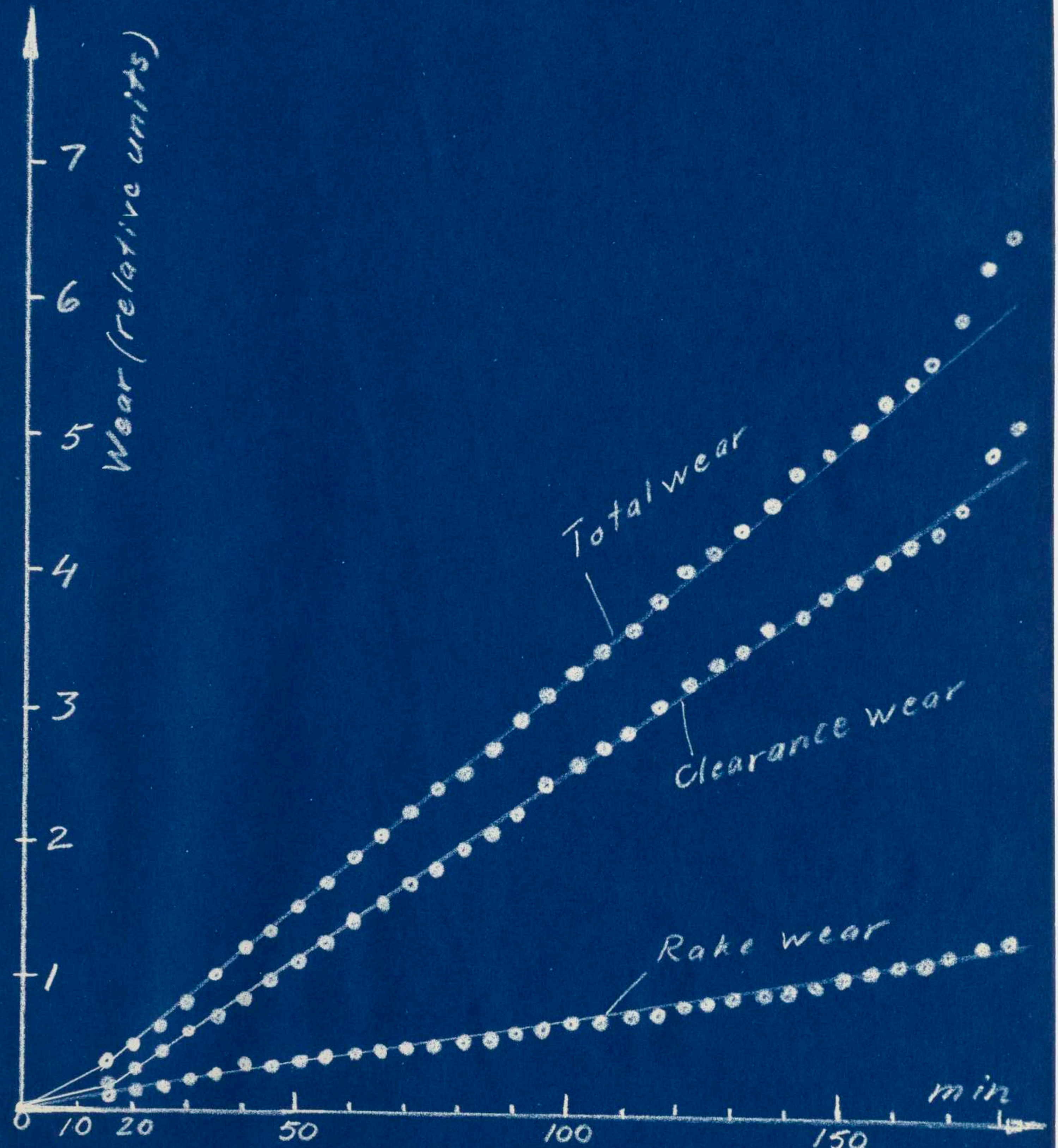


Fig. E
Close up
View of tool
and holder

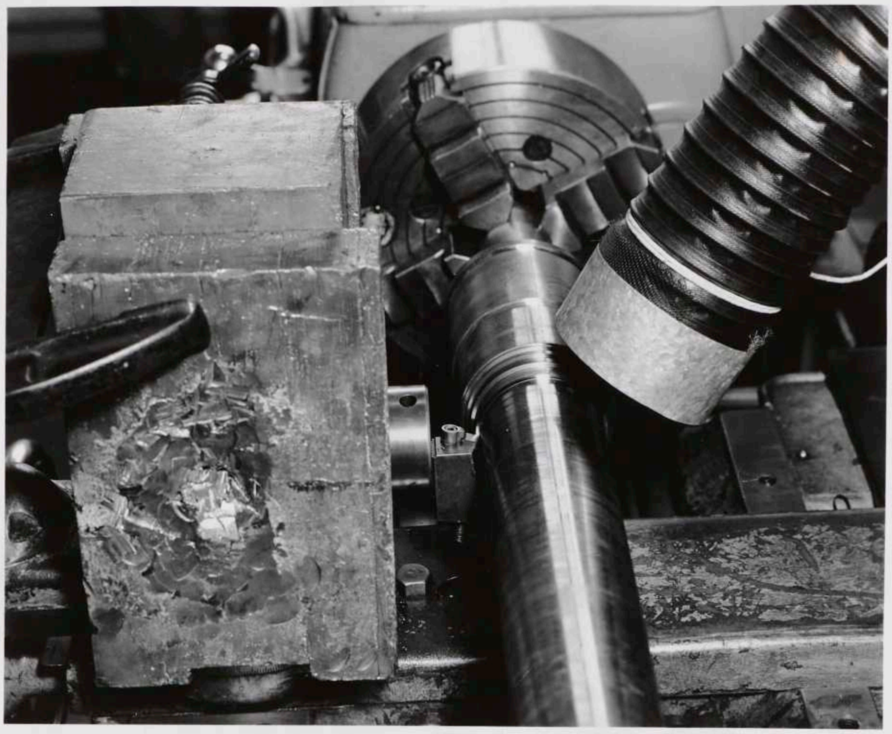


Fig. F
View of lathe

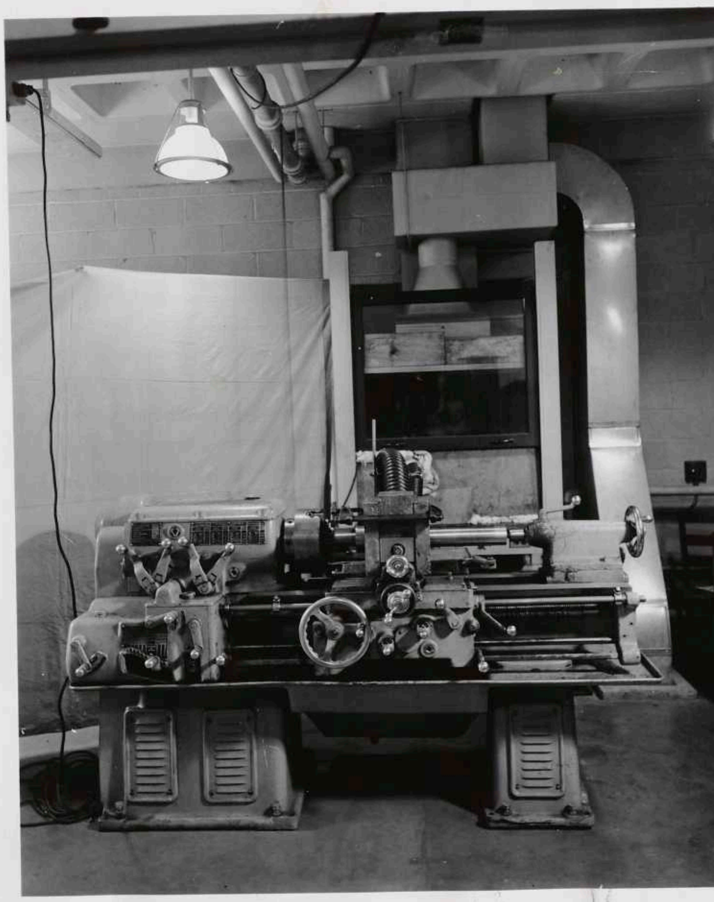


Fig. G.
Chip samples

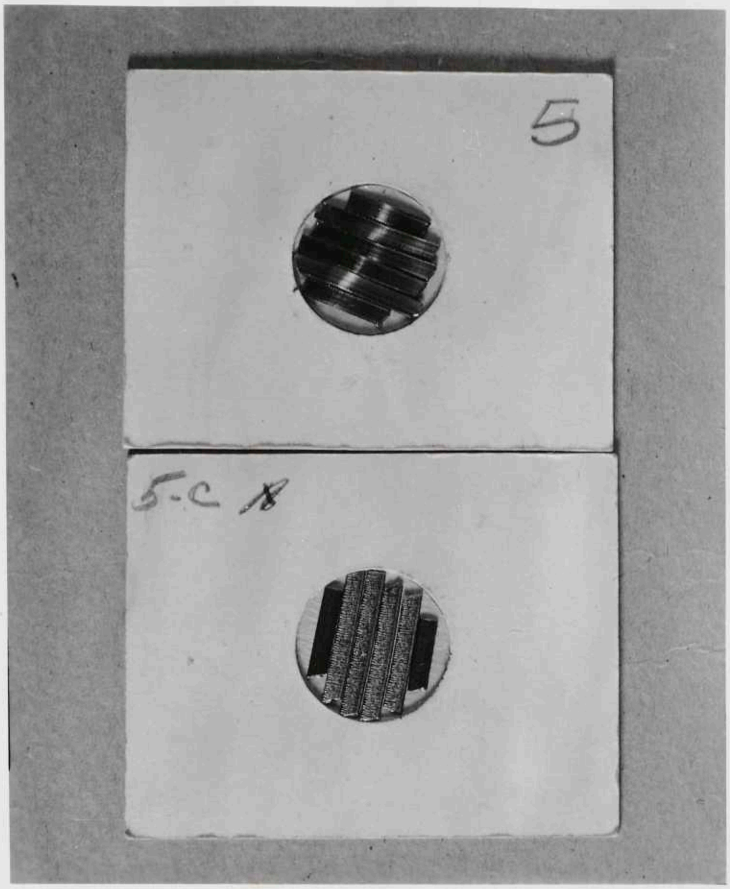


Fig. H
Measuring set up

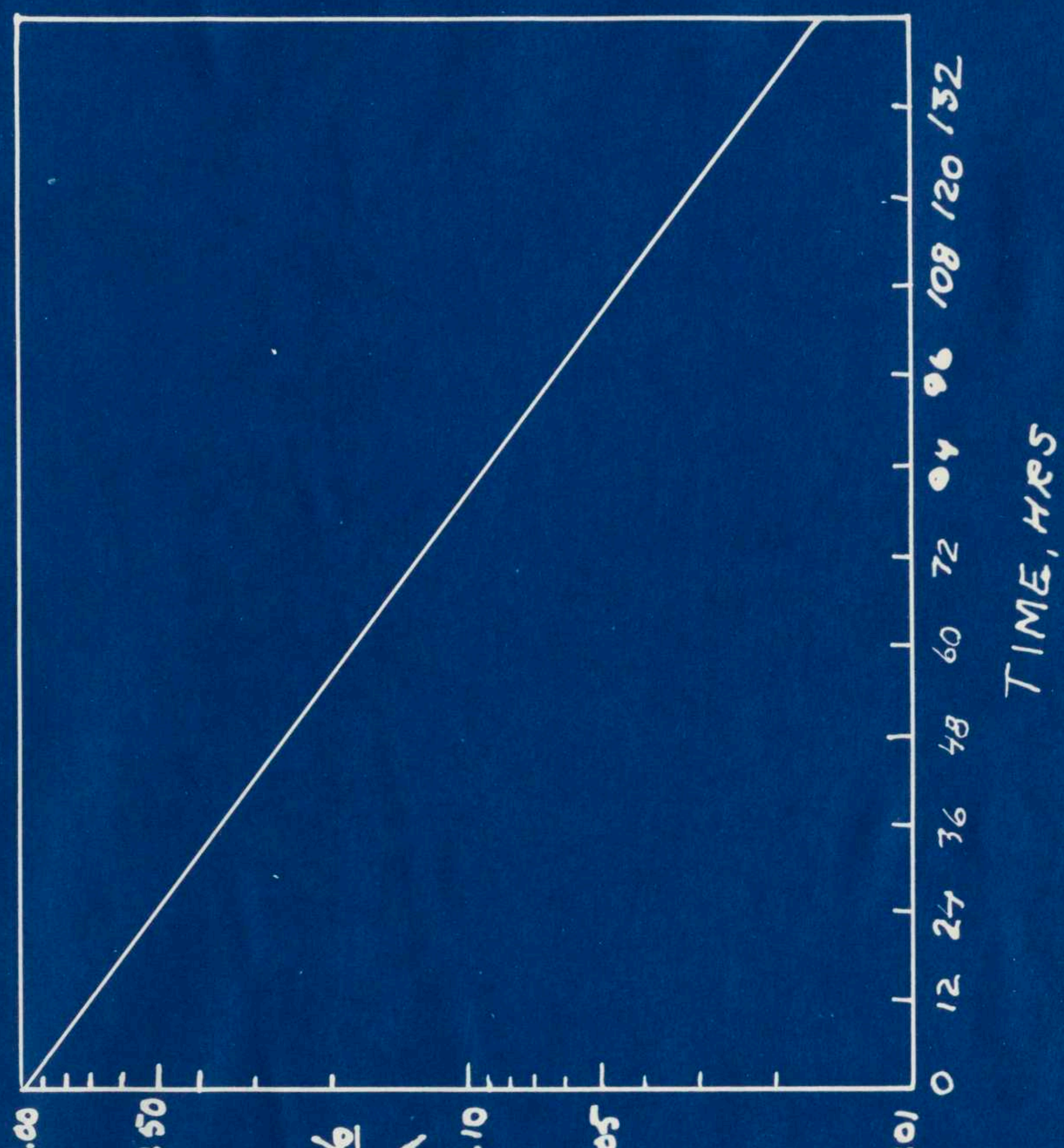


Fig. I Graph for correcting activity values to reference time.

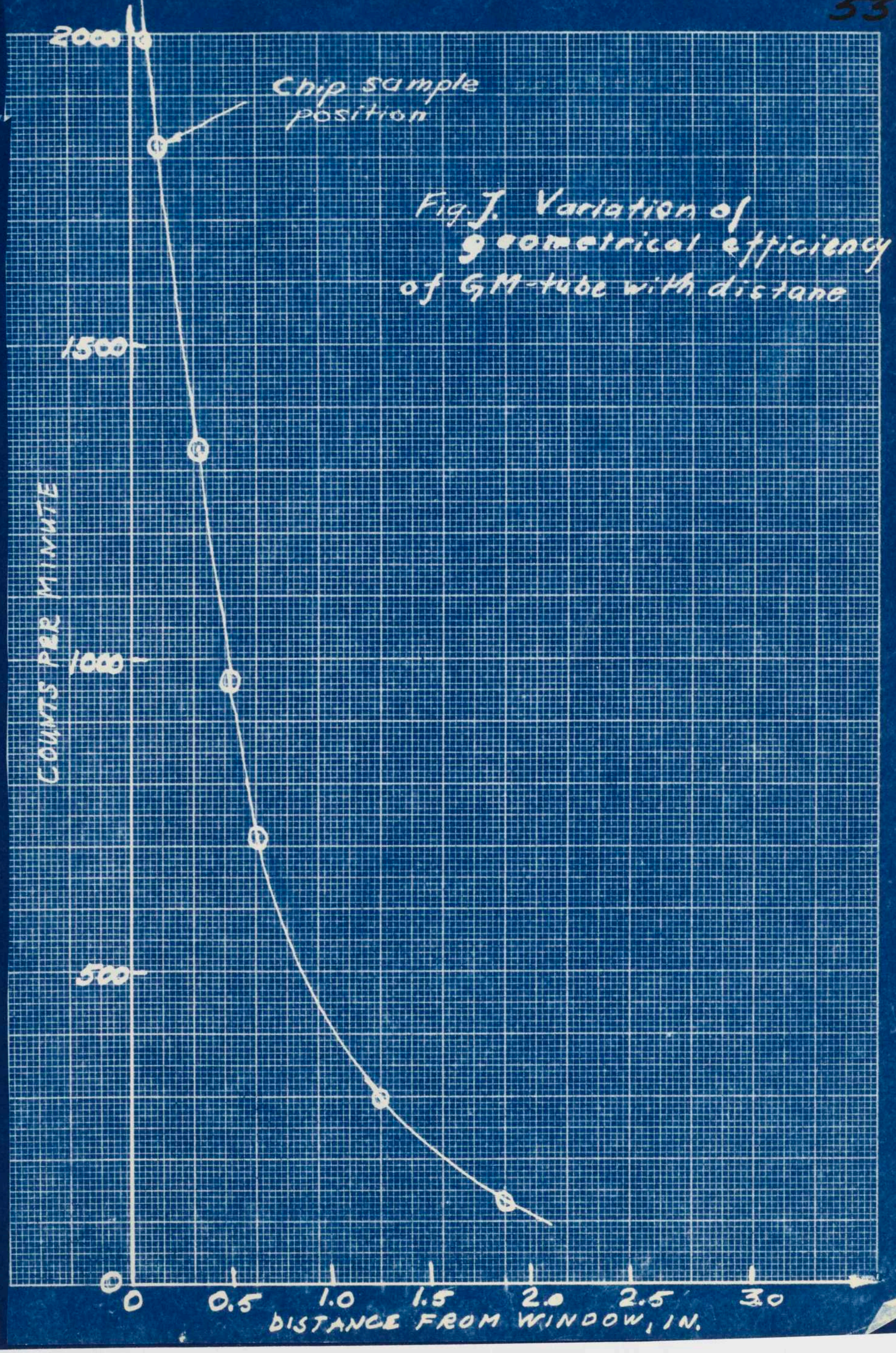

Chip sample position
Fig. J. Variation of geometrical efficiency of GM-tube with distane
COUNTS PER MINUTE
2000
1500
1000
500
0
0
0.5
1.0
1.5
2.0
2.5
3.0
DISTANCE FROM WINDOW, IN.

Fig. K a) Clearance wear as function of speed for AISI 4340

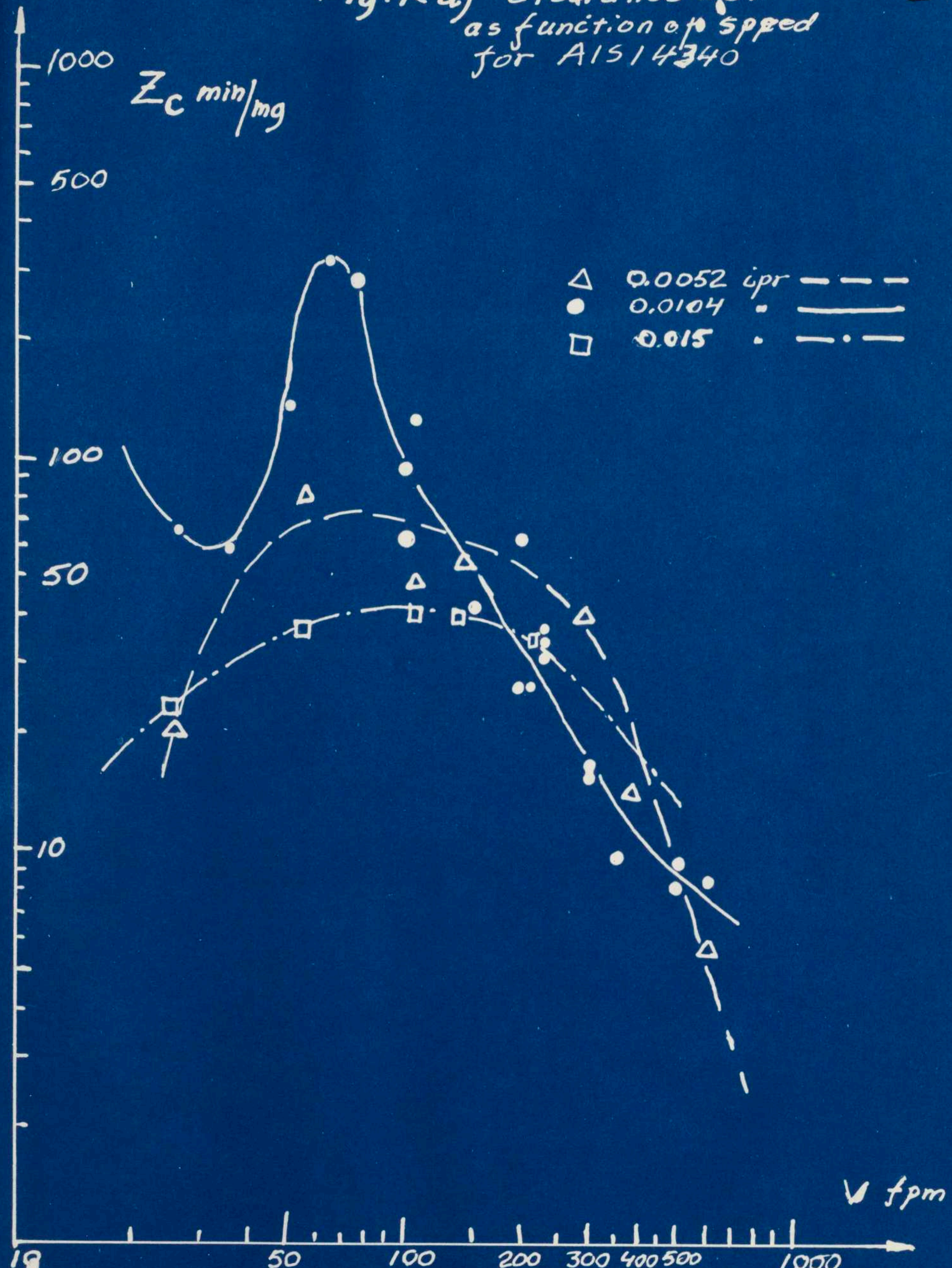


Fig. K Rake wear as function of speed for AISI 4340

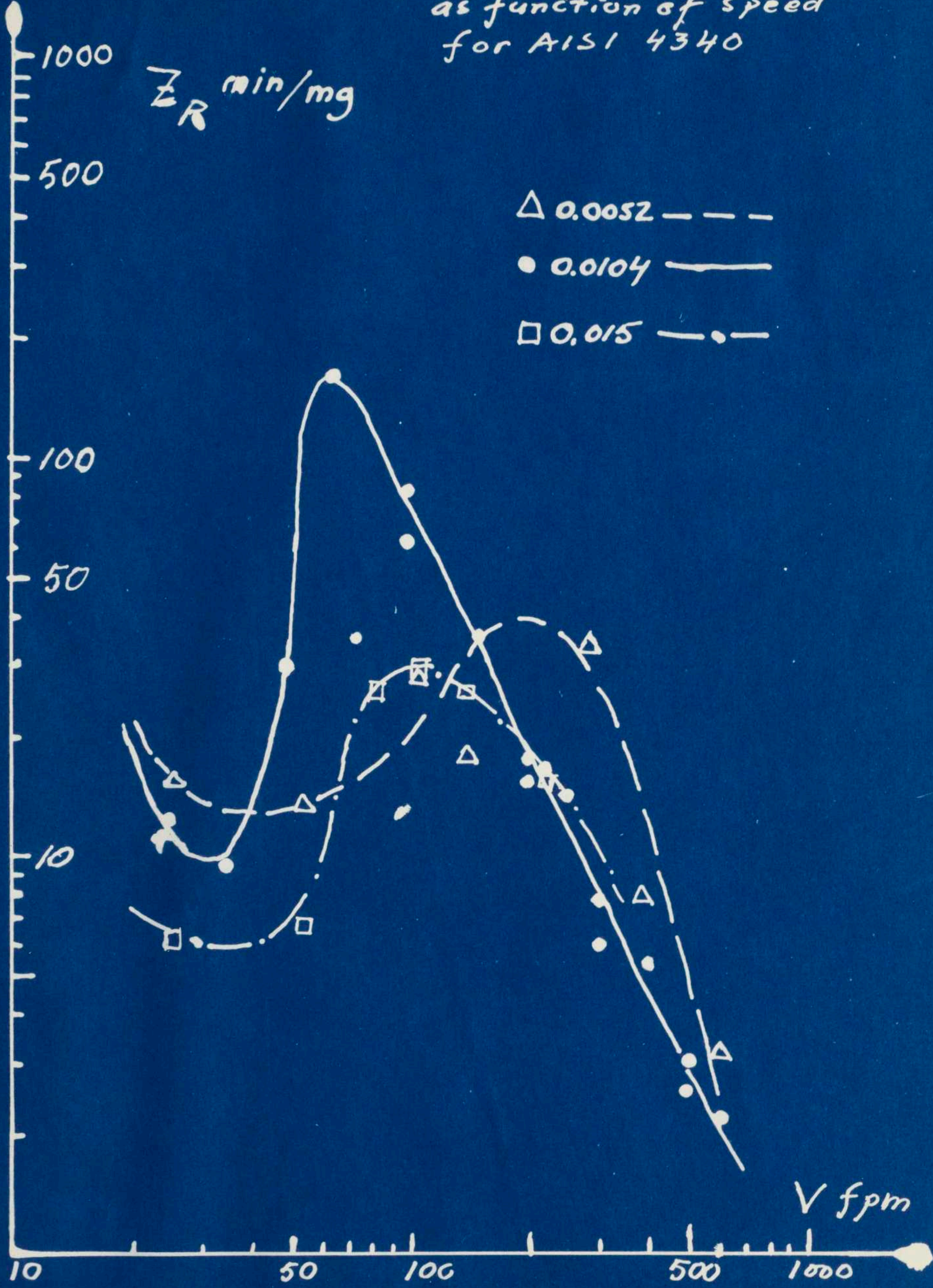


Fig. Kc) Wear land curves and total destruction for AISI 4340

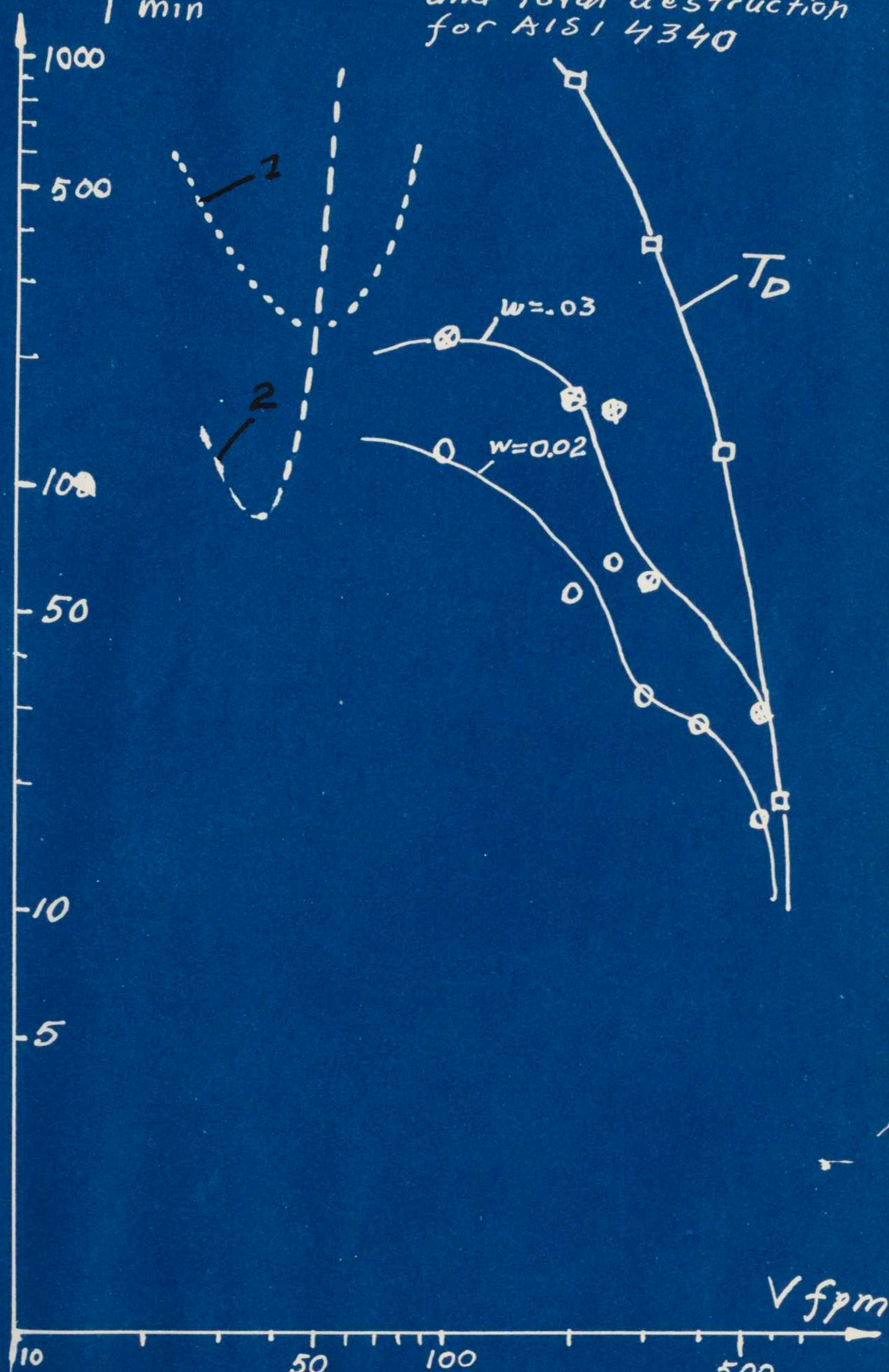
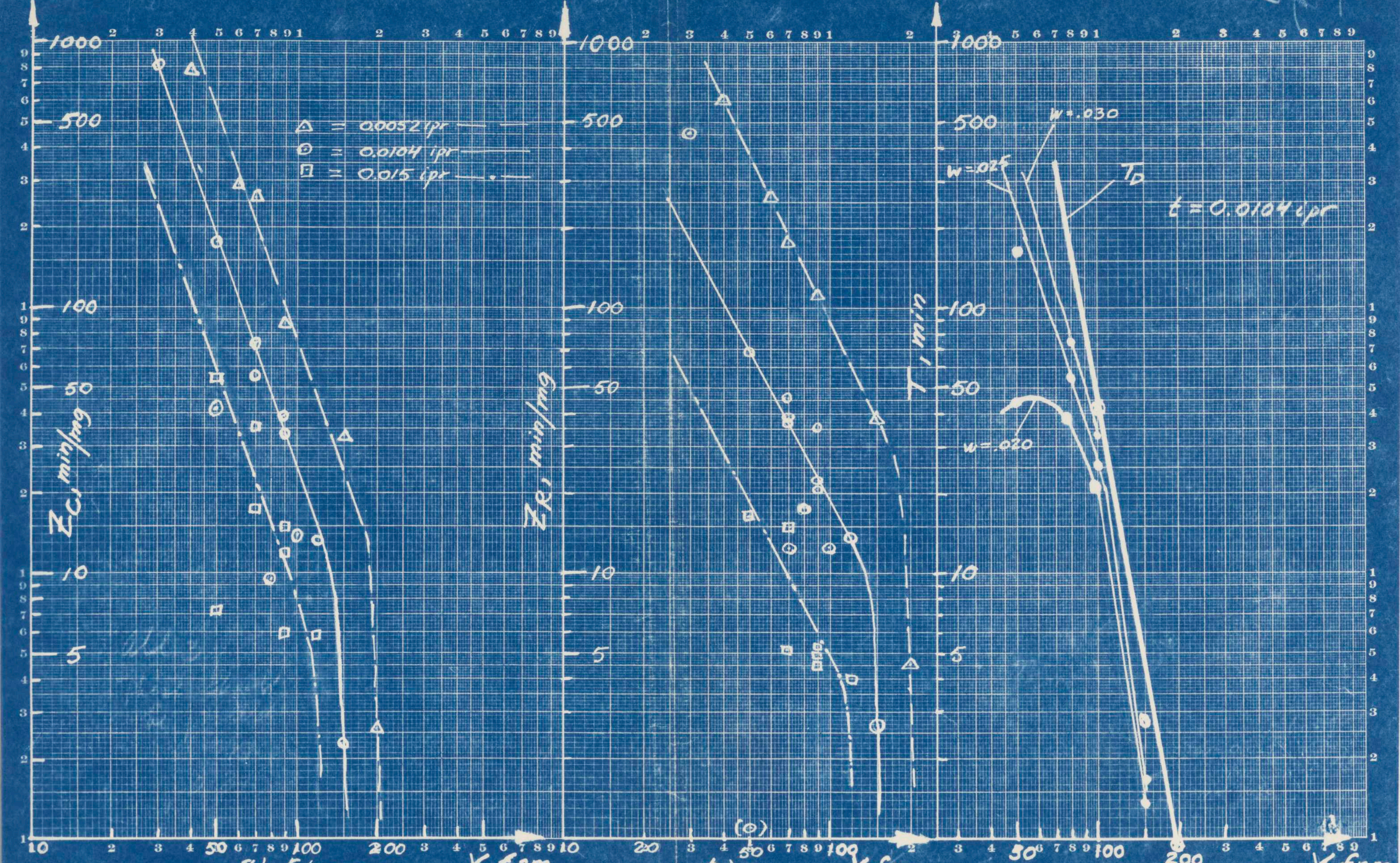


Fig. L



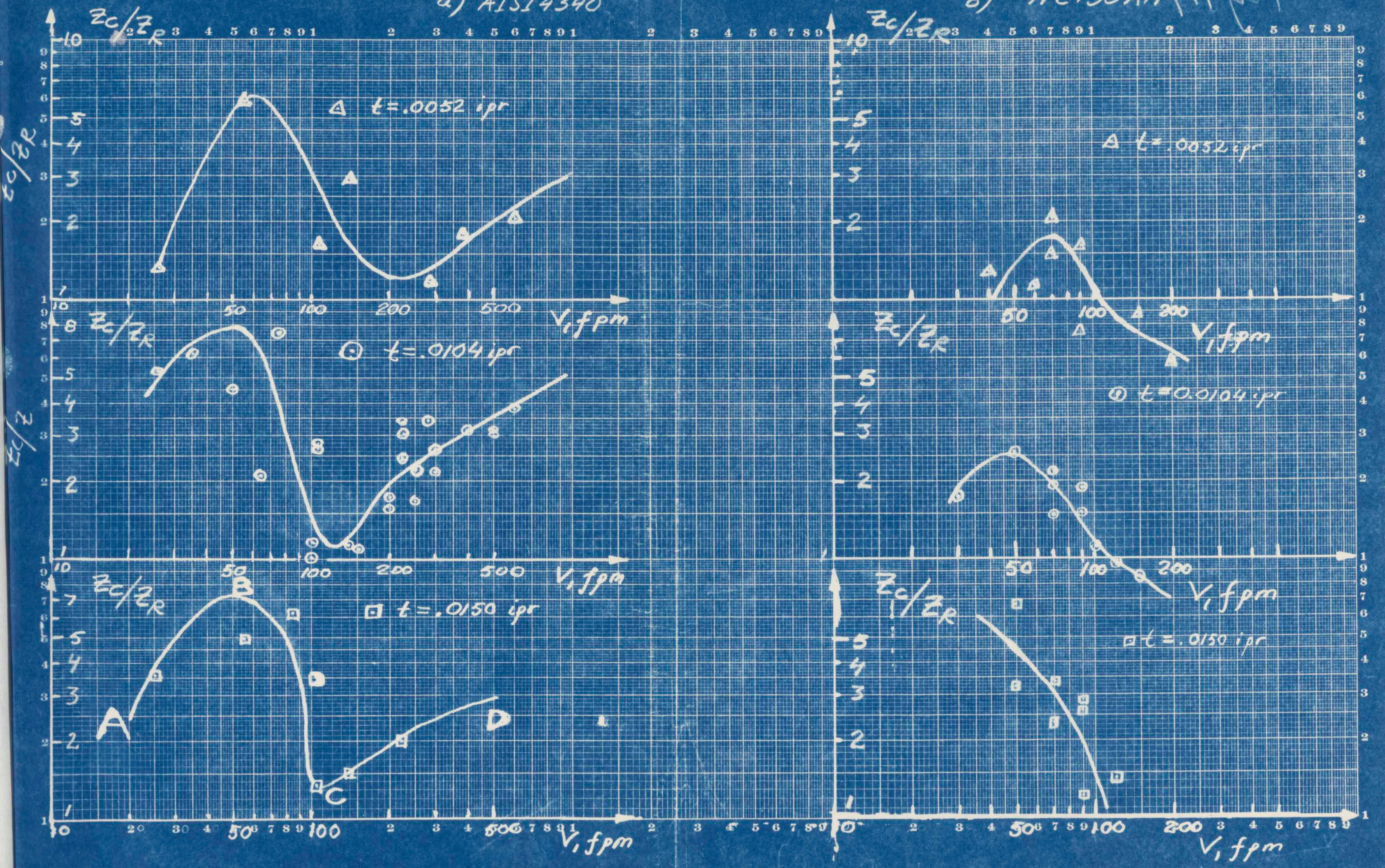
a) Clearance wear as function of speed for TiC130AM

b) Rake wear as function of speed

c) Wear land curves and total destruction curve TiC130A

Fig. M. Variation of rake wear to clearance wear ratio

a) AISI 4340 b) TiC130AM



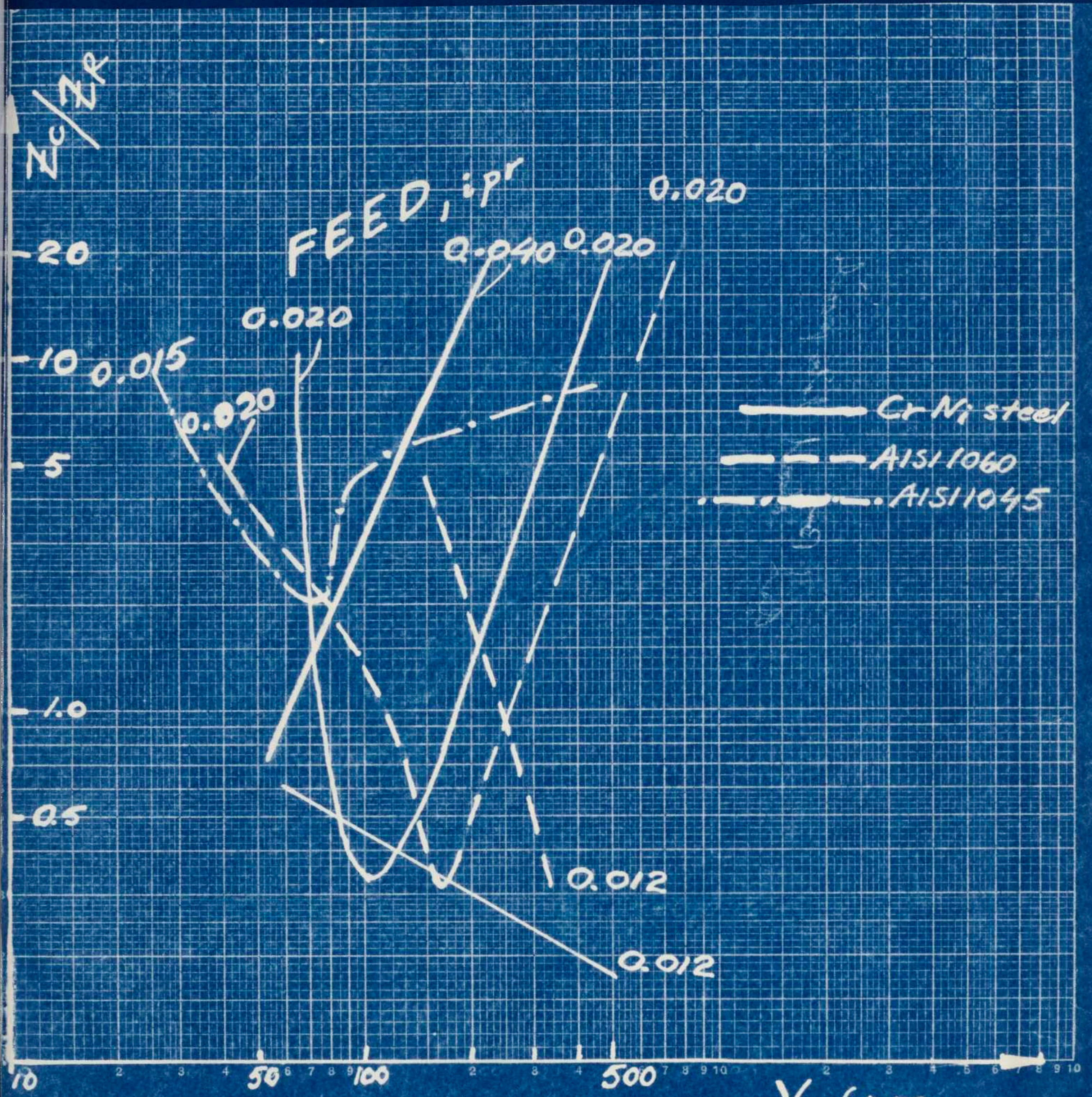
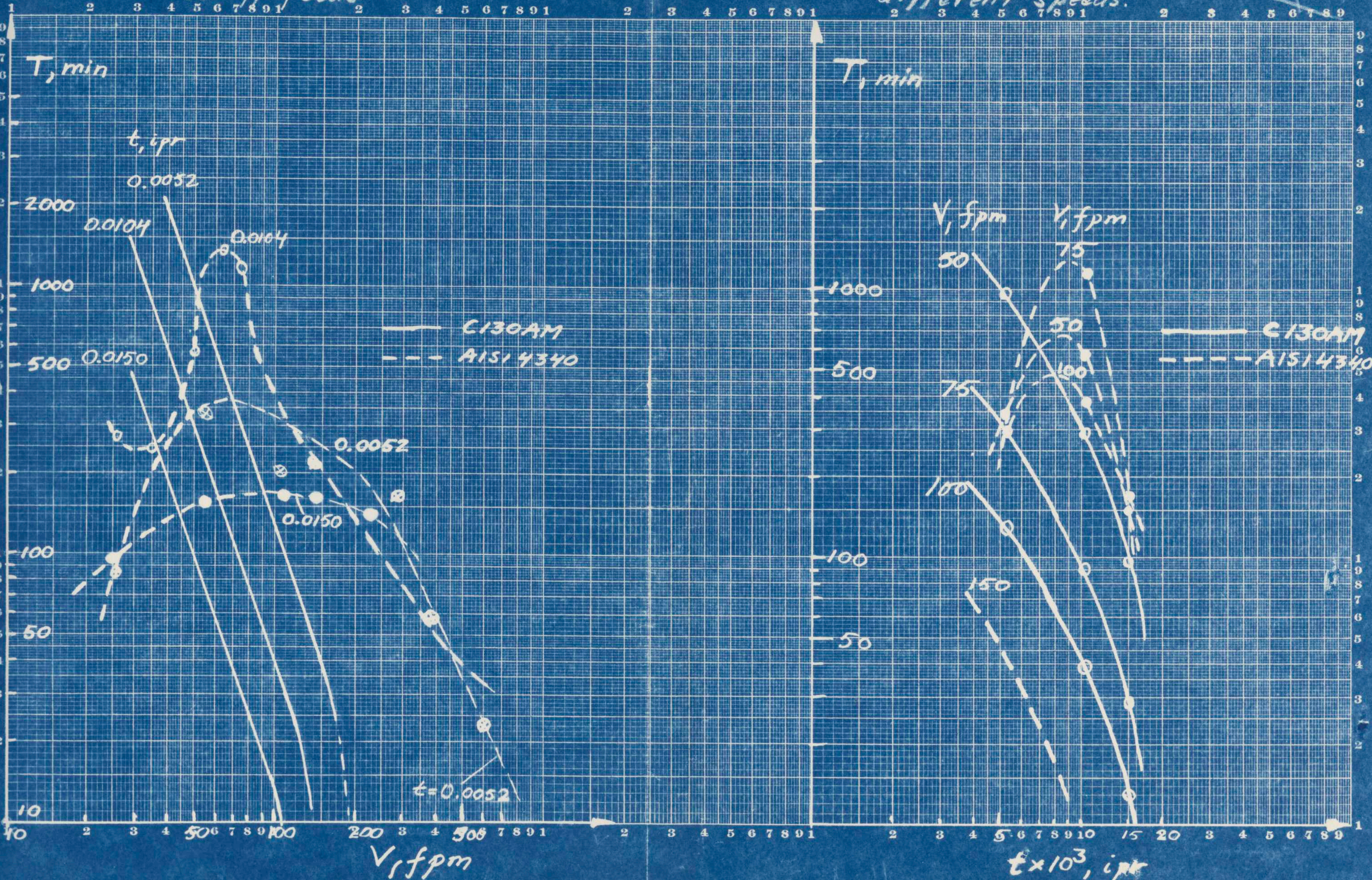


Fig. N. Results of similar tests as in Fig. M for AISI 1060, 1045, Cr-Ni-steel

Fig. O


a) Tool-life as function of speed for three diff. feeds
T, min
t, ipr
0.0052
0.0104
0.0150
0.0104
0.0052
0.0150
t=0.0052
C130AM
AISI 4340
V, fpm
b) Tool-life as function of feed for different speeds.
T, min
V, fpm
V, fpm
50
75
100
150
75
50
100
C130AM
AISI 4340
t×10³, ipr

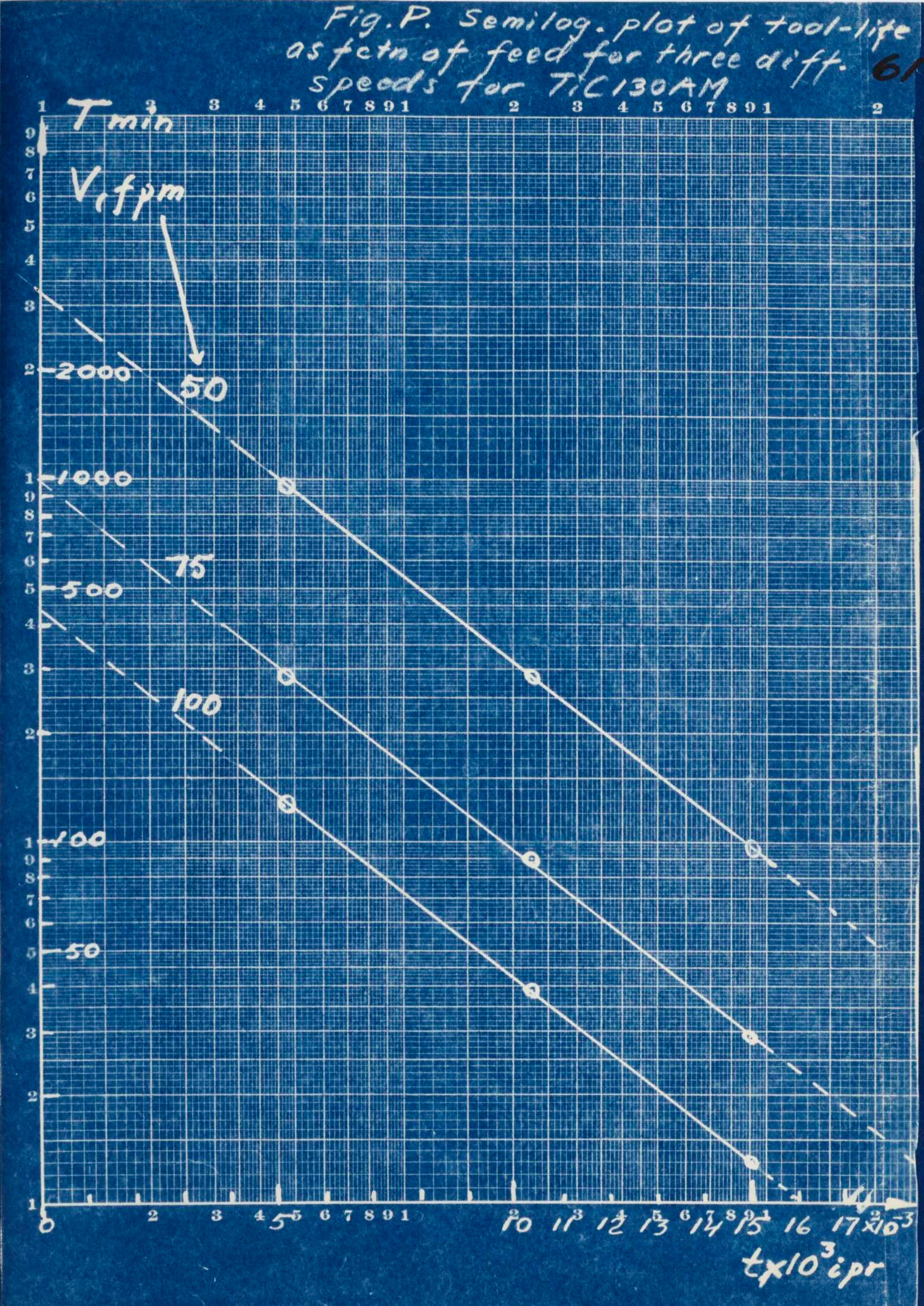
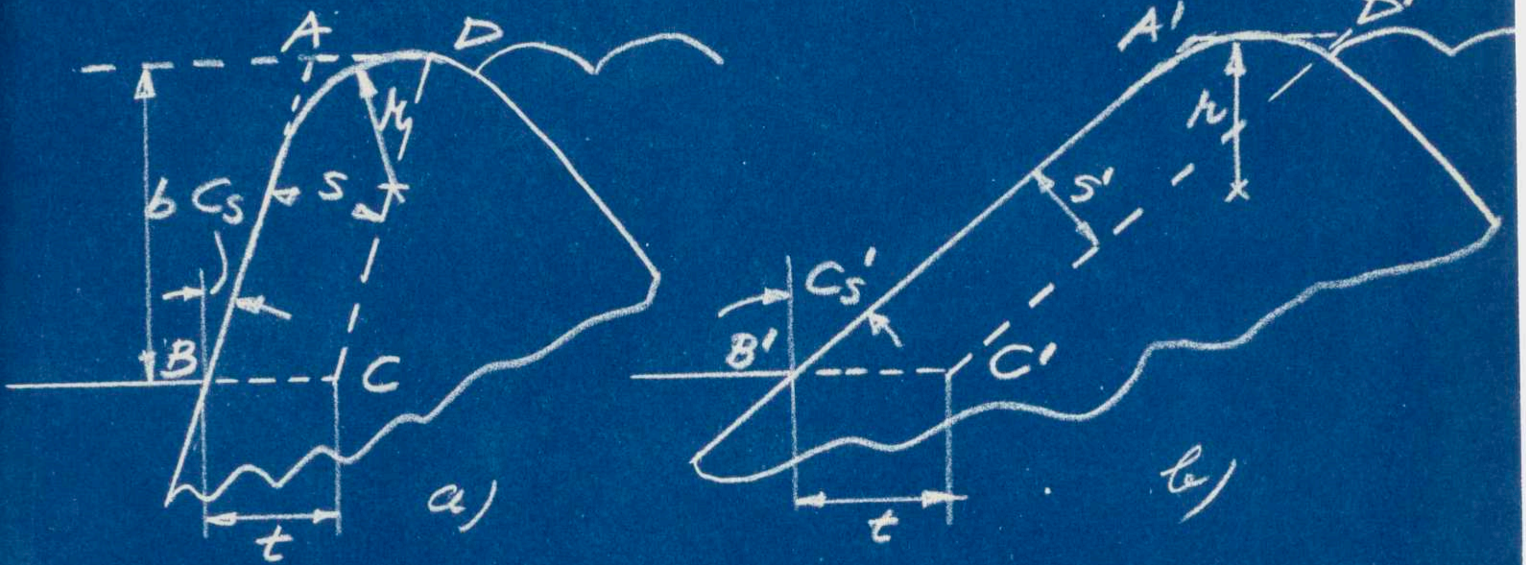


Fig. P. Semilog. plot of tool-life as fctn of feed for three diff. speeds for TiC130AM
61
T min
V, fpm
50
75
100
2000
1000
500
100
50
t x 10³ ipr

Fig. Q. Change of sidecutting edge angle



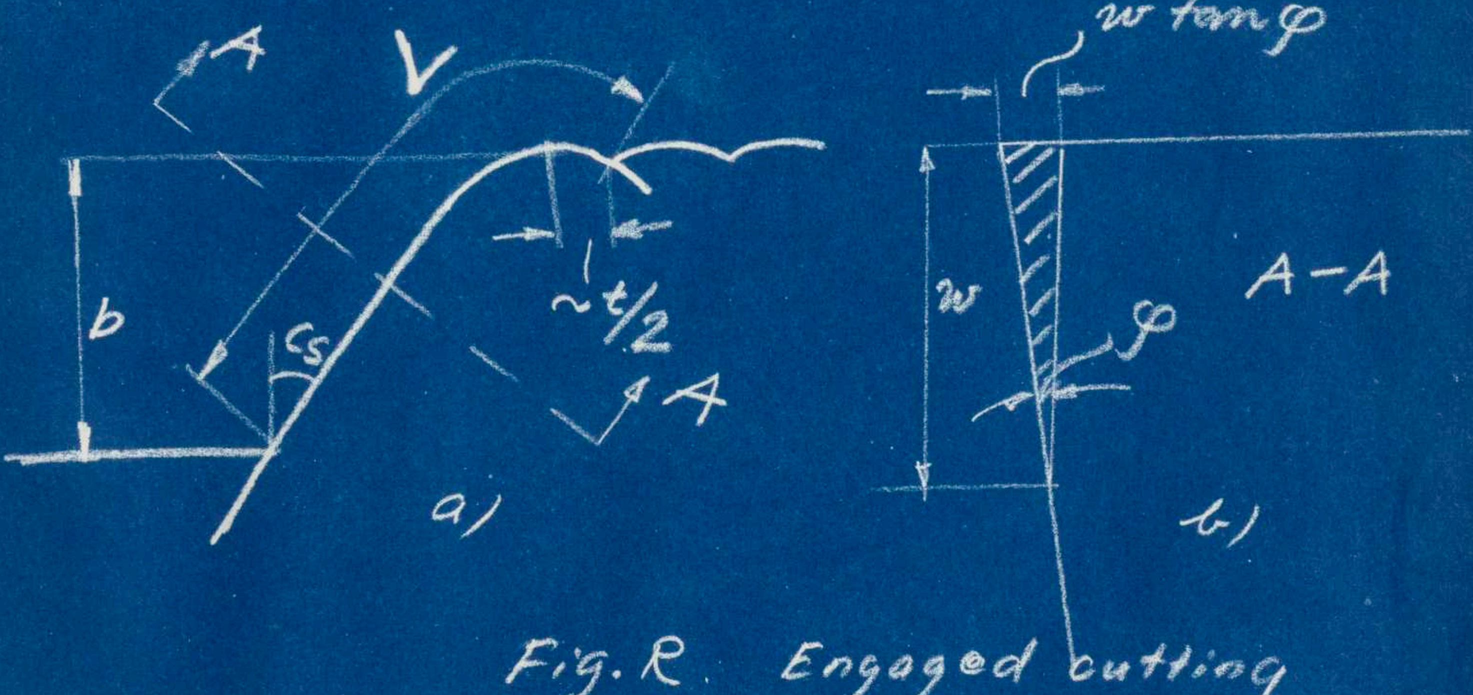


Fig. R Engaged cutting edge length, a), section through edge, b)

Fig. S. Rel. tool-lives when changing SCEA.

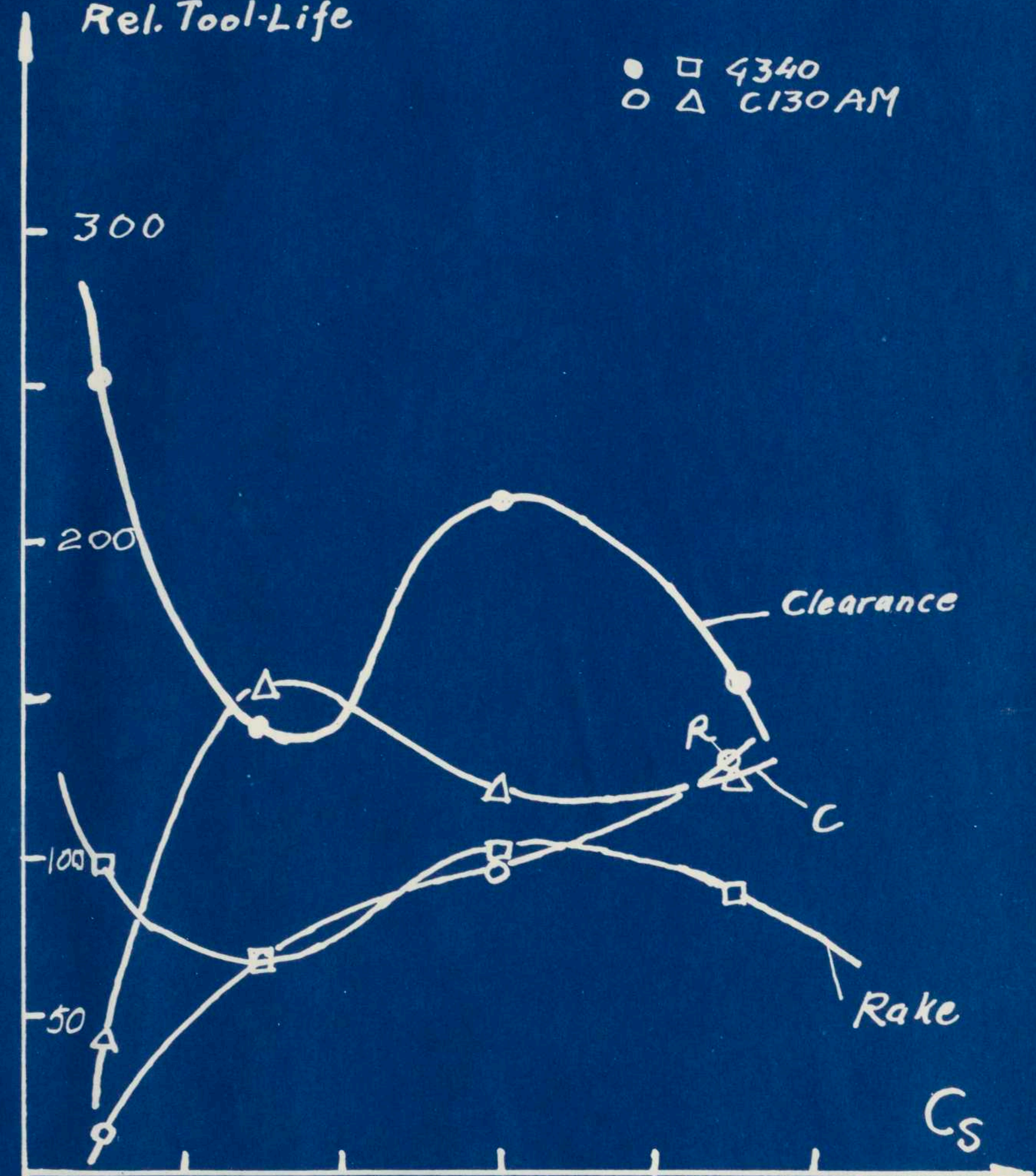


Fig. T. Rakê to clearance wear ratio for 4340 and C130AM when changing SCEA.