THE CHEMICO-PHYSICAL ACTION OF A CUTTING FLUID

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Introduction

A cutting fluid can be defined as any solid, liquid or gas applied to a cutting tool in order to control the quality of the surface produced or to alter the facility of metal removal. The idea of using a fluid in connection with a metal cutting process came very long after machine tools were in general use. In 1883, F. W. Taylor conceived the idea of using a cutting fluid and applied a stream of water to his carbon steel cutting tool (52). It was not until 1884 that a cutting fluid was first used commercially. The Midvale Steel Company employed a soda water system to cool tools engaged in rough turning operations. In 1900, the first oil in water emulsion was used as a cutting fluid (52).

Since 1900, those using machine tools have become more aware of the great benefits to be derived from the use of cutting fluids. At first, the chief function of the fluid was to keep the plain carbon steel tools cool. With the development of high speed steels, this initial duty became less important but other functions appeared. Recently, Ballard (5) has given the following list of duties of a cutting fluid:

1. To provide lubrication between the tool and the chip. (This would be more accurately described as the maintenance of an anti-adherent layer between the rubbing surfaces.)

2. To cool both the tool and the work.

3. To minimize the power consumed.

4. To increase the tool life.

5. To assure a good finish and accurate dimensions of the work piece.

6. To prevent corrosion.

7. To flush chips away from zone of cutting.

From about 1900 until the present time, greater and greater quantities of cutting fluids have been produced, until today, the production of these fluids is a large industry. During this period, very little has been done to explain the workings of a cutting fluid. Swift (86) sums up the condition of knowledge in the cutting fluid field by saying: "Up till the present time, no correlation has been established between the efficiency of a cutting lubricant and any other physical or chemical properties, and the only satisfactory method of assessment is by direct test with a cutting tool."

Almost without exception, the fluids which have been used to any extent have been mineral, animal or vegetable oils or oil in water emulsions. However, many instances are to be found in the literature where very unusual materials have been used for a particularly difficult job. For example, Kopp (67) reports the successful use of cows' milk as a cutting fluid for low carbon tungsten steel after the usual cutting oils had failed. Huffman (64), in a report on a survey of many industrial plants, says the following types

of fluids are in general use: emulsifiable oil, sulfurized mineral oil, sulfurized mineral plus vegetable oil, sulfurized vegetable oil plus mineral oil and straight mineral oil plus vegetable oil.

The cutting fluid literature is large and is limited entirely to engineering articles. In these papers, the authors do little more than describe equipment used in a specific application, describe tests involving so many uncontrolled variables that the data reported are almost worthless, or give the authors' ideas of the requirements of the ideal cutting fluid. After a comprehensive literature search, not one fundamental article dealing specifically with cutting fluid action was found. About a dozen cutting fluid references are given in the bibliography and these are typical of the many other existing papers.

Many authors say that it is necessary for a cutting fluid to have good lubricating properties (5) and claim that a good cutting fluid is one which assures a layer of fluid between the tool and the sliding chip, attributing the ability of a fluid to maintain such a film to a property of the liquid which they term "oiliness". Now, it is very unlikely that such a fluid will maintain a hydrodynamic film between the tool and the chip because of the extremely high pressures and temperatures involved in cutting processes together with the nature of the geometry of chip formation. It has been

shown (43) that in general no large gap between the chip and the work piece extends beyond the tool point. The chip follows the face of the tool very closely, and there is a labyrinth of small capillaries between these two surfaces. Such a condition is not favorable to the establishment of a hydrodynamic film. Cutting fluid action is therefore not akin to lubrication but belongs to that large class of problems unfortunately called problems of boundary lubrication. (The word "lubrication" naturally conveys the idea of a hydrodynamic film which is completely incorrect in the case of boundary lubrication). Since many of the problems involved in a study of cutting fluid action are the same as those which are met in boundary lubrication, a brief review of the literature in this field is given below.

The great value of a cutting fluid, from the standpoint of the finish produced is illustrated by fig. 1. Fig. 1-a is a photograph of an aluminum surface produced at a cutting speed of 5.5 inches per minute using n.decanol as a cutting fluid (a good cutting fluid at this speed), while fig. 1-b shows the surface formed at the same speed when benzene was the cutting fluid. Both of these surfaces were photographed forty times full size. By realizing the great values to be derived from the use of a cutting fluid, one of which is illustrated above, and the great lack of work done in the development of the theory and laws governing the actions of cutting

fluids, it is easily seen that such a problem offers an excellent field for research.

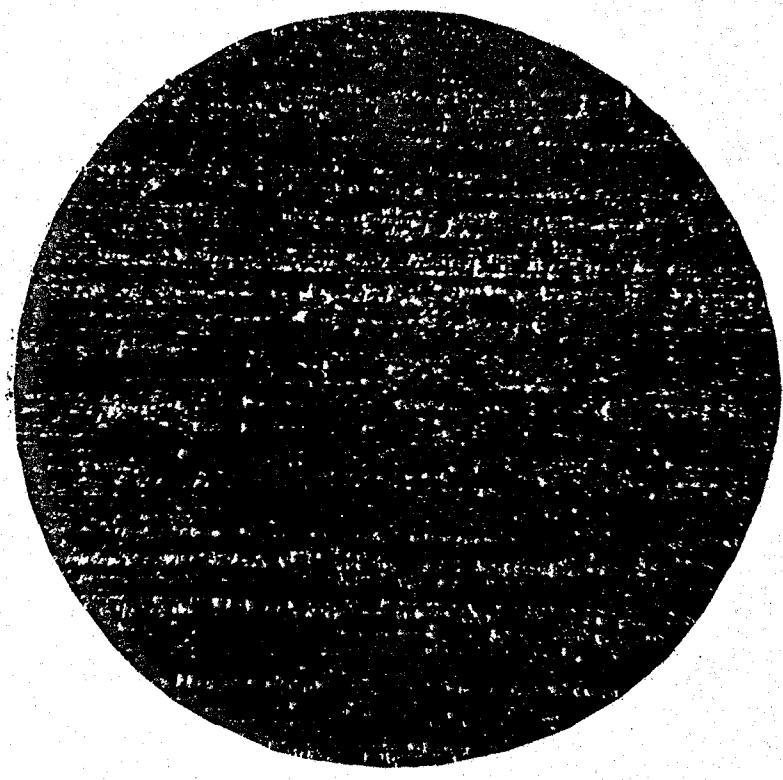


Fig. 1-a: Aluminum Surface Formed Using n.Decanol as the Cutting Fluid

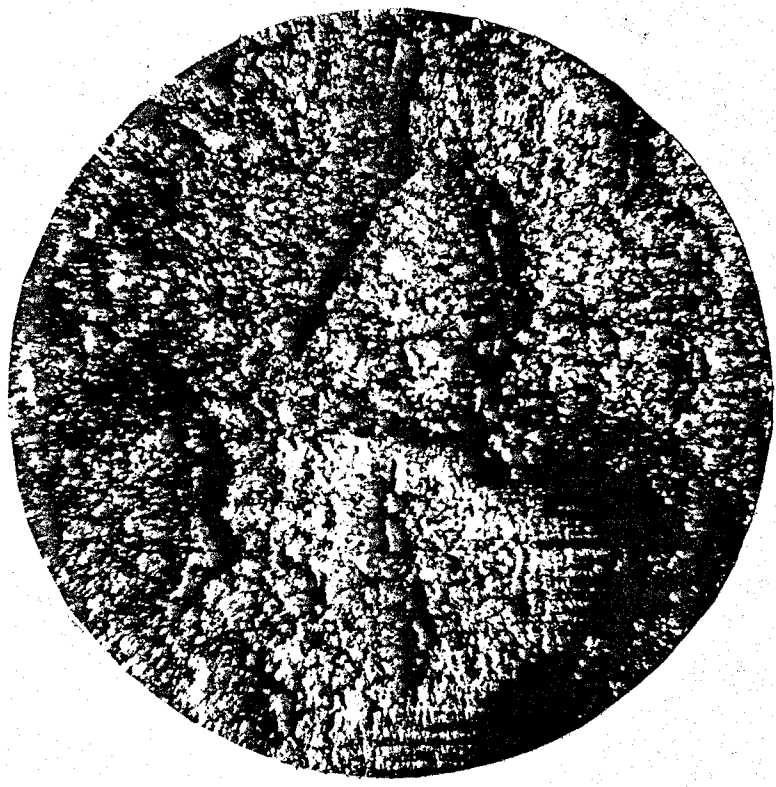


Fig. 1-b: Aluminum Surface Formed Using Benzene as the Cutting Fluid

Review of the Literature of Boundary Lubrication and Related Subjects

Introduction

The field of lubrication can be divided into two parts - fluid lubrication and boundary lubrication. Fluid lubrication usually occurs with relatively high sliding speeds and light loads. This true lubrication exists only when a hydrodynamic film is maintained continuously between the sliding parts. Boundary lubrication usually occurs with relatively low sliding speeds and high bearing pressures, and the moving surfaces are not completely or continuously separated by a fluid film. In fluid lubrication, the property of prime interest is the viscosity of the fluid while in boundary lubrication, both the physical and chemical properties of both fluid and surface are important (51). Oiliness is a property which is peculiar to boundary lubrication. It is defined by the Society of Automotive Engineers as that term signifying a difference in the friction greater than can be accounted for on the basis of viscosity when comparing different lubricants under identical test conditions. Kyropoulos (68) says that oiliness is not a fundamental physico-chemical property of a lubricant, but that it sums up all lubricating phenomena not entering into hydrodynamic theory. The origin of oiliness is the discontinuous nature of the structure of

matter, and a lubricant cannot be considered as a continuum in boundary lubrication.

The boundary lubrication problem seems to have been introduced by Lord Rayleigh (78) in an article in which he seeks an explanation of the fact that a teacup is more stable on a saucer if the base of the cup is first wetted. Hardy became interested in this problem and as a result started his famous investigation into the laws of sliding surfaces. A knowledge of friction existed, of course, very much earlier than this. In 1699, Amontons set forth his famous law which states that friction depends upon the normal force and is independent of the area. Coulomb, in 1785, claimed that practically all friction was due to the interlocking of surface irregularities. In 1854, Hirn first noted the effect of a lubricant upon friction. In 1892, Ewing put forth the idea that friction is due only to the interaction of surface forces. Hardy's work dated from about 1920. He studied the static friction of various materials both with and without a lubricant. Since Hardy, there have been many workers in the field of friction and boundary lubrication, but Bowden and his co-workers are the outstanding group in this period.

The Nature of Friction and Boundary Lubrication

The exact nature of boundary lubrication is not known, but it is known that the coefficient of static friction is related to this quality of a lubricant (46), and therefore friction is very closely connected with any study of boundary lubrication.

Hardy's theory maintains that friction is due to the interaction between the surface layers of the adsorbed films of a lubricant. Hardy (60) says that all resistance to slipping is due to cohesion and he maintains that when a film is present, there is no metal to metal contact, the only contact being between the stable ends of the adsorbed molecules. A lubricant decreases friction by partially masking the cohesive forces of the solid surfaces. Hardy (60) says that the function of a lubricant is opposite to that of a flux.

According to Adam (1), the surface atoms have a field of force extending outward a distance of 1 to 3 Å which decreases as the sixth power of the distance from the surface. Adam (1) pictures welding and subsequent rupture of the high spots on the surfaces at a high rate of speed. He gives 10^{-4} seconds as a likely value for a cycle when the sliding speed is 100 cm/sec.

Beeck (11) says that surface irregularities are greater than the thickness of a boundary layer and that, due to the

high local pressures developed at high points, even monomolecular layers will not stand up and metal to metal contact will occur. High temperatures at local contact points will cause decomposition of trapped molecules and the polar groups will react with the metal surface at these points.

Bikerman (13) believes that friction is due entirely to surface roughness. He says that friction cannot be due to welding of high spots and cites the friction of wood on wood and wood on platinum as cases which are difficult to explain on the basis of adhesion.

Concerning the mechanism of boundary lubrication Bowden and Leben (18) write: "It seems probable that metal is deformed plastically and flows until a joint is formed that is capable of supporting the load. As a result of the deformation, a film of lubricant will be trapped between the two metal surfaces and there subjected to a very high pressure. It is reasonable to suppose that under a sufficiently high pressure, the lubricant film can be broken down allowing the metal surfaces to come into contact and weld together. Only a portion of the lubricant film in the region of contact (the most compressed portion) will be broken down and the extent of breakdown and subsequent seizure will vary for different lubricants. The formation of these metallic joints will greatly increase the resistance to motion, and the extent to which breakdown of the film occurs will therefore largely

determine the nature and magnitude of the friction force necessary to maintain sliding. Differences in the nature of sliding would be expected for different lubricants. According to this view, the frictional behavior and the wear between the lubricated surfaces are largely determined by the ability of the lubricant film to prevent metallic contact." Bowden and Leben thus claim that fluids which "break down" will give poor results.

Bowden and Leben (18) explain the action of an acid in reducing frictional resistance by saying that the carboxyl group of the acid makes it polar and that this end group is adsorbed strongly on the surface. Southcombe and his coworkers (85) say that all extreme pressure addition agents (in E. P. oils) are characterized by their chemical instability at high temperatures and that it would appear that this instability is essential to their operation. Concerning this question, Adam (1) states that if a fluid decomposes, it is useless or worse than useless. Fogg and Hunwicks (46) describe tests they made in order to see if fluids act by chemical means. They allowed the metal to stand in the fluid overnight in order to determine if it would be attacked by the fluid. Upon noting no change, they thereupon concluded that there was no chemical action when this fluid was used as a boundary lubricant. Such a conclusion is not correct,

for the conditions of the tests were widely different from those existing in the extreme boundary state. When two surfaces are moved relatively, with a boundary film between them, high temperatures and pressures are developed at the surface together with the production of considerable new (nascent) surface. The reactivity of a metal and a fluid will in general vary greatly under these two widely different sets of conditions.

Clark and his co-workers (35), Andrew (3), and Finch and Zahoorbux (45) have made X-Ray and electron diffraction studies of various types of films adsorbed on metallic surfaces. These workers claim that they can correlate the degree of orientation of the film with its effectiveness as a boundary lubricant. Little convincing work has been done in this field, and the writer believes that the methods are too new and incompletely developed to be sure of the results claimed.

Beare and Bowden (9) show that actual contact between surfaces occurs even when a fluid film is present and that the solid surfaces are torn and distorted far into the body of the metal. Thus, friction is not a surface phenomenon but affects the body of the metal far below the surface.

Blok (15) says that there are two types of boundary lubricants - those which act by chemical means (sulfur, chlorine and phosphorous compounds) and those which act by

physical means. The former changes the upper layer of metal and prevents seizure by anti-flux action during actual sliding, little or no chemical action occurring with the surface at room temperature and atmospheric pressure. Usually the chemical reaction occurring is non-reversible and the chemical product is expendible.

Hardy (53) claims that two surfaces separated by a fluid film will sink to an equilibrium position depending upon the load. Each load has an equilibrium value equal to the distance at which the capillary pressure (Leslie's pressure) is just balanced by the load. Bastow and Bowden (8) say that they could find no Leslie effect when clean air and clean vapors were employed. They explain the separation observed by Hardy as due to dust particles.

Hardy (53) also reported a latent period - a period after which the coefficient of friction does not change with time due to either the establishment of the Leslie pressure equilibrium or to the orientation of the lubricant molecules. Hardy found a latent period for polar fluids only. Andrew (3) reports increased orientation of a film on a surface with time as measured by electron diffraction methods. Beare and Bowden (9) could find no evidence of a latent period. This latent period may be the time required for sufficient reaction to occur to supply the quantity of product needed to decrease the frictional resistance to its lower observed equilibrium value.

Bowden and his co-workers report a condition which they call stick-slip. They say that sliding is discontinuous - that kinetic friction is made up of a large number of cycles in which the two members stick together followed by a slip. This slip takes place in about 1/1000 second and the total motion is of the order of 0.003 cm. The magnitude of the slip was found to be less as the melting point of the stationary member was decreased. Bowden and Leben (20) say that stick-slip occurs with poor fluids (benzene, water, hydrocarbons, alcohols, etc.) but does not occur with more effective boundary lubricants (long chain fatty acids, etc.) These authors report that no relation could be found between the hardness of the metal and its stick-slip action.

Bowden, Leben and Tabor (21) say there are three types of sliding. First, the sliding of a hard metal on a soft metal (molybdenum on steel). In this type of sliding, the hard metal moves into the softer one until enough load is on it to plow through. The second type of sliding occurs when a lower melting metal slides upon one with a higher melting point. In this case, the stick-slip is much more pronounced, the fluctuations are much greater and there is more smearing. The third type of sliding occurs when identical metals are employed. In this case, the coefficient of friction is very high and there are large irregular fluctuations.

When platinum slides on silver, the initial coefficient

of friction is about 0.6 and the sliding is of type 1 variety. Soon, however, type 1 gives way to type 3 and the coefficient of friction increases to about 1.5, the fluctuations being great and irregular. In this example, at first the coefficient of friction of platinum sliding on silver is being measured and thus the sliding is type 1. After a short time, a layer of silver builds up on the platinum and the sliding is, in effect, that of silver on silver (type 3). The coefficient of friction for silver on silver is 1.5. In metal cutting, type 3 sliding is probably the type which obtains, particularly when a built-up edge is present on the nose of the tool.

Bikerman (13) says that stick-slip has no bearing upon the mechanism of friction. Blok (15) shows that stick-slip is a characteristic of the particular mechanical apparatus used in the investigation and not a fundamental frictional phenomenon.

Lubricated and Unlubricated Friction Tests

The boundary lubrication literature contains a great deal of actual data, coefficients of friction for both lubricated and unlubricated surfaces being given. It would be impractical to give all of the data and deductions furnished by each author in this brief review of the literature. Only those few actual friction values which will prove to be of

interest later will be given here.

Bowden and Hughes (25) point out the difficulty experienced in getting values of the coefficient of friction between absolutely clean surfaces. They report a value of 6 for clean, outgassed nickel surface sliding on tungsten. This is twenty times the usual value for an ordinary "clean" surface. These authors also show that the presence of oxygen lowers the coefficient of friction.

Ernst and Merchant (42) state that the coefficient of friction is little affected by the roughness of the surface for clean surfaces. They give many values for the coefficient of friction for clean like metal pairs as well as for unlike metal pairs. It was found in general that the mixed pairs for mutually soluble metals gave higher values than the mixed pairs for insoluble metals. These authors report the coefficient of friction for aluminum on aluminum as 1.05 and for aluminum on iron also as 1.05.

Beare and Bowden (9) have made the following observations on the friction of lubricated surfaces:

1. The coefficient of friction is independent of the sliding velocity (from 5 cm/sec to 600 cm/sec).
2. The coefficient of friction is independent of the area of contact.
3. The coefficient of friction varies with the load in two ways:
   a) Remains constant with load (for example when octane, tetradecane, cetyl iodide, ethyl palmitate, or bayonne oil are used).
   b) Decreases with load (for example when octanol, heptylic acid, oleic acid or rape oil are used).

These authors say that there is no satisfactory explanation for this phenomenon and that it cannot be explained on the basis of polarity or viscosity. It was also found by these authors that there was no change in the coefficient of friction with load when octanol or heptylic acid were used on glass surfaces. Might not all of these findings be explained by the fact that the chemical reactivity increases as the pressure and temperature between the surfaces are increased? Those compounds which show no change in the coefficient of friction with load are rather chemically inert. No change in the coefficient of friction with load would be expected for glass surfaces even with the more chemically active alcohols and acids.

4. The coefficient of friction decreases (not linearly however) with increase in the length of an alkyl chain.

5. Abrasion of the rubbing surfaces was noted even with the best fluids, thus indicating that actual metal to metal contact occurs at all times.

Bowden and Leben (18) made tests with thin films produced by the Langmuir - Blodgett technique. They found that the rate of rise of the coefficient of friction increased rapidly as the number of layers deposited decreased.

Hardy has done a considerable amount of work in the field of static friction of lubricated surfaces. A few of Hardy's many deductions are given below:

1. Glycerol, water and benzene are neutral substances and do not appreciably lower the coefficient of friction (57).

2. When water is present and is miscible with a fluid, the coefficient of friction is increased by the presence of the water. However, if water is immiscible with the fluid, the coefficient of friction is decreased (57). Campbell (32) has also reported a rise in the coefficient of friction when moisture is adsorbed on a surface.

3. Hardy (56) gives the following formula for the coefficient of friction (μ) of any homologous series:

$$\mu = b - aM$$

where "b" is a constant for any homologous series-solid surface combination, "a" is a constant for a given homologous series, and "M" is the molecular weight of the fluid.

This equation says that the relation between μ and "M" is linear and does not agree with either the findings of Bowden and Leben (18) or with the writer's data. Both Hardy and Bowden plot their data against the molecular weight. The writer believes such curves have much more meaning when plotted against the number of carbon atoms in the molecule.

4. No ring compound is a good lubricant (60).

Hardy makes many other observations which, in the writer's opinion, are based upon insufficient data (some statements are based on one or two isolated examples) or the basis for the observation is unsound. For example, in making a certain deduction, Hardy compares a ketonic double bond (= O) with an olefinic double bond, treating them as though they were

alike. While Hardy's work is not entirely correct and has been much criticized both here and by other writers, it must be remembered that he was a pioneer in this field and as such, did not have the literature advantage which all present workers possess.

The Temperature of Sliding Surfaces

The actual temperatures at the interface between two sliding surfaces may reach quite high values, depending upon the surface speed, the load, and the physical constants of the metal (hardness, melting point and heat conductivity).

Shore (84) seems to have been the first one to employ the thermoelectric principle to measure the surface temperature developed between sliding surfaces. He cut metal with a steel tool and made the tool - work interface one junction of a thermoelectric circuit. Shore showed that the cutting pressure had no effect upon the e.m.f. generated. In cutting brass at 16'/min., Shore reports a temperature rise of from 42° to 106°C depending upon the depth of cut. For steel cut at 13.5'/min., the temperature rise was from 112° to 292°C. Herbert (63) has also made numerous tests using the thermoelectric method to measure cutting temperatures. Herbert reports surface temperatures up to 700°C for steel. Temperatures were found to increase with the cutting speed.

Bowden and Ridler (29) calculated hypothetical surface temperatures based upon the following conditions: Load = 100 grams, diameter of specimen = 1mm., velocity of sliding = 100 cm/sec., coefficient of friction = 0.23 and heat distributing factor = 1/2. Based upon these assumptions, the following data were calculated:

Fraction of Surface Area in Contact	Calculated Temperature Rise °C
1	75
1/10	414
1/100	2372

Bowden and Ridler (30) measured the surface temperature of sliding metal pairs using the thermoelectric method. With fusible metals, the temperature reached was that of the lower melting metal. The following data for lead (melting point 328°C) are typical.

Sliding Speed cm/sec	Surface Temperature °C
0	17
15.8	42
48.4	54
134	215
485	327
720	327
1570	327

Bowden and Ridler (29) report a rise of surface temperature which is directly proportional to the load and to the sliding speed (except near the melting point), but inversely proportional to the square root of the thermal conductivity. For a lubricated surface, the rise in temperature is propor-

tional to the coefficient of friction, and the film is continually destroyed and reformed during sliding. Local temperatures may exceed 1000°C, and even when a boundary lubricant is present, the temperatures may exceed 600°C.

Morgan and his co-workers (76) claim that the local surface temperatures reached during sliding, as given by Bowden et. al., are too high due to the shunting effect of parallel couples formed during sliding. These authors report that in no case did they find temperature rises beyond 50°C.

Macaulay (71) introduced the idea that in polishing, temperatures sufficient to cause surface melting are produced. The lower melting metals lose the most weight during polishing. The amount of surface flow is governed not by the properties of the solids at room temperature but by their relative mechanical properties at the higher temperature of the sliding surfaces. It is shown that only 1/100,000 of the frictional heat is required to melt ten monolayers, thus producing the Beilby layer (the layer of flowed metal on a polished surface). Bowden points out that the hardness of a polishing medium is not the important criterion but rather its melting point relative to the surface being polished.

The Real Area of Contact

Beeck (10) points out that the area of contact between two surfaces depends only on the load; it is independent of the size, shape and roughness of the surface. The real area of contact varies as the normal load. The pressure developed is a constant for any given material (22) and is equal to the hardness of the metal.

Bowden and Tabor (22) say that in friction, the plastic and not the elastic theory holds. From conductivity experiments, it was found that all of the deformed surface was in contact. Bowden and Tabor (22) give the following interesting data:

Load	Fraction of Macro Area in Contact
300	1/300
100	1/700
20	1/10,000
3	1/170,000

It was further found that there was considerable variation in the area of contact with moving surfaces.

Wear and Wear Prevention

Bowden and Leben (18) say that the rate of wear is greatly increased as the thickness of the fluid film is decreased. Beeck (10) claims that there is no relation between the coefficient of friction and wear. Beeck (12) further says that

wear preventing agents act by a chemical polishing action in which the load is distributed over a larger surface and the pressure and temperature thus decreased. The practice of using an antiweld material (S, P, or Cl) adds corrosive wear to mechanical wear. If only the high spots are corroded away, then we have a temperature preferential polishing agent. Beeck explains this preferential polishing on the basis of a eutectic theory of wear prevention. With tricresylphosphate, a phosphide layer is formed which alloys with the metallic surface, lowering the melting point and making polishing easier. The same wear preventing agent will obviously not be good for all metals. Beeck carefully distinguishes between extreme pressure agents and polishing agents. He says extreme pressure agents must of necessity be corrosive in their action.

Brownsdon (31) has devised a simple test for quickly measuring the wear producing properties of a fluid. He rotates a crowned hardened steel disc against a plane metal plate in the presence of the fluid, measuring the length of the elliptical wear pattern after a given standard running time. The axis of the disc is kept parallel to the plane metal surface. Brownsdon reports that with a brass plate, no reduction in wear is found with acetone, petroleum ether or benzene. Most of Brownsdon's very interesting data are, unfortunately, for mixtures of fluids and complicated oils.

Statement of the Theories Held Concerning the Chemico-Physical Action of a Cutting Fluid

In order that the following work may be more easily interpreted and more effectively discussed, a brief statement of the position taken by the writer is inserted at this point. Here an attempt will be made to give a broad description of the principles which the forthcoming data are meant to substantiate.

The fact that cutting fluid action cannot be accounted for on the basis of hydrodynamic theory has already been pointed out. The nature of cutting fluid action is rather that of "very extreme boundary lubrication". The field of boundary lubrication is a very broad and ever widening one. It is generally understood to include all problems involving the reduction of the resistance to sliding, experienced by rubbing surfaces which make direct contact. Blok (15) has divided boundary lubrication into four main types on the basis of the existing temperature and pressure:

1. Low pressure and temperature boundary lubrication which he calls "Mild Boundary Lubrication".
2. High Temperature Boundary Lubrication.
3. High Pressure Boundary Lubrication.
4. High Pressure and Temperature boundary lubrication called "Extreme Boundary Lubrication".

The first two of these types are represented by lightly loaded, sliding surfaces at low and high temperature. The chief requisite for an effective fluid for these two low pressure types of boundary lubrication is that the compound be highly polar and capable of being strongly bonded to the surfaces. These two classes of boundary lubrication can be explained in terms of the same mechanism, the effect of increased temperature upon the stability of the boundary layer being just an additional consideration.

A very much different mechanism will hold for the latter two types of boundary lubrication. Under such high pressure, there will be a condition of much more concentrated contact between the surfaces. A physically bonded surface layer would not be capable of withstanding the very high pressures involved and therefore another theory of action must be considered. Under high local pressure, it is quite feasible that certain fluids will react with the metal, giving a reaction product between the sliding surfaces. Organometallic compounds or metal salts are generally solids and are thus capable of withstanding very much higher pressures than liquids. In general, metal compounds have much lower shear strengths than the corresponding metals and hence the cutting force will be considerably reduced if metal to metal contact is decreased by the formation of such a metal compound

between the sliding surfaces. The same general mechanism can be considered to hold for both boundary lubrication types 3 and 4, the only difference being that some fluids will become effective at a much lower temperature than others.

In addition to temperature and pressure, a third variable should be considered in the classification of boundary lubricants. This third quantity is the amount of fresh metal surface produced. The amount of nascent surface present will have an important bearing upon the chemical reactions taking place between the metal and the fluid. In boundary lubrication types 1 and 2, the amount of fresh metal surface formed will be a minimum since the actual area of contact is small due to the relatively low loads involved. In types 3 and 4, contact is more complete because of the higher pressures and therefore, the amount of nascent surface produced during sliding will be greater. In the case of metal cutting, the amount of freshly formed surface will be a maximum since all of the cut surface is nascent at the instant of rupture.

It is thus clear that cutting fluid action occupies one small corner of the huge field of boundary lubrication. In metal cutting, extreme pressures are involved (pressures up to the hardness of the metal cut), the surface temperatures

will vary from moderate values to very high values (up to the melting point of the metal being cut) depending upon the cutting speed, and all of the newly formed chip surface will be in a nascent state. Thus, it appears that the only type of mechanism feasible in cutting fluid action is the one in which the fluid reacts chemically with the newly formed metal. This mechanism has been termed chemico-physical because the action is initiated by a chemical reaction between the fluid and the nascent surface and is followed by the decrease in frictional resistance accounted for by the relative shear strengths of the metal compound and of the work material.

Experimental Part

Each of the various pieces of apparatus employed in the cutting fluid investigation is described below. The low speed cutting tests involved a planer type of cut, while the tests made at higher speeds used a fly type of milling cutter. In all tests the tools were made of 18-4-1 high speed steel. The "rake angle" of these tools was always 15° unless otherwise specified and the clearance angle was 5°. Tools were checked frequently for dulling by means of a standard fluid (carbon tetrachloride) and when necessary, were reground on a universal tool grinder.

Simple Planer Apparatus

The first cutting tests were made using a relatively simple set-up in which metal could be removed at various cutting speeds by means of a planer tool. A diagramatic sketch of this first apparatus is shown in fig. 2. A No. 4 Plain High Power Cincinnati Milling Machine was the basis for this apparatus. The cutting tool was held firmly by means of a holder which was fastened to the overarm of the machine. The work piece was clamped to the table of the machine and was fed against the stationary tool by means of the table feed. The cutting speeds available were those of the table feed which ranged from 1 inch per minute to 125 inches per

minute (the rapid traverse). Most of the tests were made at a cutting speed of 5.5 inches per minute. The depth of cut was adjusted before each cut by raising the table by means of the vertical feed screw. The depth of cut used was 0.005 inch in nearly all cases.

The horizontal component of the cutting force was measured by noting the deflection of the tool block relative to the column of the machine. This deflection was measured by means of a dial type indicator reading in units of 1/10,000 inch. A preloading device was used to take up any lost motion in the entire dynamometer set-up and to obtain a linear relationship between load and deflection. The assembled apparatus was calibrated by putting known horizontal loads on the cutting tool and noting the corresponding deflection of the indicator.

The fluid tested was introduced between the chip removed and the tool face by means of a dropper. The work piece was 3 inches long and 1/4 inch wide in all cases. Each chip removed was recovered and saved and the length of the chip was subsequently measured. This chip length was determined by means of a specially constructed phosphor bronze spiral scale. The scale was hooked to the chip and made to follow its contour (usually some sort of spiral), the length being read from the scale at the far end of the chip.

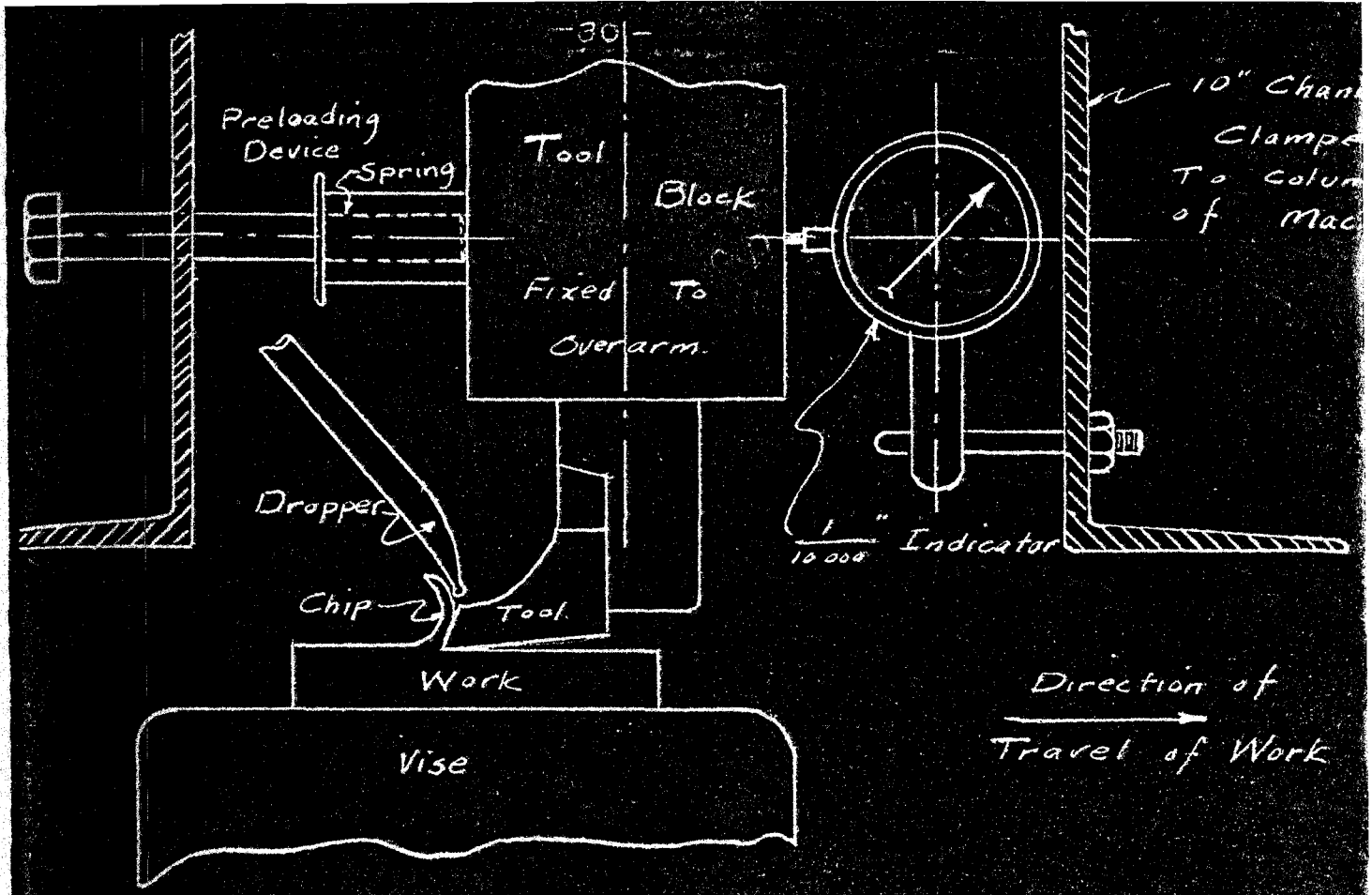


Fig. 2.

Simple Planer Apparatus

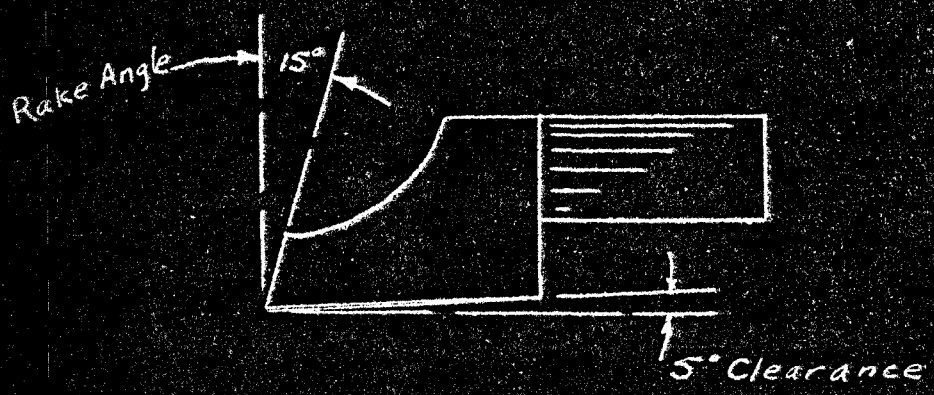


Fig 3.

Finishing Type Planer Tool

The tools used in all of these tests were planer type finishing tools. A sketch of such a tool is shown in fig. 3. The apparatus described above will be referred to henceforth as "the simple planer apparatus".

High Speed Turning Apparatus

A few tests were made using the No. 4 high power milling machine mentioned above with the same type of planer tool but this time, the cutting operation was that of turning. The arrangement of the apparatus is shown roughly in fig. 4. The work piece was slotted and clamped to the spindle of the machine. Rotation was as shown in the figure and the tool was fixed rigidly to the table. The cutting speed was variable from 120 to 2500 inches per minute by changing the speed of rotation of the spindle. The diameter of swing of the work was kept approximately constant by sliding the work piece out after every few cuts. The tool was fed down 0.005" after each cut by means of the table vertical feed screw. The fluid was applied by means of a dropper. It should be noted that with this arrangement, the rake angle and clearance angle will be slightly different from those given in fig. 3, due to the curved path of the work piece.

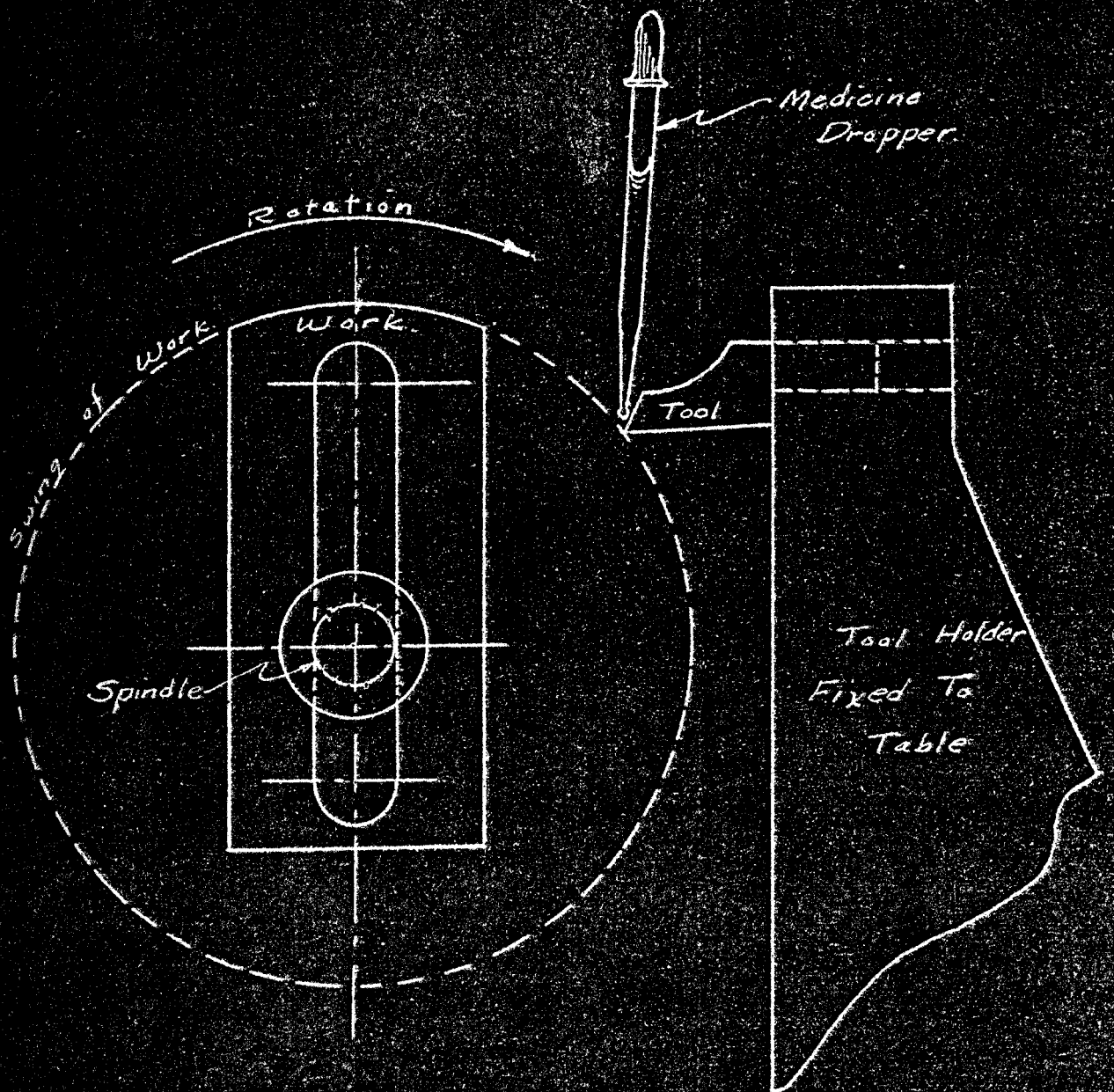


Fig. 4.

High Speed Turning Apparatus.

Improved Planer Apparatus

A more elaborate apparatus was constructed to test the cutting fluid action of very pure samples of organic chemicals. The basis for this new equipment was a new 0-8 Cincinnati Milling Machine. Fundamentally, this apparatus is the same as the simpler model, but in this new device, much more sensitive dynamometers are used. The tool is fixed to the overarm of the machine by means of a dynamometer which is capable of deflecting in the horizontal direction only. The deflection is read by means of a 1/10,000 inch dial type indicator, each division of which represents a horizontal force of 5.65 pounds. The same type of cutting tool is used in this apparatus as was employed in the simple planer apparatus. Fig. 5 is a drawing of the improved planer apparatus.

The work piece is carried by a second dynamometer which is used to measure the vertical component of the resultant force. This dynamometer is not independent of horizontal loads and a correction must be made for the horizontal component of the force which is present. The deflection of this dynamometer is likewise measured by means of a 1/10,000 inch dial type indicator, each division of which represents a vertical force of 2.70 pounds. The vertical component of the force varies a small amount with the height of the work surface above the dynamometer, but this variation is easily allowed for by a correction.

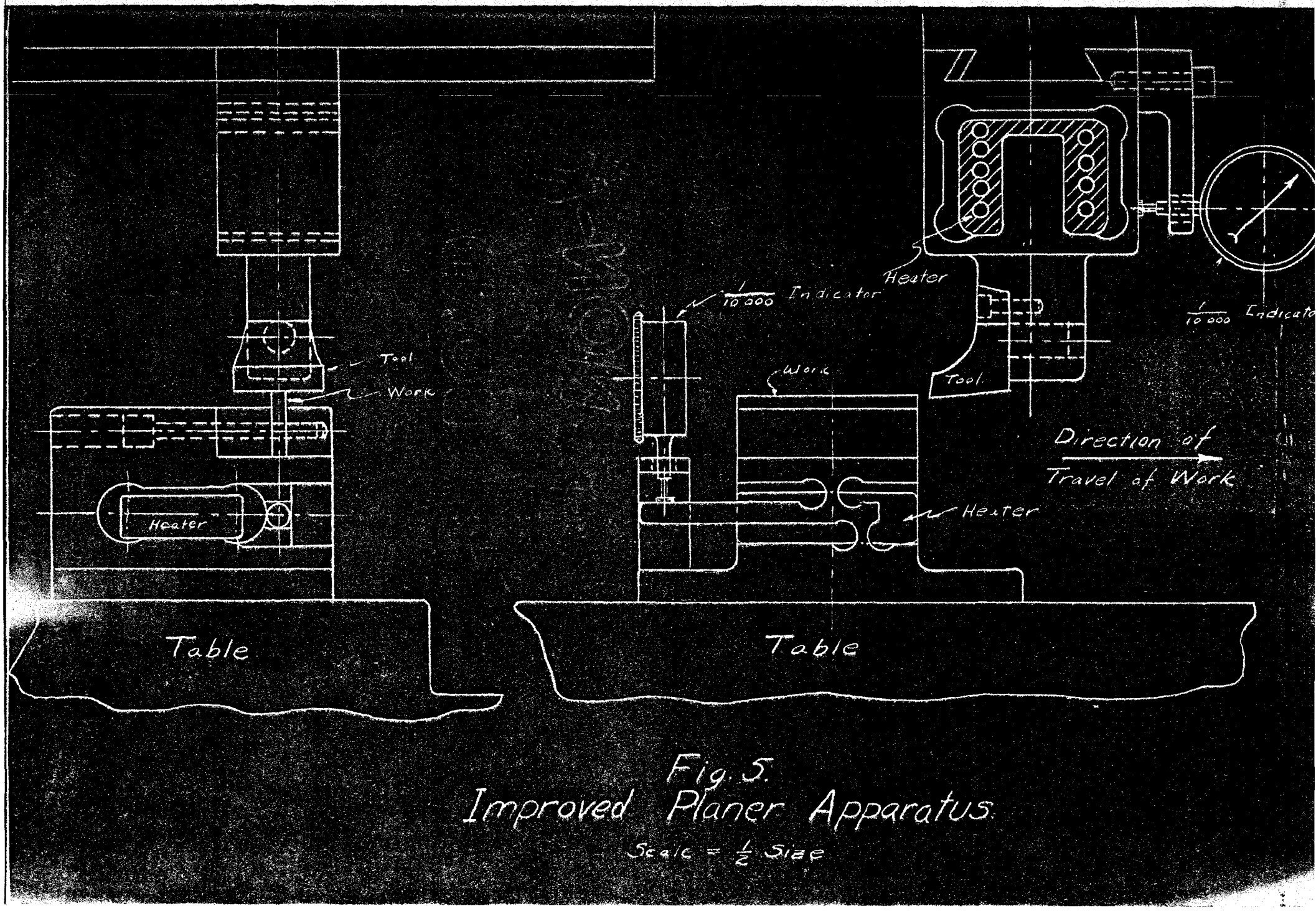


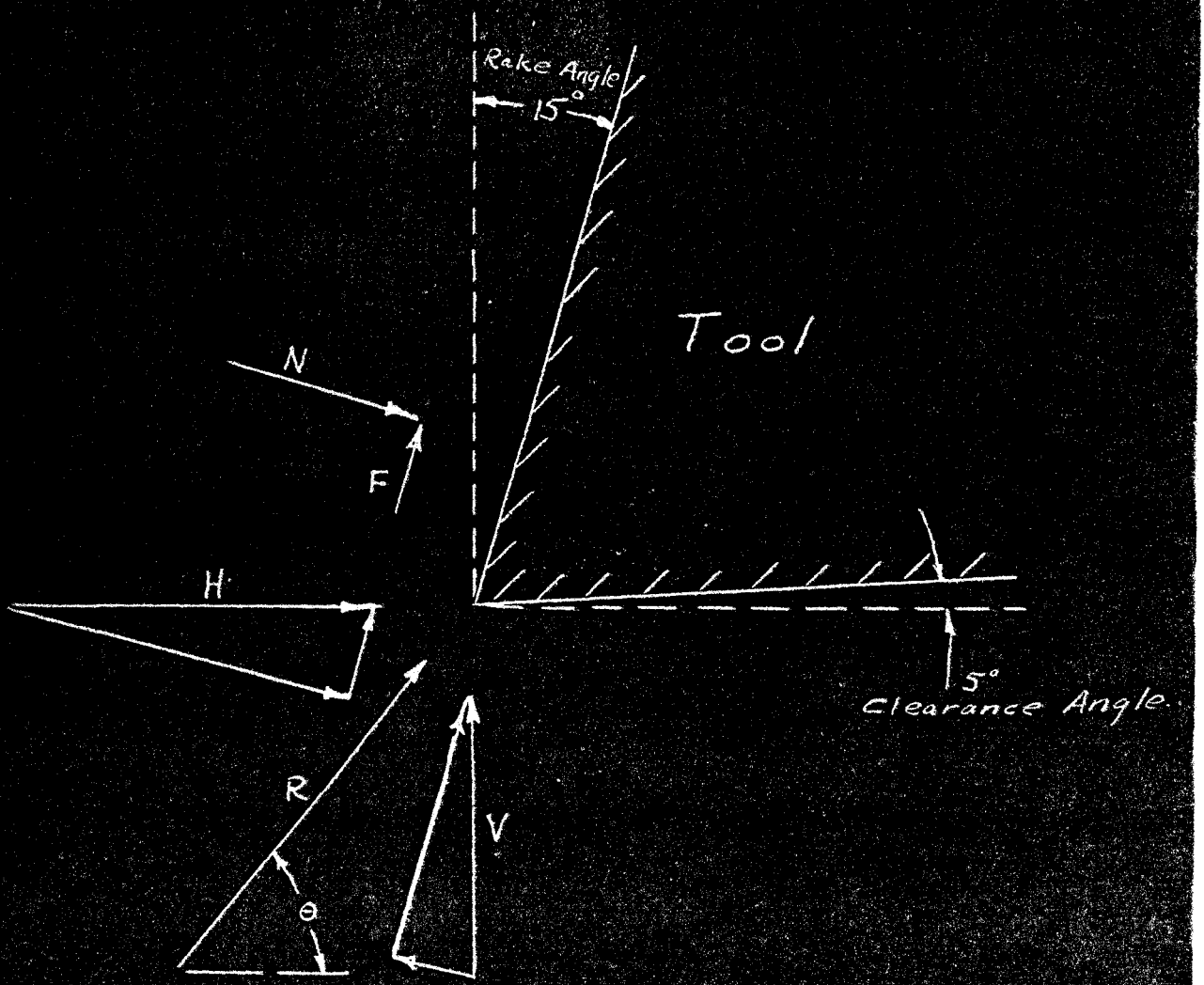
Fig. 5.
Improved Planer Apparatus.
Scale = 1/2 Size

This improved apparatus has been designed for cutting tests with pure aluminum. In order to make the sensitivity of this apparatus a maximum, it was necessary to fix the upper limits of the force components to values slightly greater than those obtained when cutting aluminum. Hence, this apparatus cannot be used for cutting tests with steel or other hard metals. This apparatus was designed for a 0.005 inch depth of cut and the cutting speed is 4.85 inches per minute.

Both the tool and the work dynamometers are equipped with heaters so that their temperatures may be varied independently. The entire apparatus is surrounded by a sheet metal hood which is connected to an efficient exhaust fan. Thus, obnoxious organic vapors are quickly disposed of.

With this improved planer apparatus, it is possible to calculate the coefficient of friction involved when aluminum is cut in the presence of any cutting fluid. In fig. 6, the forces acting on the planer tool are shown, together with their relation to the coefficient of friction - μ. In this figure, "V" represents the vertical component of the resultant force, and "H" the horizontal component of the resultant force.

An idea of the reliability of the values of the coefficient of friction may be obtained from the following example. By averaging individual readings, the horizontal and vertical



$$\mu = \text{Coefficient of Friction} = \frac{F}{N}$$

$$= \frac{H \sin(15°) + V \cos(15°)}{H \cos(15°) + V \sin(15°)}$$

Fig. 6.

Relationship Between Cutting Forces And Coefficient of Friction.

deflections when cutting with a good fluid can be obtained with an accuracy greater than that indicated in the example shown below:

Vertical deflection = 0.00048" ± 0.000002
Horizontal deflection = 0.00113" ± 0.000002

Values have been calculated below for the coefficient of friction with the various possible combinations of the values given above.

Deflections Considered Vert. -in.	Hor. - in.	Coefficient of friction	Percent Error
4.8×10^{-4}	11.3×10^{-4}	0.294	0
4.6×10^{-4}	11.1×10^{-4}	0.300	2
5.0×10^{-4}	11.5×10^{-4}	0.300	2
4.6×10^{-4}	11.5×10^{-4}	0.281	4.4
5.0×10^{-4}	11.1×10^{-4}	0.319	8.5

It should be noted that the above example is for a good fluid (μ is small) and therefore for a given deviation from the correct value, the percent error will be large. By averaging values and making readings carefully, it is safe to say that the maximum deviation of the coefficient of friction from the correct value will be about 5%.

Attachment for Testing Fluids in the Vapor Phase

An attachment was made for the improved planer apparatus with which the cutting action of a vapor could be studied. This apparatus consisted of a glass vaporizing apparatus con-

nected to a box fixed to the work dynamometer. This box was equipped with a sliding lid (attached to the tool by means of a rubber diaphragm) which kept the vapor from escaping during the cutting operation. The apparatus used is shown diagramatically in fig. 7.

The vapor was generated in the flask "A" and rose to the superheating coil "B" where it was superheated many degrees. The temperature of the superheated vapor was measured at "C" and the vapor was then conducted through the heated tube "D" to the chamber "E". The chamber, tool dynamometer and work dynamometer were heated by the previously mentioned electric heaters so that their temperature was kept above the boiling point of the fluid being tested. The vapor was free to escape at the right end of the chamber (at "F") and the temperature of the exhaust gas was measured by the thermometer "G".

By means of this relatively simple arrangement, it was possible to test vapors above their boiling point, without any chance of the liquid fluid being present at the cutting point. Cutting forces could be measured just as without the chamber since the sliding lid offered no resistance to the horizontal movement of the work. The front of the chamber was equipped with a window through which the cutting process could be observed while tests were being made.

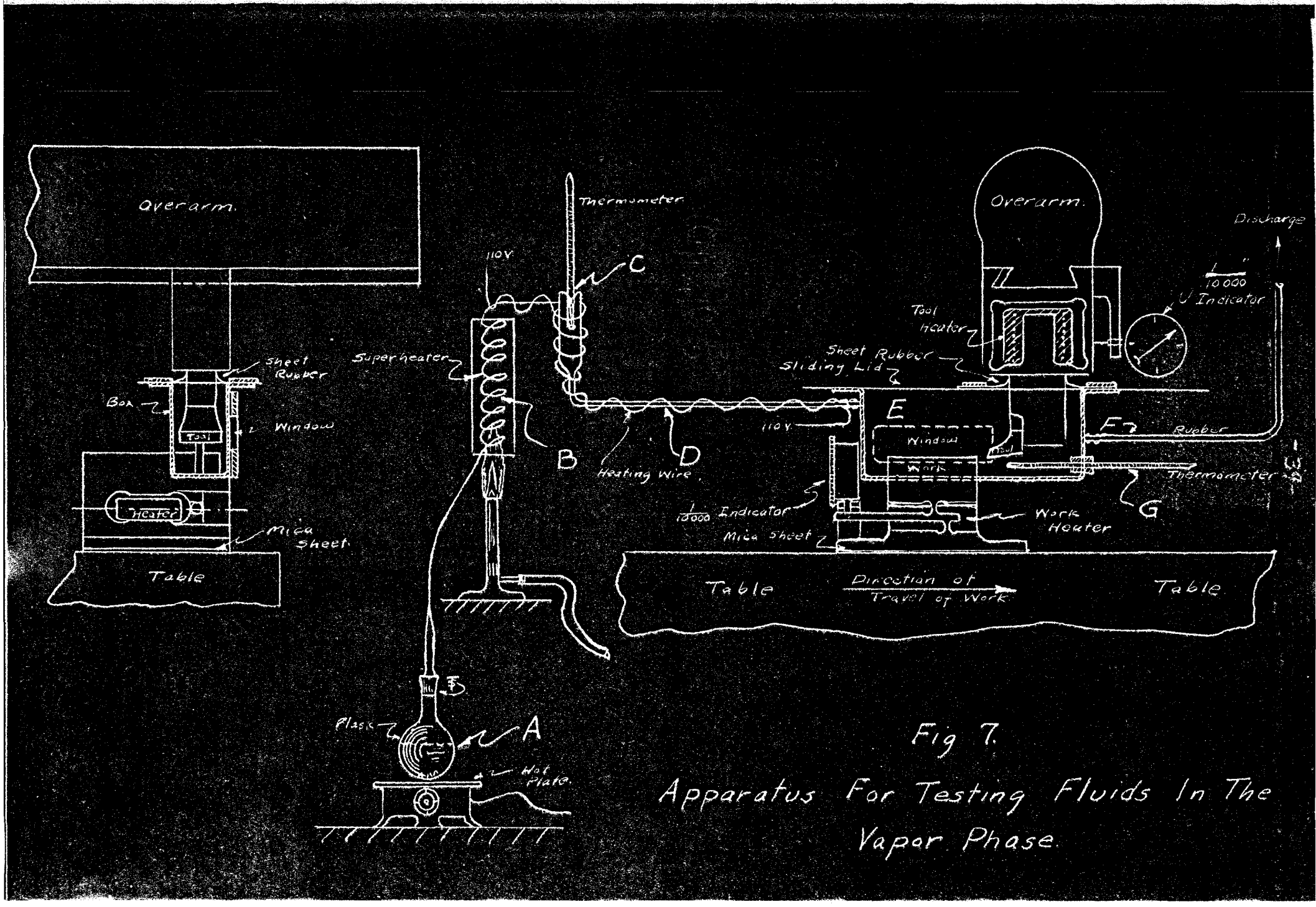


Fig 7.

Apparatus For Testing Fluids In The Vapor Phase.

Fly Milling Apparatus

An apparatus was built with which to study the chemical reactions involved in the use of cutting fluids over a wide range of cutting speed. In brief, this device consists of a single point cutter which removes chips from an aluminum work piece in a small closed chamber. This chamber holds the cutting fluid and cutting is carried out in direct contact with the liquid. The chief feature of this apparatus is that a large amount of cutting can be carried out in the presence of a small amount of liquid, thus increasing the quantity of any chemical product available for analysis.

Fig. 8 is a drawing of the final equipment. The apparatus is also shown photographed in figures 9 and 10. The 1/4 inch diameter aluminum specimen is fed down into the cutting chamber through the top of the block. The fly milling cutter is made of high speed steel and has a 15° rake angle and a 3° clearance angle. This cutter is inserted in the 3/4" diameter end of the shaft and is held in place by an Allen head set screw. A detail view of the cutter is shown in fig. 8. The shaft is carried by two sealed ball bearings and is rotated by a V-belt drive.. Two pulley sizes are available in order to further extend the 9 to 1 infinitely variable speed change supplied by the 3/4 H.P. Master "Speed Ranger" motor. This motor will give any speed, at its high speed shaft, from 600 R.P.M. to 5200 R.P.M. An arrangement is employed (as shown

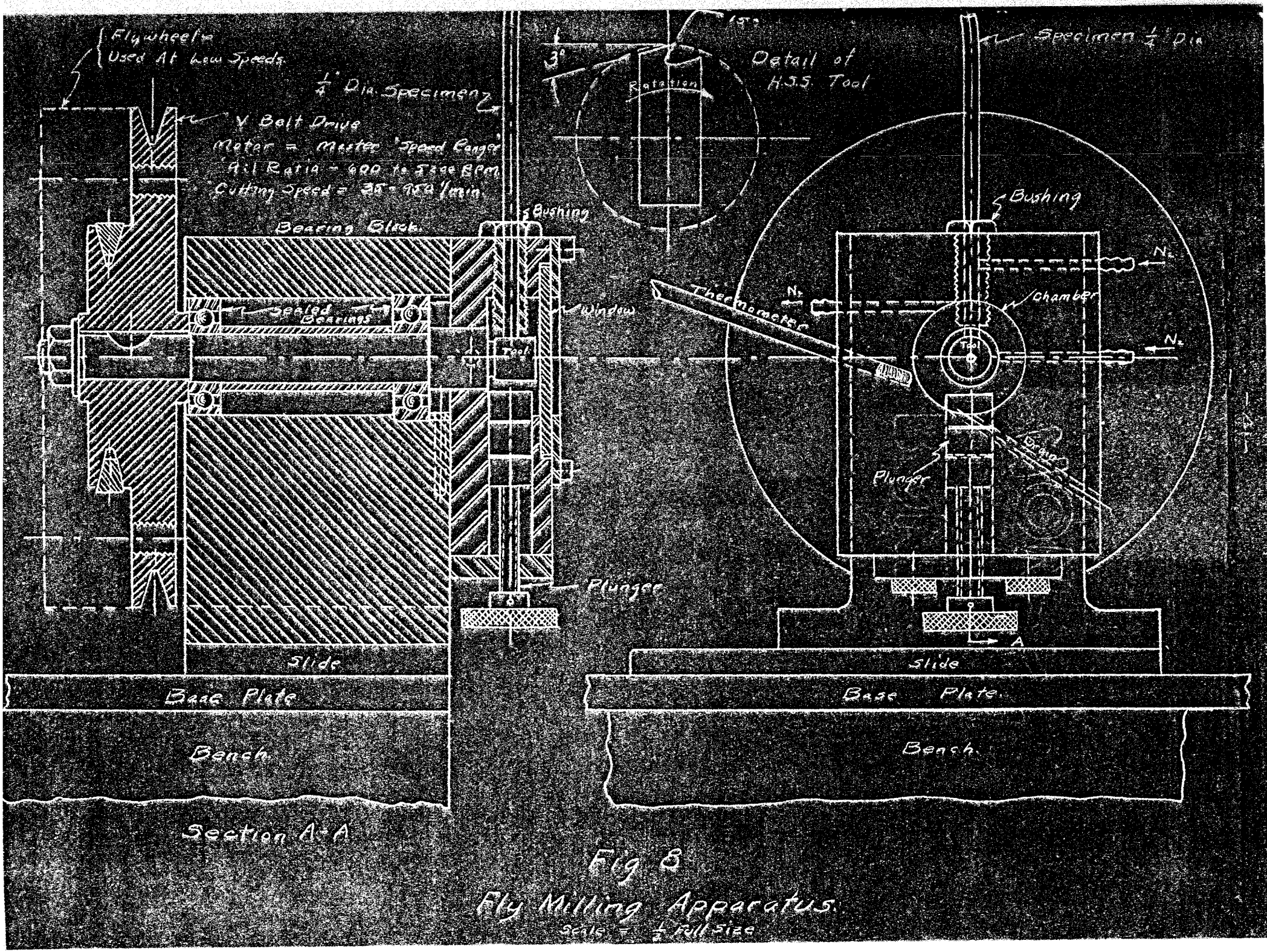


Fig 8

Fly Milling Apparatus.

Scale = 1/2 Full Size

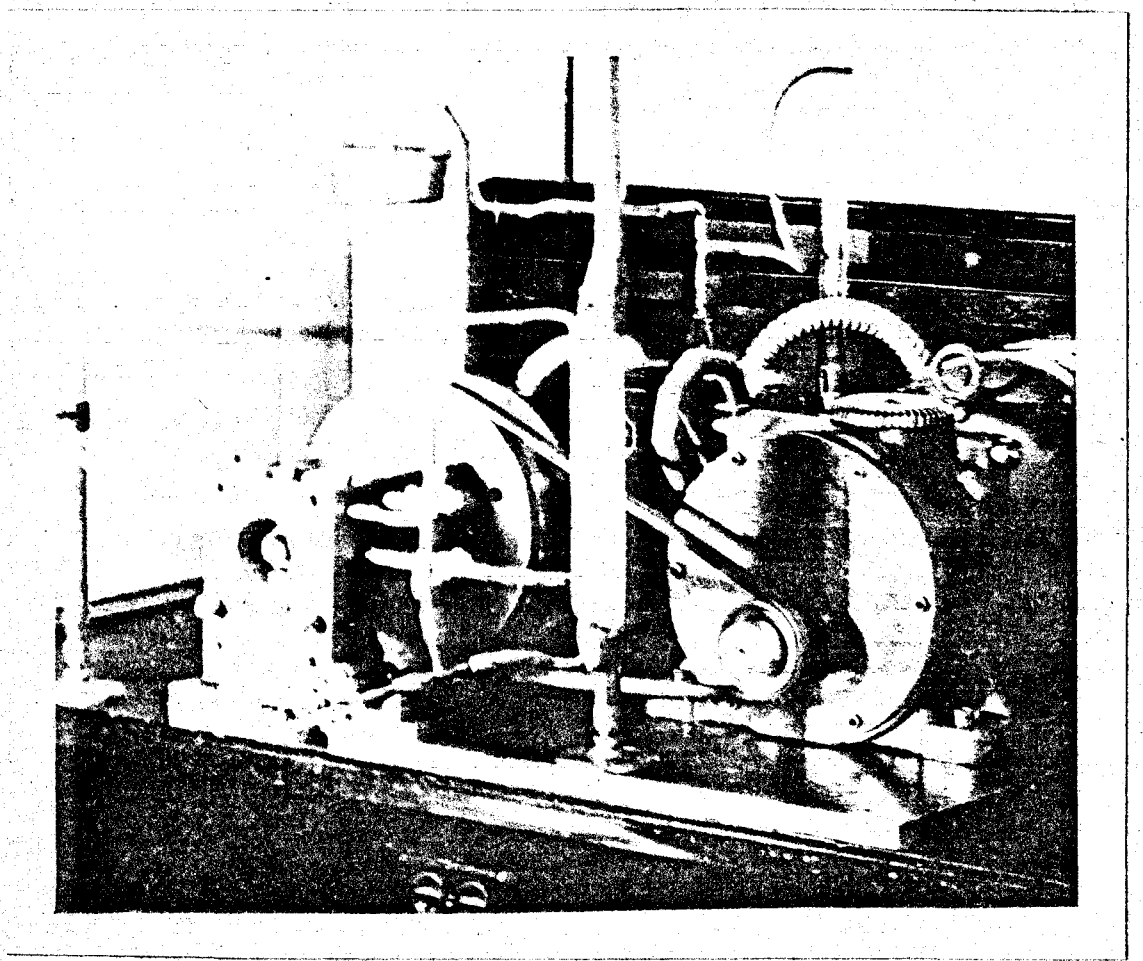


Fig. 9: Fly Milling Apparatus

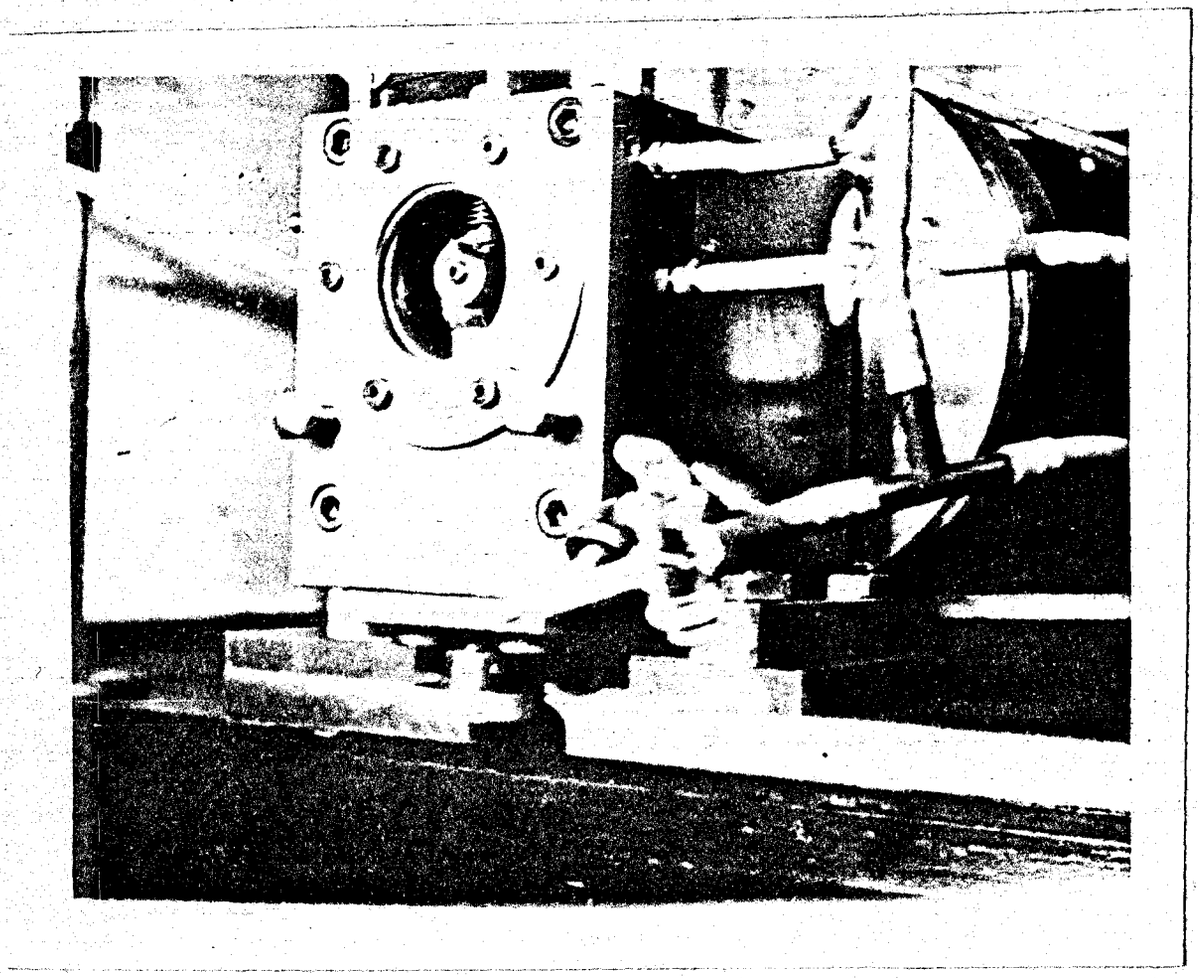


Fig. 10: Close-up View of the Chamber of the Fly Milling Apparatus

in fig. 8) such that a fly wheel may be attached to the shaft of the apparatus when it is operating in the slow speed range. This gives much steadier speeds and smooths out any slowing down produced by the action of the cutter. The cutting speeds available at the cutter cover the range from 35 surface feet per minute to 950 surface feet per minute.

The tip of the cutter projects about 0.001 inch above the surrounding shaft and between cuts, the work piece rides on the shaft. Weights are placed on the work piece to make sure that it feeds down and rides on the shaft after each cut. A window is supplied in the front of the block through which the cutting can be observed. This window is ground in with the block and thus no gasket need be used. The bottom of the block has an opening fitted with a 7/8 inch diameter lapped plunger, through which opening, the chips and fluid can be removed at the end of a run. The shaft enters the block through a close fitting hole and the liquid is kept from leaking out through this opening by a stream of nitrogen introduced at the center of the hole (see fig. 8).

Nitrogen is also introduced at the midpoint of the hole through which the specimen enters the block. The purpose of this nitrogen is to exclude air from the chamber and thus supply an inert atmosphere in the chamber at all times. The nitrogen is carefully purified by passing it through the system shown diagramatically in fig. 11. The excess nitrogen leaves

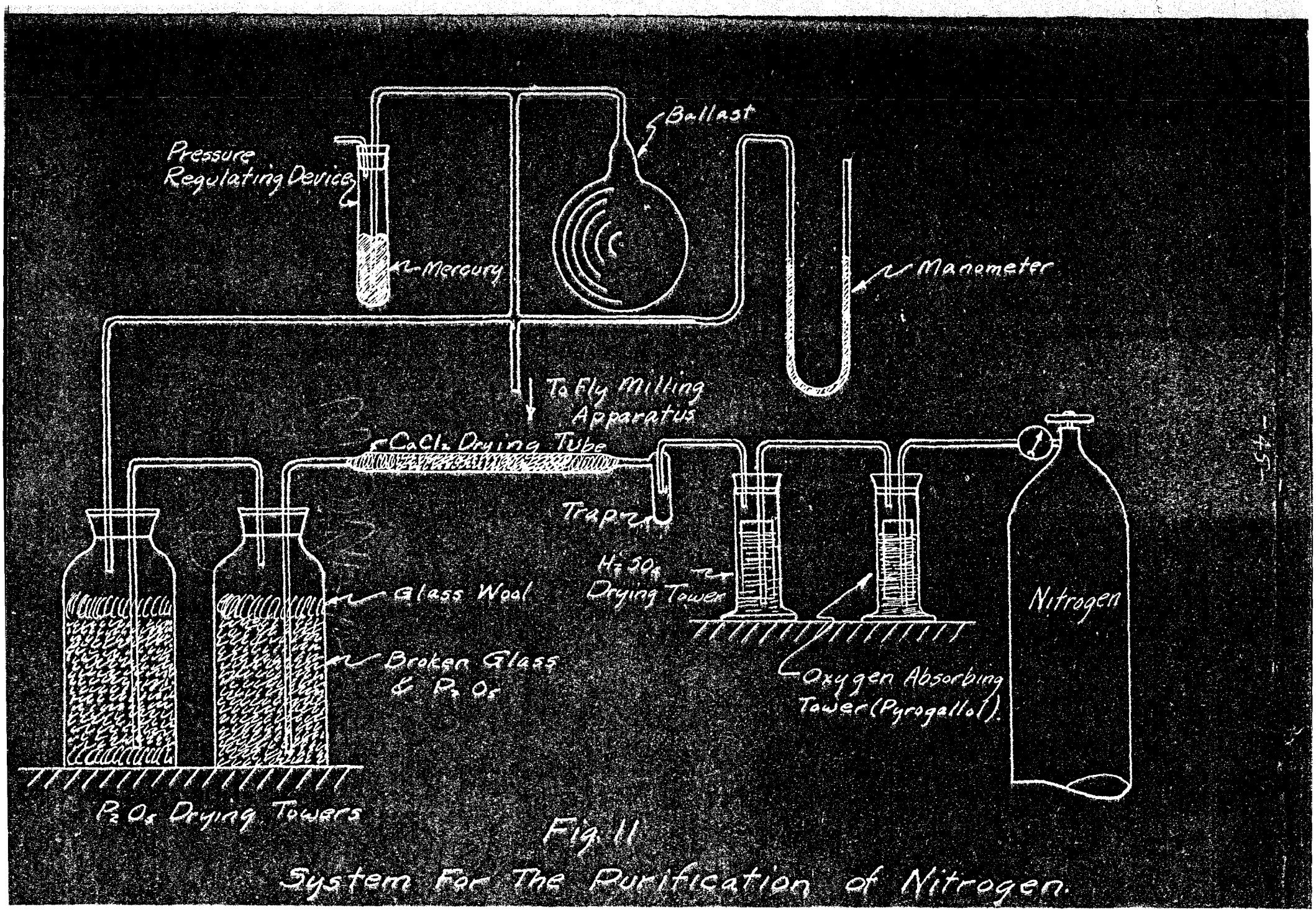


Fig. 11

System For The Purification of Nitrogen.

the chamber by the exit supplied on the left side of the block.

The liquid to be tested is introduced through the specimen hole and then the specimen is inserted and the air displaced by nitrogen. The chamber is filled with the liquid, nearly to the top of the rotor, and if a great deal of cutting is necessary, the plunger can be lowered at a rate equal to the production of the chips, thus keeping the liquid level approximately constant. A thermometer well is drilled in the side of the block with its end very close to the chamber. Thus, any appreciable rise in temperature of the liquid in the chamber can be noted approximately.

Fractional Distillation Apparatus

The chemicals used in this work may be divided into two classes - those of unknown purity and those which were highly purified. In the preliminary work, a great number of chemicals of unknown purity were used (such as those chemicals of Eastman grade distributed by the Eastman Kodak Company). Later, the more interesting findings of this preliminary investigation were re-examined using highly purified fluids.

A very small amount of a fluid is required to make a test with the planer type apparatus (about 10 ml. is ample). Therefore, a special fractional distillation apparatus for handling very small quantities was designed and constructed from Pyrex

glass. Such a special still was necessary for, in many cases, the chemicals used were very expensive and consequently only a small amount was available.

A drawing of the fractional distillation apparatus is given in fig. 12. The distilling flasks are of 50 ml. capacity. The column of the still is packed with single turn glass helices which constitute a very efficient packing material. The air surrounding the column is heated by means of a nichrome ribbon wound around the heater wall and a third wall surrounds the heater to insulate further the column and heater from drafts. The still head is designed so that the hold up will be a minimum. All condensers and connections are made as small as possible and the take off is made of capillary tubing. Dropping tips are located at both the reflux and take off ends of the still head in order that the reflux ratio may be easily determined. Ground glass joints are used at all connections. A pressure regulating device and the pressure measuring apparatus are shown diagramatically in fig. 12. This still has an efficiency equivalent to about nine theoretical plates and the hold up is from 3 to 5 ml.

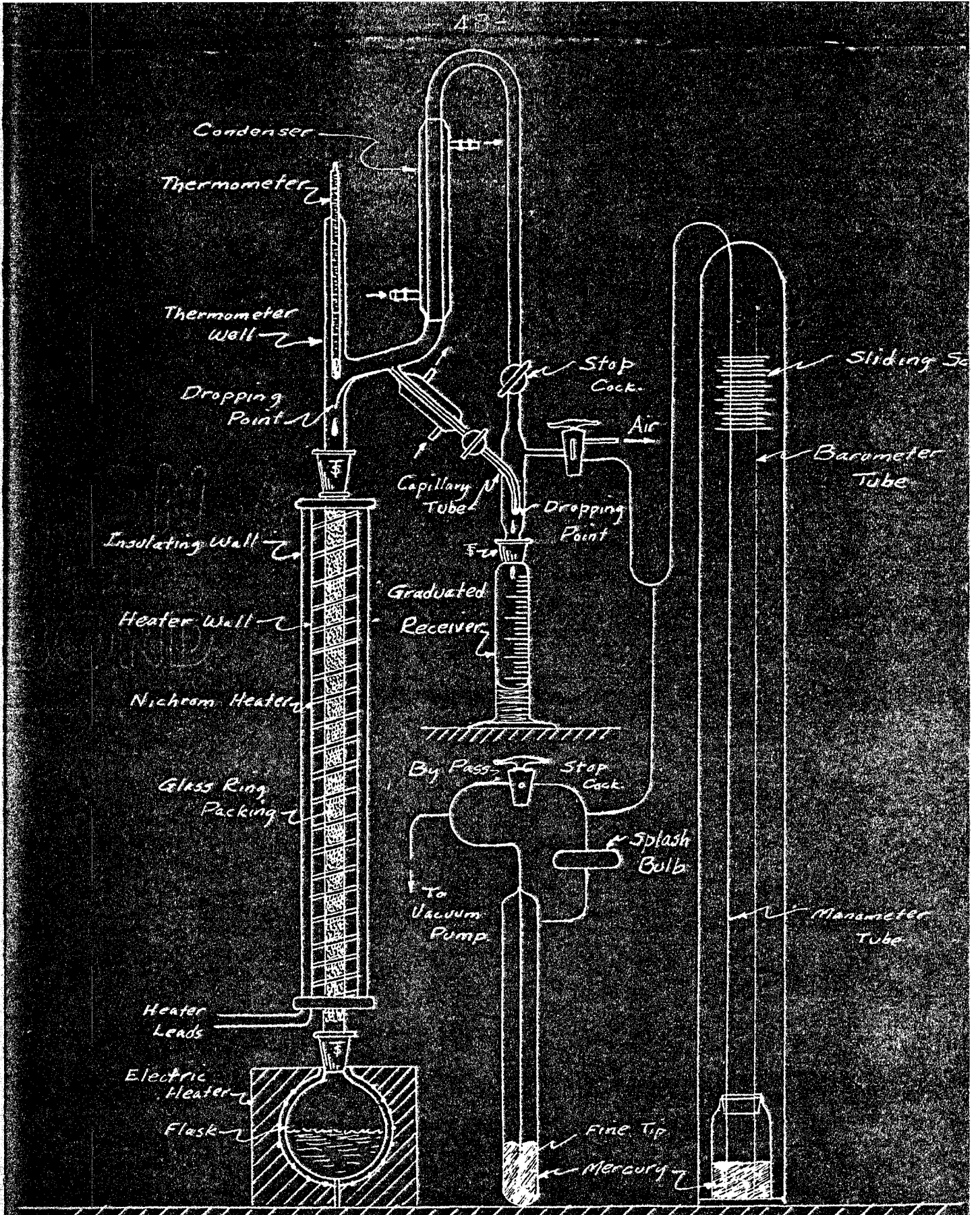


Fig 12

Fractional Distillation Apparatus

Data and Discussion of the Data

A great deal of data has been gathered in the course of the cutting fluid investigation, mainly because this has proven to be such a fertile field of endeavor. Only that part of the data directly related to the chosen subject will be presented here. The discussion will be given under several sub-headings and the data will be introduced as it is needed.

The photomicrographs presented in figs. 13 to 17 show at a glance the great effectiveness of a good cutting fluid and also the wide variation in the mechanism of chip formation as influenced by the fluid used. In these illustrations, all of the variables were held constant except the cutting fluid employed. The work material was SAE 1020 steel, the depth of cut was 0.005 inch and the cutting speed was 5.5 inches per minute. The photomicrographs are presented in the order of decreasing effectiveness of the fluid used. The chips can be seen to grow thicker as the cutting fluid becomes less effective. The chip is seen to change from type 2 (43), which is continuous and has a continuously escaping compressed layer adjacent to the tool face, to type 1 which is discontinuous. It is obvious that less power will be required and a smoother surface created with cutting as shown in fig. 13 than with the cutting shown in figs. 16 or 17.

SAE 1020 Steel Cut in the Presence of Various Fluids

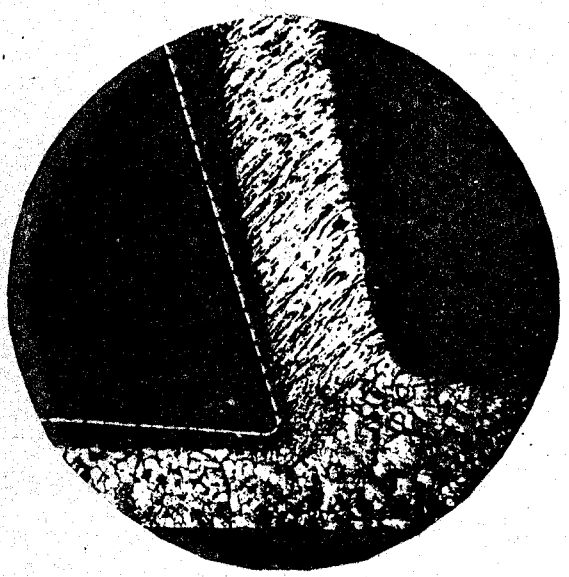


Fig. 13: Carbon Tetrachloride 100X

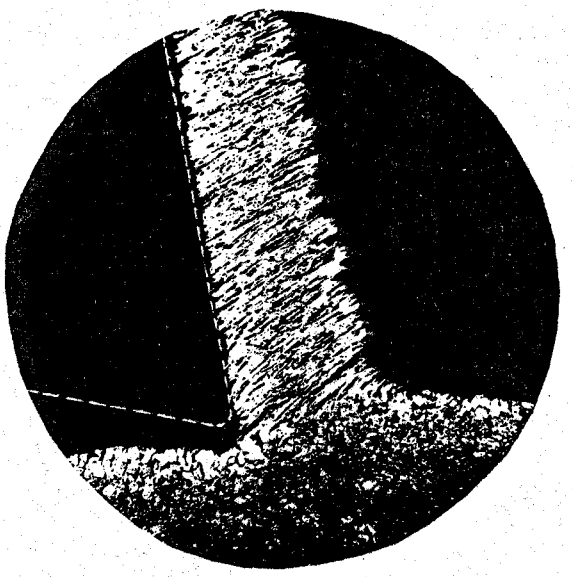


Fig. 14: Oleic Acid 100X

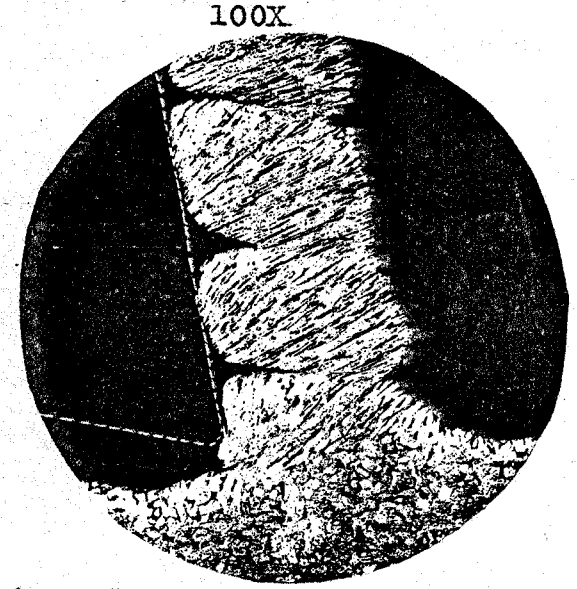


Fig. 15: Ethanol 100X

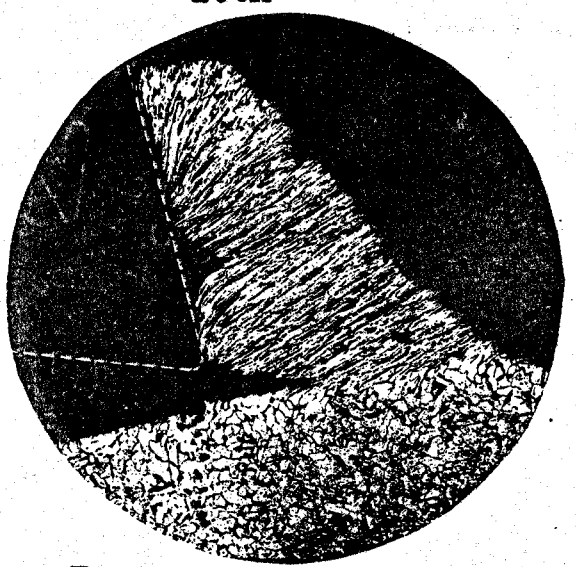


Fig. 16: Dry 100X

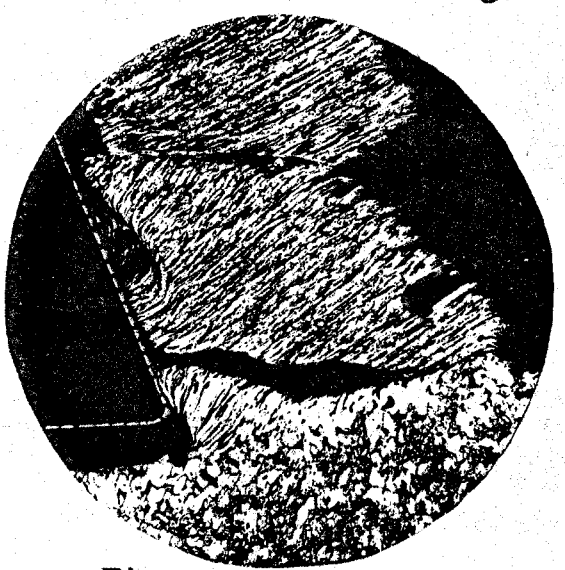


Fig. 17: Benzene 100X

Some General Concepts

It has been shown above that the type 2 chip is desirable from the point of view of minimum power consumption and the quality of the surface produced. This type of chip is produced only when the tool point is kept from adhering to the work material. One of the best methods of preventing the chip from adhering to the tool is to introduce a film between the tool and the work piece.

In the first tests made, tools were coated with various films and then tested. The quality of the surface was noted, and it was found that different films produced widely different results which were found to be fairly reproducible. These preliminary tests with coated tools showed definitely that the presence of a film prevents the formation of a built-up edge. The fact that none of the treatments used produced films that would remain on the tool for more than a short time, indicates that some means must be employed to continually replenish the layer between the tool and the work.

In previous experiments performed in the laboratory of the Cincinnati Milling Machine Company, Dr. Martelotti had found carbon tetrachloride to be a promising cutting fluid. It was therefore decided that other organic compounds should be applied in order to try to discover what properties of the carbon tetrachloride (physical or chemical) made it such a good cutting fluid.

Generalizations from the Preliminary Survey

The apparatus used in this work was the previously described simple planer apparatus. Soon after starting the investigation, it was found that the length of the chip had a definite bearing upon the efficiency of the cutting fluid employed. The chips were therefore saved in all cases and the cutting ratios recorded. The cutting ratio may be defined as the length of the chip divided by the length of the work piece. The longer the chip, the greater will be the cutting ratio and the better the cutting process.

The following generalizations have been made from the data of the preliminary survey:

1. In general, the saturated hydrocarbons are poor cutting fluids, the longer chain length compounds being slightly better than the lower homologs.

2. The saturated chlorinated hydrocarbons were found to be very effective cutting fluids, but no relationship could be found between the cutting efficiency and the degree of chlorination.

3. The unsaturated chlorinated derivatives of ethylene were found to be very inferior to the corresponding saturated compounds.

4. Aromatic compounds were found to be very poor cutting fluids.

5. The presence of halogen substituted in the benzene ring improved the surface quality in the order: Chlorine, bromine, iodine. For example, phenyl chloride, phenyl bromide and phenyl iodide had respectively the following cutting ratios: 0.143, 0.177 and 0.207.

6. In several cases, the phenyl group gave about the same effect as the methyl group. To illustrate this, the following pairs are cited:

Cutting Fluid	Cutting Ratio
Acetophenone	0.187
Acetone	0.183
Nitrobenzene	0.193
Nitromethane	0.173
Phenol	0.253
Methanol	0.250

7. All of the mercaptans, sulfides and disulfides gave very good results and the cutting ratio increased with the chain length.

8. The presence of sulfur in the molecule was not sufficient, since several such fluids gave poor results (i.e. carbon disulfide, dimethyl sulfate and benzene sulfonyl chloride).

9. The normal primary monohydric alcohols were found to give good surfaces, their efficiency increasing rapidly at first with increase in chain length and then remaining about constant.

10. The various isomers of the normal primary alcohols were inferior to the straight chain alcohols of equal molecular weight. This observation shows that the members of an homologous series should be compared on the basis of chain length and not molecular weight.

11. Polyhydric alcohols were found to be inferior to the corresponding monohydric alcohols.

12. The organic acids gave a considerable increase in cutting ratio with chain length. The lower homologs were quite poor, but the higher fatty acids were good fluids.

13. The cutting ratio was found to increase with the molecular weight for esters.

14. Distilled water gave a surface nearly as bad as that produced with a dry tool.

Some of the above statements can not be rigorously proven by the data of the preliminary survey. The chemicals used in this initial work were not highly purified (most of them were of Eastman grade of purity) and in some cases, the generalizations are based upon too little data. It is interesting to note, however, that already there are several statements which can readily be explained in terms of the chemico-physical theory of cutting fluid action, previously described.

On the basis of this theory, the hydrocarbons and aromatic compounds would be expected to be poor cutting fluids because they are noted for their chemical stability. The fact that the unsaturated chlorinated derivatives of ethylene are so much poorer than the corresponding saturated compounds is also significant. Wilson (94) points out that if a halogen atom is attached to a carbon atom holding a double bond, then the halogen atom is very stable. However, if the double bond is one removed from the carbon atom holding the halogen, then the reactivity of this halogen will be greater than in the corresponding saturated molecule. In this preliminary survey, the saturated and unsaturated chlorinated hydrocarbons have been found to act in the order of their chemical reactivity.

The most effective phenyl halides were also found to be the most reactive. It is well known that phenyl chloride is much more stable than phenyl bromide which, in turn, is more stable than phenyl iodide. Those sulfur compounds which are

reported above as being inefficient cutting fluids are relatively unreactive compounds toward aluminum. Water would be expected to be quite ineffective according to the chemico-physical theory because of its chemical stability toward aluminum.

The Effect of Cutting Speed

Since all of the preliminary cutting tests were made at the very low cutting speed of 5.5 inches per minute, it was important to know how the efficiency of cutting would change as more practical cutting speeds were approached. By changing the cutting speed of the simple planer apparatus, a great deal of data was obtained. These data showed that a few fluids were still good at the higher speeds while others were much less efficient at increased speeds.

A number of tests made with the high speed turning apparatus showed that at higher, more practical speeds, the difference between the chip lengths of the very good fluids and of the very poor fluids was much less than at a cutting speed of 5.5 inches per minute. A series of tests was made at various speeds using carbon tetrachloride as the fluid. These data are shown in fig. 18. It will be noted that the cutting ratio was high at very low cutting speeds, reached a minimum at about 750 inches per minute and then rose slowly with further increase in speed. The chips produced are shown

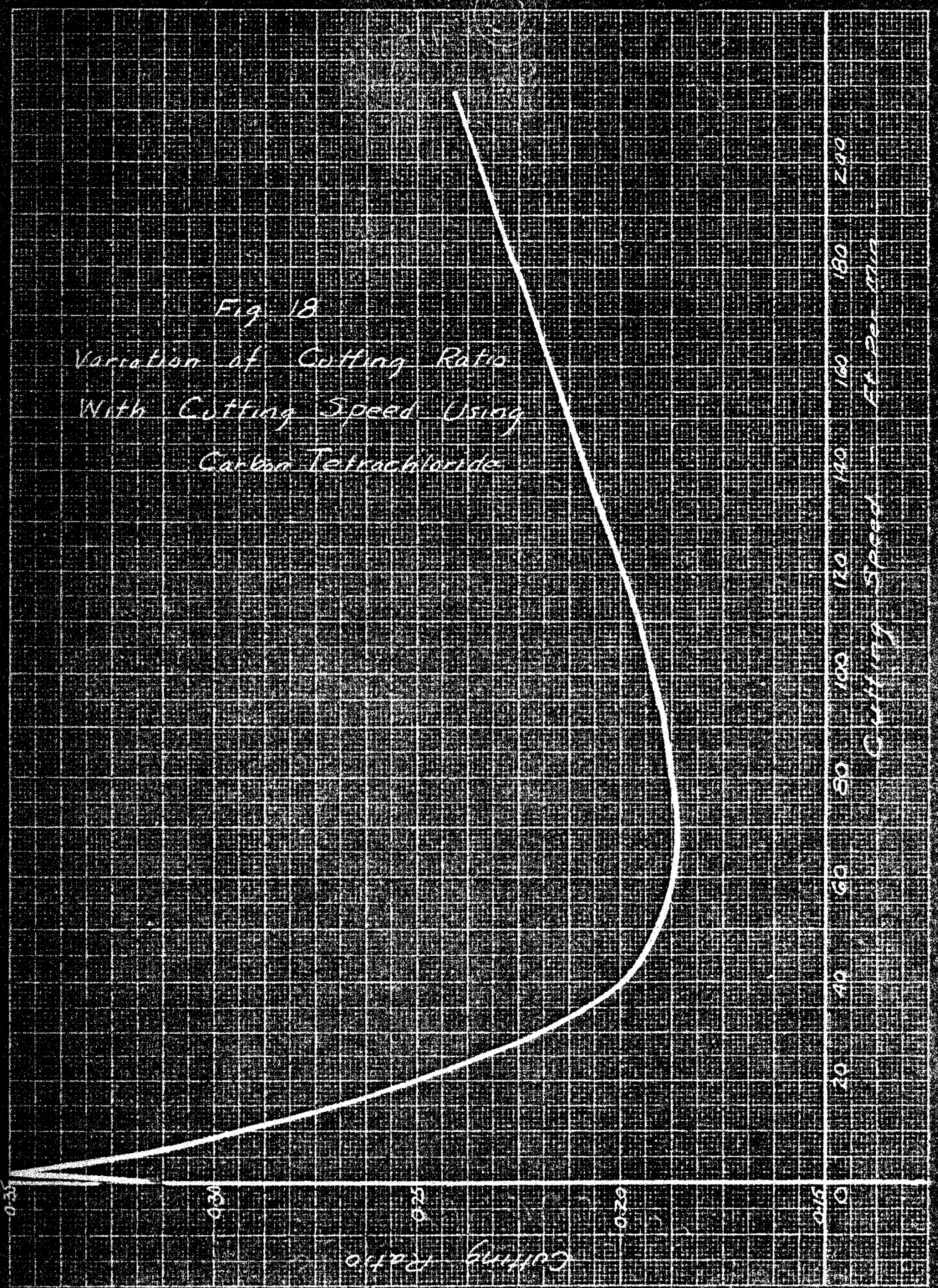


Fig. 18

Variation of Cutting Ratio With Cutting Speed Using Carbon Tetrachloride

opposite the rate at which they were removed.

The above data can be logically explained on the basis of the chemico-physical theory of cutting fluid action. It is probable that the amount of product formed in a given time when carbon tetrachloride reacts with nascent aluminum will increase with increased temperature and pressure. The temperature and pressure at the cutting point will be greater at higher cutting speeds and therefore, the total amount of product formed in a given time will increase with cutting speed. However, as the speed is increased, the time of contact of the tool with any particular infinitesimal area will decrease. The amount of product per unit area of surface will decrease with increased cutting speed due both to the finiteness of the reaction time and to the fact that more area is traversed at the higher speed, in a given time. Thus, there are two opposing conditions which are affecting the way in which the cutting efficiency will vary with speed. It is generally found that either a maximum or a minimum point is reached when two opposing forces act upon a system in such a way that as one increases, the other decreases. This explanation thus partly accounts for the minimum point occurring in fig. 18.

A further factor which was not considered in the above discussion is known to influence the efficiency of metal re-

moval. Schmaltz (81) reports that the built-up edge is greatly reduced as the cutting speed is increased. He explains this by saying that an increase in stress occurs with an increase in the rate of deformation, and that this increase in stress is caused by the decrease in relaxation time of the material at the higher rate of deformation. He says that at lower speeds of deformation, a certain amount of stress distribution occurs due to the rate of relaxation being appreciable, compared with the rate of cutting. The writer has also observed an improvement in surface quality and an increase in cutting ratio with increase in cutting speed when cutting with a dry tool.

The Effect of Surface Condition

The direction of cutting relative to the direction of rolling was found to be significant. Tests were made with rolled pieces of lead, cuts being taken both parallel and transverse to the direction of rolling. The following data were obtained:

Parallel to Direction of Rolling

Fluid	Cutting Ratio
Carbon tetrachloride	0.267
Benzene	0.430

Transverse to Direction of Rolling

Carbon tetrachloride	0.247
Benzene	0.417

The above data show that lead cut parallel to the direction of rolling requires less force than the lead cut transverse to the direction of rolling. It is interesting to note that carbon tetrachloride is a much poorer fluid for cutting lead than benzene. This is just the reverse of the usual order of effectiveness of these two fluids when used with other metals. The pressure developed in cutting lead is quite low compared with the values obtained when other metals are cut. Carbon tetrachloride and other chlorinated and sulfonated fluids that are quite good under extreme boundary conditions are relatively poor (compared to higher polar compounds) when used as low pressure boundary lubricants. Thus, it may be said that carbon tetrachloride is a poor cutting fluid when used with lead, because the pressure developed is not sufficient to cause the fluid to form a low shear strength compound between the chip and the tool. Another possible explanation for the fact that carbon tetrachloride is a poor cutting fluid for lead can be given in terms of the relative shear strengths of lead and lead chloride. It is quite possible that lead chloride may have a greater shear strength than the lead itself as some calculations of Dr. Merchant indicate.

Another surface condition affecting the metal cutting process is that of work hardening of the surface. If a cut is taken with a dry tool, the surface produced will be much better

The Effect of Cold Working of Aluminum on the Quality of the Surface Produced with a Dry Tool

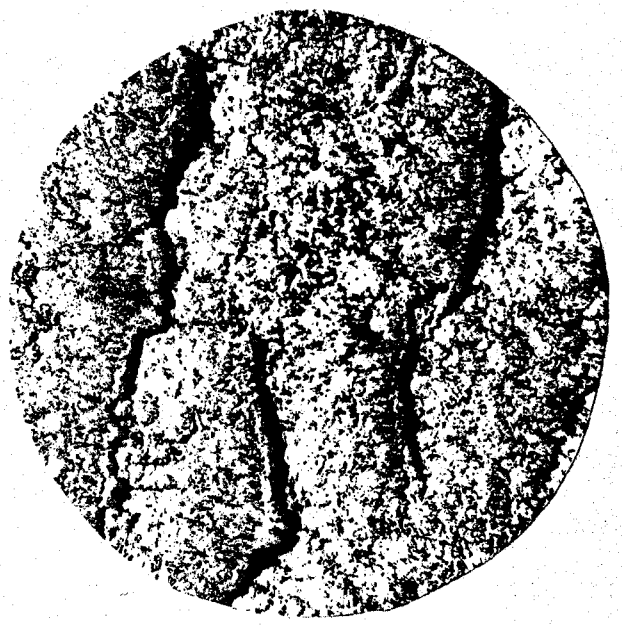


Fig. 19-a: .003 Inch Cut Preceded by .003 Inch Cut

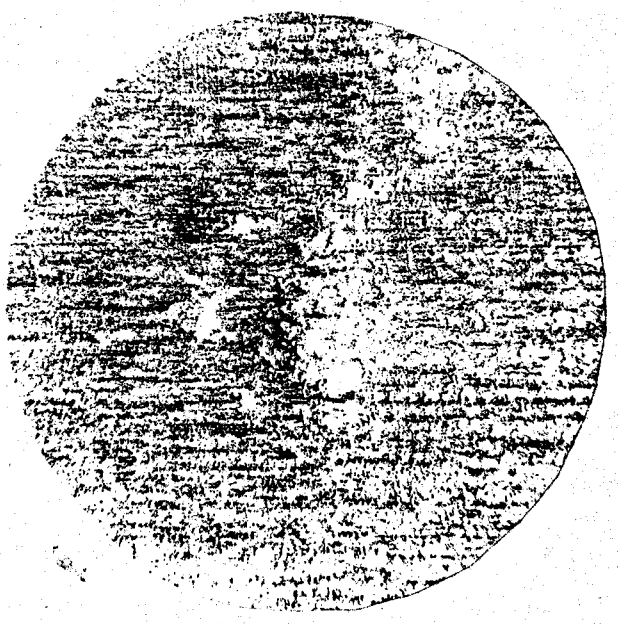


Fig. 19-b: .003 Inch Cut Preceded by .025 Inch Cut

if the metal has been previously work hardened. In fig. 19, two photomicrographs of aluminum surfaces are shown. Fig. 19-a is the surface produced by making a .003 inch cut preceded by several .003 inch cuts. Fig. 19-b is a surface formed by making a .003 inch cut preceded by a 0.025 inch cut. It is obvious that the surface which was work hardened most (fig. 19-b) gave the better finish. The above example is for a dry tool. Similar results were obtained when work hardened and unwork-hardened surfaces are cut in the presence of a fluid. It is feasible that the work hardening of a surface will change its chemical reactivity under the conditions existing in the extreme boundary state, so that this effect of work hardening will be superimposed upon the dry tool phenomenon described above.

The Effect of a Film between Chip and Tool

The preliminary tests cited above, using coated tools, demonstrate the effectiveness of the existence of a film between the chip and the tool. As long as a tool is covered with a layer of low shear strength iron chloride, little metal to metal contact occurs and the surface produced is quite smooth. However, as soon as the layer of chloride is worn away, metal to metal contact is established and the surface is just as rough as one produced using a dry tool.

In order to prove further that a low shear strength halide film is capable of decreasing the coefficient of friction, aluminum was cut with several mixtures of iodine in pure benzene. The improved planer apparatus was used in this determination. Benzene was chosen as the solvent since it is very ineffective when used as a cutting fluid. The data obtained are given in Table I below:

Table I

Fluid	Cutting Ratio	Coefficient of friction
Benzene	0.123	.892
0.001% I_2 in benzene	-	.853
0.01% I_2 in benzene	-	.853
0.1% I_2 in benzene	0.146	.838
1% I_2 in benzene	0.160	.707
10% I_2 in benzene	0.223	.613

It is quite evident from these tests that the iodine is effective in decreasing the coefficient of friction by reacting with the freshly formed aluminum surface, producing an aluminum halide with a low shear strength.

Dependence of Cutting Fluid Performance upon the Metal Cut

In general, the same cutting fluid will not be found to be equally good when used with different metals. The data given in Table II show the results of a series of tests with four different cutting fluids on two different work materials. The fluids have been selected to show four representative cases:

1. A fluid bad on aluminum but good on steel
2. A fluid good on aluminum but bad on steel

3. A fluid excellent on both aluminum and steel
4. A fluid very bad on both aluminum and steel

It is obvious that a statement that a certain cutting fluid is good or bad only has meaning when the metal cut is also specified.

Table II

Case	Cutting Fluid	Work Material	Surface Condition	Cutting Ratio	Cutting force (lbs)
1	Acetic Anhydride	Aluminum	Bad	0.18	154
	Acetic Anhydride	SAE 1020 steel	Good	0.41	363
2	Turpentine	Aluminum	Good	0.35	78
	Turpentine	SAE 1020 steel	Bad	0.25	493
3	Carbon tetrachloride	Aluminum	Excellent	0.39	65
	Carbon tetrachloride	SAE 1020 steel	Excellent	0.48	212
4	Benzene	Aluminum	Very bad	0.13	182
	Benzene	SAE 1020 steel	Very bad	0.22	535

A Cutting Fluid Need Not be a Liquid

A test was made in the fly milling apparatus at a cutting speed of 300 feet per minute, in which vaporized carbon tetrachloride was used in place of liquid. The entire apparatus was heated to a temperature above the boiling point of the fluid, and the vapors were superheated. The chips formed had exactly the same appearance as those when liquid carbon tetrachloride was used - they were colored red and their appearance was definitely different from that of chips produced using a dry tool.

Following the above initial test, others were made with the improved planer apparatus using the attachment for testing fluids in the vapor phase. The data thus obtained are given in Table III and in all cases, the tool, work, dynamometers, etc. were kept above the boiling point of the compound.

Table III

Fluid	Cutting Ratio		Coefficient of friction	
	Vapor	Liquid	Vapor	Liquid
Carbon tetrachloride	.327	.243	.614	.717
Bromine	.333	.240	.724	.647
Chloroform	.250	.317	.687	.468

The above data prove conclusively that a vapor can act effectively as a cutting fluid. It is seen that the vapor is even more effective than the liquid in the case of carbon tetrachloride. These tests indicate that it is possible that all cutting fluids may be vaporized before penetrating between the chip and the tool. The fact that cutting fluids are effective in the vapor phase is of importance because it makes available for consideration fluids which are gaseous under ordinary conditions, and also because much less fluid need be used if applied in the gaseous rather than in the liquid phase. The advantageous use of vapors as cutting fluids appears to be a very promising possibility from the practical point of view and more work in this direction should be carried out immediately.

Preliminary Evidence of the Chemical Action of Cutting Fluids

In making cuts with carbon tetrachloride, a white vapor was noticed coming from the tool. Also after the cut had been completed and the remaining carbon tetrachloride had evaporated, a white powder was observed clinging to the work surface and to the tool. This powder was very hygroscopic; it was soluble in carbon tetrachloride but insoluble in benzene. Upon analysis of the water solution, both aluminum and chloride ions were detected. From the above analysis and physical properties, it was concluded that this white powder was aluminum chloride. Aluminum chloride was visible, as described above, only at low cutting speeds.

Upon making numerous other tests at very low cutting speeds, it was found that chloroform and pentachlorethane likewise produced visible quantities of reaction products. The chloroform deposit was a mixture of black and white while the pentachlorethane deposit was colored pink and white. The nature of these deposits will be discussed later.

Another interesting experiment giving evidence of the chemical nature of cutting fluid action was that in which an acid copper plating solution was used as a cutting fluid. This liquid gave a good surface when steel was cut but a poor surface when used on aluminum. Copper does not plate out on aluminum; consequently, it does not cover the freshly cut metal

with a layer of copper and thus prevent the formation of a built-up edge. In the case of steel, the copper plates out on the freshly cut metal thus preventing the formation of a built-up edge. When the copper plating solution is used in the cutting of copper, the results are about the same as if a dry tool were used.

Indirect evidence of the chemical action of cutting fluids is offered by the demonstration that no relation exists between the physical properties of the various fluids tested and the cutting ratio. Several of the writer's charts showing the cutting ratio plotted against such properties as absolute viscosity, boiling point, surface tension, specific heat, dielectric constant, electric moment and density are given in figs. 19 to 25 in "Chip Formation, Friction and Finish" (42).

The Coefficient of Friction in Metal Cutting

A number of tests were made with highly purified organic chemicals in order to study the variation of the coefficient of friction, between the chip and the tool, with the fluid used. The improved planer apparatus was used in this work. Three members were chosen from each of several homologous series in order to check the effect of the active end group. In order to study the effect of the chain length, the C_2, C_6 and

C_{12} normal compounds were included in all cases.

Many tests were made with the tool and the work at room temperature. The tool was checked frequently for sharpness, using carbon tetrachloride as the control fluid. In making these tests, the first two or three cuts were neglected to allow conditions to come to a steady state. In this way, very consistent results were obtained. In returning the tool to the starting point, it was raised so that it would not drag over the surface of the specimen. The data obtained is given in Table IV and is arranged in groups according to the chemical structure of the compound. Each of these values is the average of five or more individual cuts.

Table IV

Test No.	Fluid	Cutting Ratio	Coefficient of friction
1	CCl_4	.427	.288
2	$CHCl_3$	.401	.312
3	CH_2Cl_2	.265	.477
4	C_2HCl_5	.230	.648
5	$Cl_2C - CCl_2$ (H H)	.320	.419
6	$ClC - CCl_2$ (H_2 H)	.344	.407
7	$Cl_3C - CH_3$	.340	.422
8	$H_2C - CH_2$ (Cl Cl)	.250	.481

Table IV (cont.)

Test No.	Fluid	Cutting Ratio	Coefficient of friction
9	$H\,C - CH_3$ Cl_2	.330	.406
10	$H_3C - C\,Cl$ H_2	.255	.511
11	$Cl_2C = CCl_2$	.195	.603
12	$Cl_2C = CCl$	.188	.623
13	$\begin{matrix} Cl & & H \\ C & = & C \\ H & & Cl \end{matrix}$	.185	.612
14	Lauryl chloride	.385	.369
15	Hexyl chloride	.308	.440
16	Ethyl Acetate	.227	.518
17	Hexyl Acetate	.403	.299
18	Lauryl Acetate	.440	.240
19	Ethyl Caproate	.391	.353
20	Ethyl Laurate	.447	.244
21	Lauryl Mercaptan	.473	.237
22	Heptyl Mercaptan	.483	.255
23	Hexyl Mercaptan	.477	.262
24	Amyl Mercaptan	.473	.265
25	Butyl Mercaptan	.473	.267
26	Propyl Mercaptan	.440	.276
27	Ethyl Mercaptan	.437	.308

Table IV (cont.)

Test No.	Fluid	Cutting Ratio	Coefficient of friction
28	Amyl Disulfide	.462	.250
29	Butyl Disulfide	.457	.257
30	Propyl Disulfide	.457	.256
31	Ethyl Disulfide	.448	.271
32	Methyl Disulfide	.417	.302
33	Lauryl Alcohol	.385	.331
34	Undecyl Alcohol	.412	.325
35	Decyl Alcohol	.400	.325
36	Hexyl Alcohol	.396	.320
37	Ethyl Alcohol	.327	.425
38	Dodecane	.156	.703
39	Hexane	.163	.639
40	Benzene	.123	.892
41	Dry	.140	.785
42	Distilled Water	.187	.690
43	Acetic Acid	.247	.496
44	Hexanoic Acid	.349	.353
45	Heptaldehyde	.430	.298

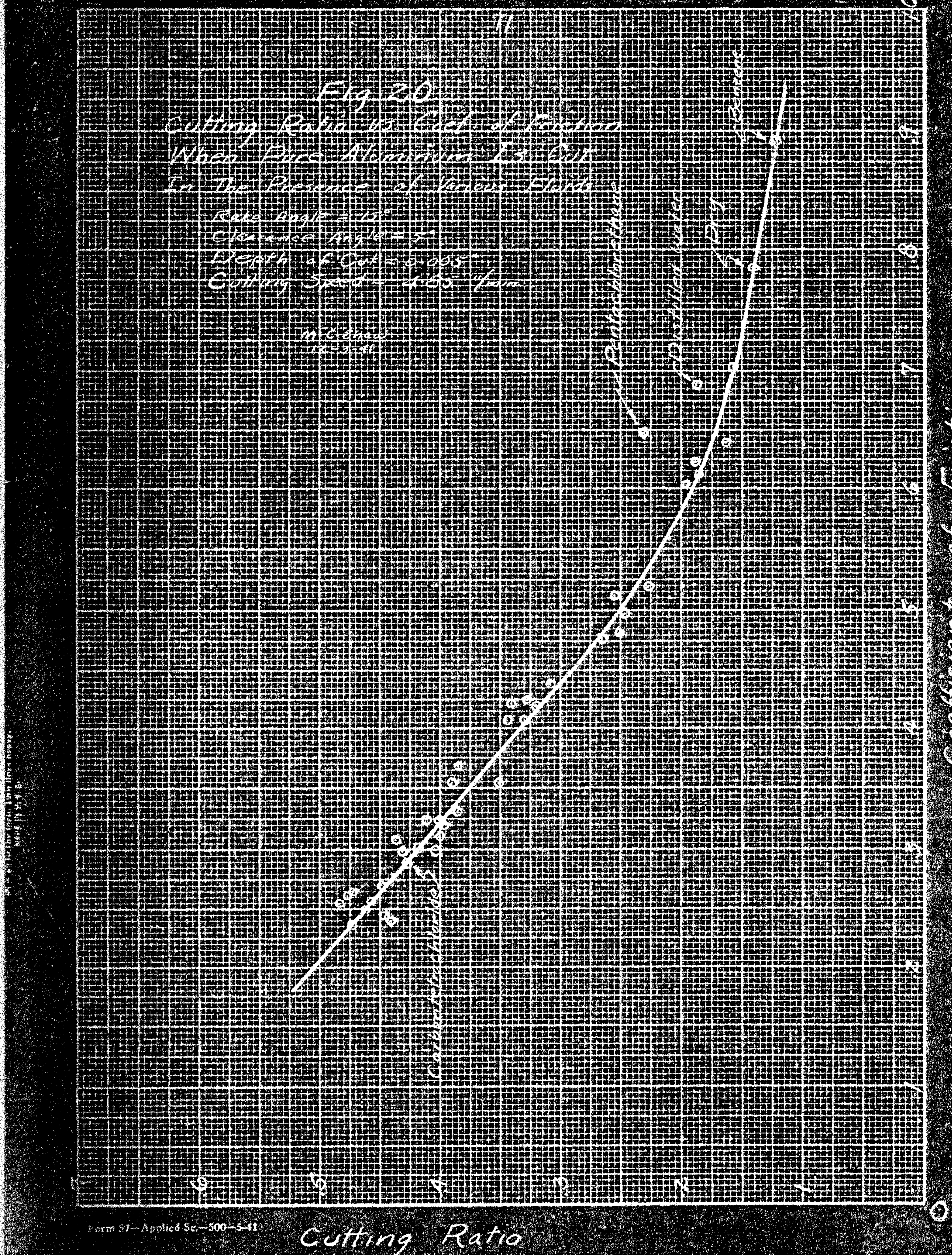
The coefficients of friction found in this investigation are of the same order as those reported by Bowden and Leben (18)

for steel sliding on steel in the presence of various organic liquids. The relative efficiencies of these pure liquids check those found in the preliminary investigation.

The cutting ratio is shown plotted against the coefficient of friction in fig. 20. All points are seen to lie fairly close to the curve, except those for water and pentachlorethane. The relation between the coefficient of friction and the cutting ratio is seen to be linear for the better cutting fluids (i.e. for fluids giving a coefficient of friction less than about 0.5).

The equations given in Merchant's thesis (72) which were derived for homogeneous and isotropic material, can be used to calculate the coefficient of friction for a tool with a 15^{o} rake angle. This has been done and the result is plotted in fig. 21. The curve of fig. 20 is plotted to the same scale for comparison. The difference between the observed and calculated coefficients of friction for a given cutting ratio, Ernst and Merchant (42) attribute to the work hardening capacity of the material.

A few tests were made to determine the magnitude of the effect of cold working upon the data obtained by taking successive cuts. The first cut using a poor cutting fluid following a cut using a good fluid will give a result worse than the equilibrium condition reached after several successive cuts have been taken. The final equilibrium value in all cases re-



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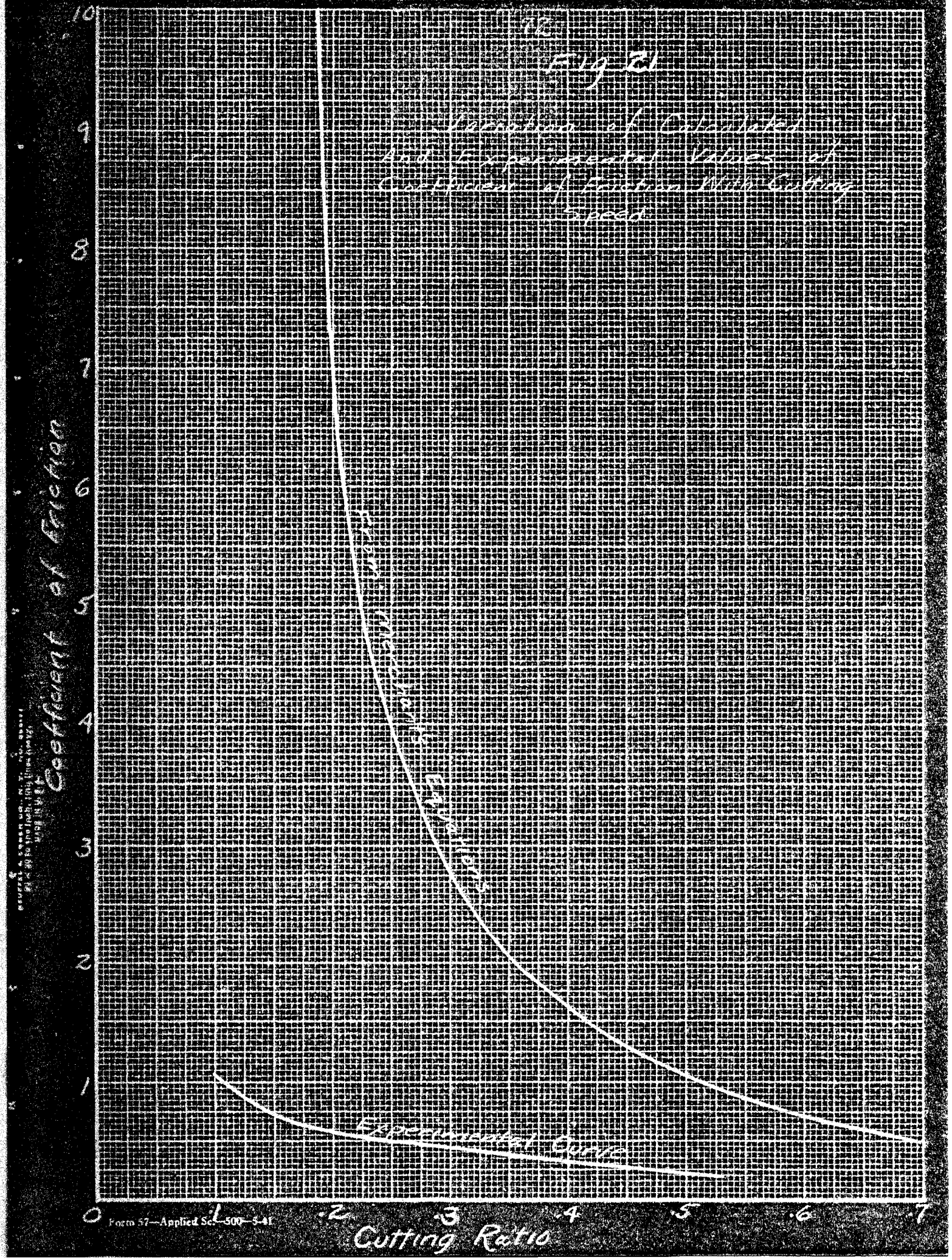

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fers to a slightly different work hardened condition. However, the effect of this difference is not large as can be seen from the following example.

Table V

Fluid	Cutting Ratio	Coefficient of friction
Carbon tetrachloride	.417	.341
Ethanol - 1st cut	.323	.500
Ethanol - 2nd cut	.327	.478
Ethanol - 3rd cut	.327	.478

Of course, the result of recording the equilibrium values is that the poorer cutting fluids will tend to look better than they really are while the better cutting fluids will tend to look worse than they really are. The spread between the very good fluids and the very poor fluids will be slightly reduced.

Several tests were repeated using a heated tool and heated work piece. The tool was heated to 79°C and the work to 76°C. The data obtained are given in Table VI below:

Table VI

Test No.	Fluid	Cutting Ratio	Coefficient of friction
1	CCl_4	.250	.540
2	$CHCl_3$	.317	.468
3	$CHCl_2$	.213	.480
4	Hexyl chloride	.229	.510
5	Lauryl chloride	.255	.475
6	Perchlorethylene	.167	.755
7	Trichlorethylene	.172	.618
8	T.Dichloroethylene	.172	.581
9	Hexanol	.255	.537
10	Hexyl Mercaptan	.417	.312
11	Amyl Disulfide	.448	.247
12	Hexyl Acetate	.375	.298
13	Ethyl Caproate	.364	.338

Table VI (cont.)

Test No.	Fluid	Cutting Ratio	Coefficient of friction
14	Hexanoic Acid	.313	.417
15	Benzene	.135	.63
16	Dry	-	.842

It will be noted that the order of effectiveness for many of the compounds at the higher temperature is different than at the lower temperature. The effectiveness of carbon tetrachloride is seen to drop off rapidly with rise in temperature. Other fluids such as the esters, mercaptans and particularly the disulfide, are seen to remain quite good or even to be more effective at the increased temperature. The unsaturated chlorinated hydrocarbons are still very poor at the higher temperature.

The Cutting Ratio

It has been stated above that the cutting ratio is a good measure of the efficiency of a metal cutting process. It has been shown (fig. 20) that the cutting ratio bears a definite relationship to the coefficient of friction involved between the chip and the tool. The cutting ratio is likewise related to the cutting force.

A great amount of data was taken with the simple planer apparatus using both aluminum and steel as the work materials. The cutting force values obtained in this investigation are shown plotted against the cutting ratio in fig. 22. Fig. 22-a

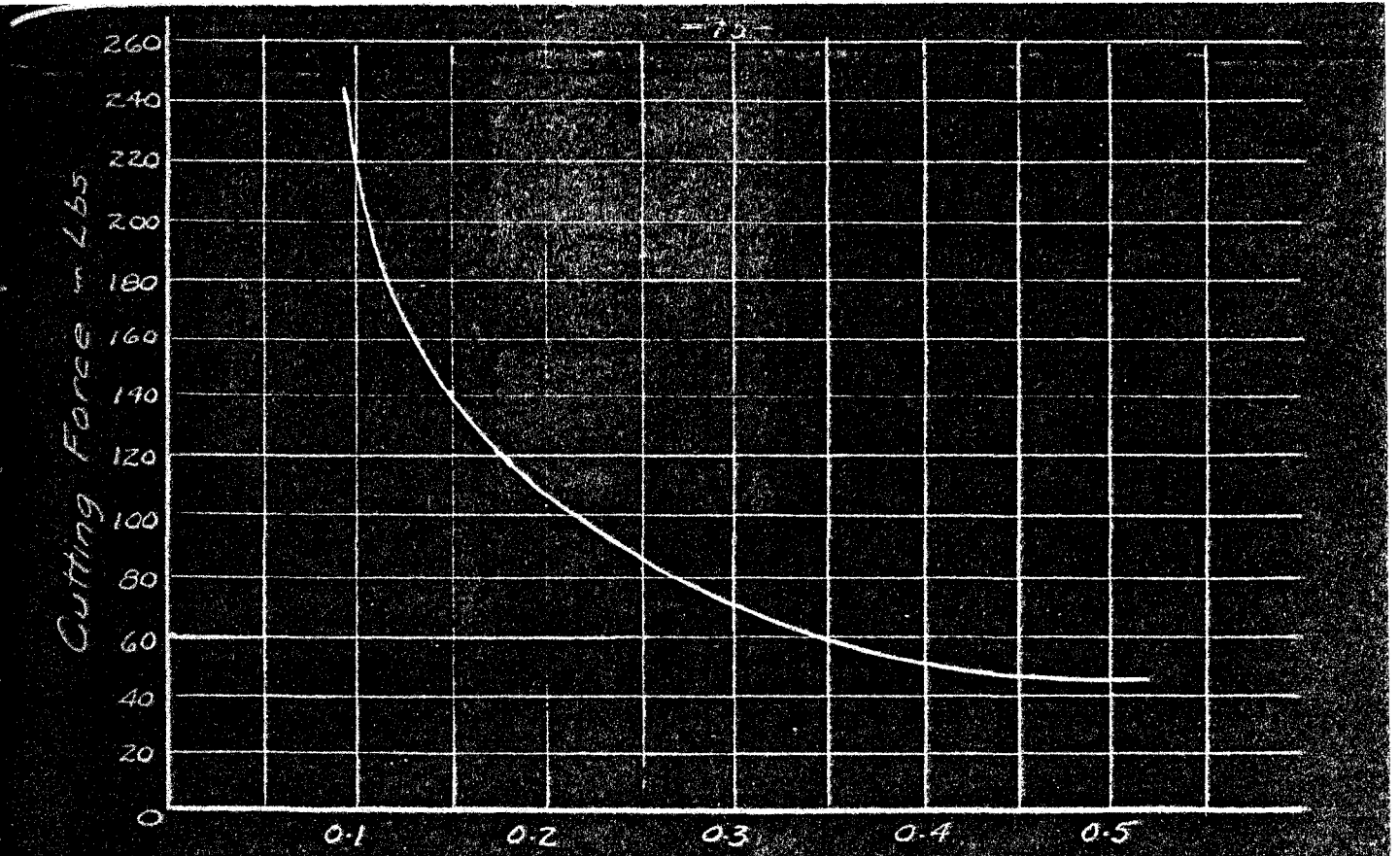


Fig 22(a).

Variation of Cutting Ratio With Cutting Force - Aluminum.

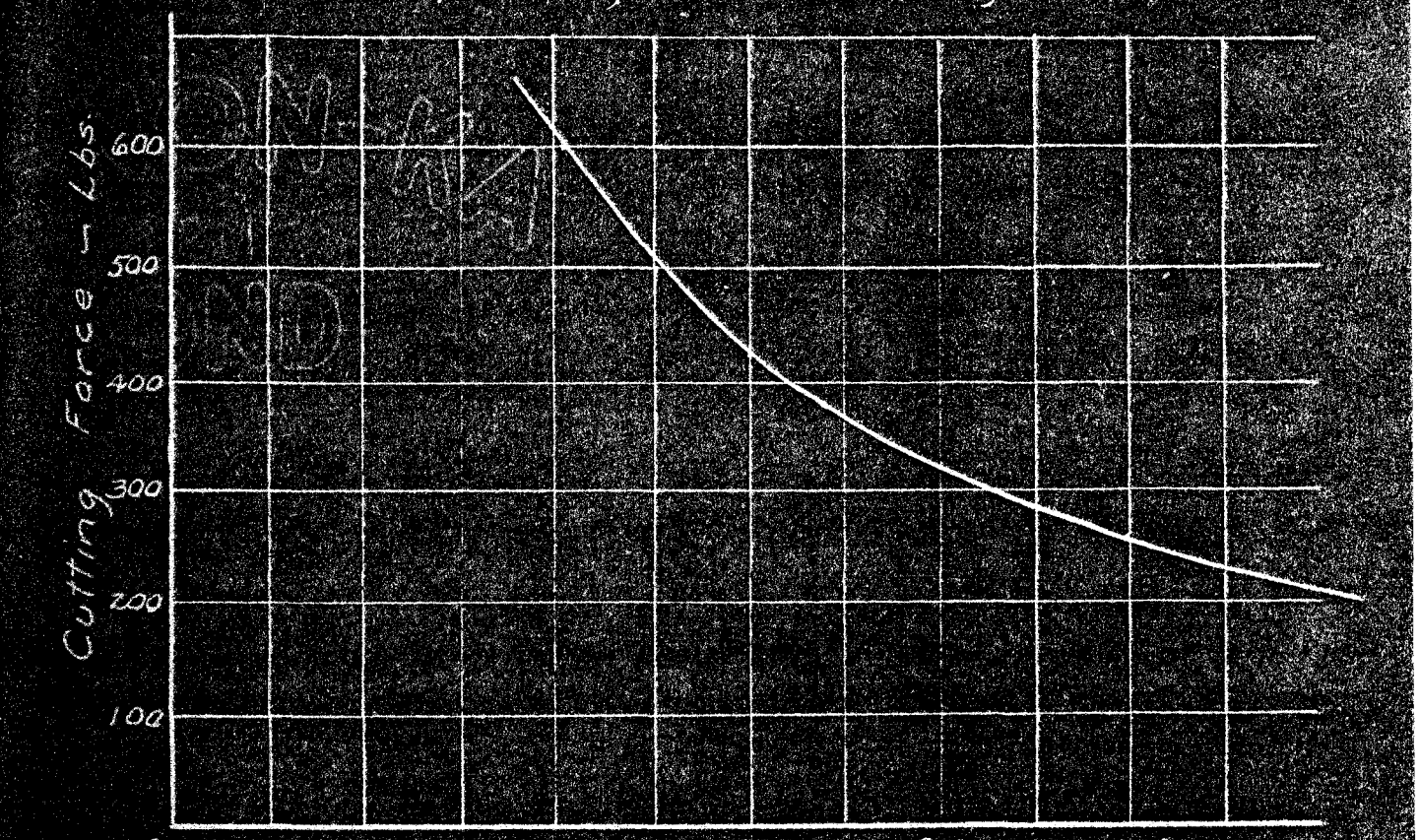


Fig 22 (b).

Variation of Cutting Ratio With Cutting Force - Steel.

shows the curve for an aluminum work piece while fig. 22-b is for SAE 1020 steel. Both of these curves are seen to be hyperbolic. When they are plotted on log-log paper, two straight lines are obtained (fig. 23).

The lines in fig. 23 may be represented by the equations:

a) For aluminum

$$\ln F = M_a \ln R + \ln K_a$$

b) For steel

$$\ln F = M_s \ln R + \ln K_s$$

where F = cutting force in pounds
R = cutting ratio
M_a and M_s = Slopes of the log-log curves
K_a and K_s = Constants depending on the material

The slope of each of the two curves is found to be exactly -1.

The equation for the aluminum curve is therefore $FR = K_a$ and K_a can be found from the coordinates of a point on the curve, giving $FR = 21.25$. Similarly, for SAE 1020 steel, the equation is $FR = 129$.

Thus, it has been shown that the cutting ratio is inversely proportional to the cutting force under the conditions of these tests, the constant of proportionality depending upon the metal being cut. The longer the chip formed, the lower will be the cutting force involved. Also, in general, the better chips are those which are curled into the tightest spirals.

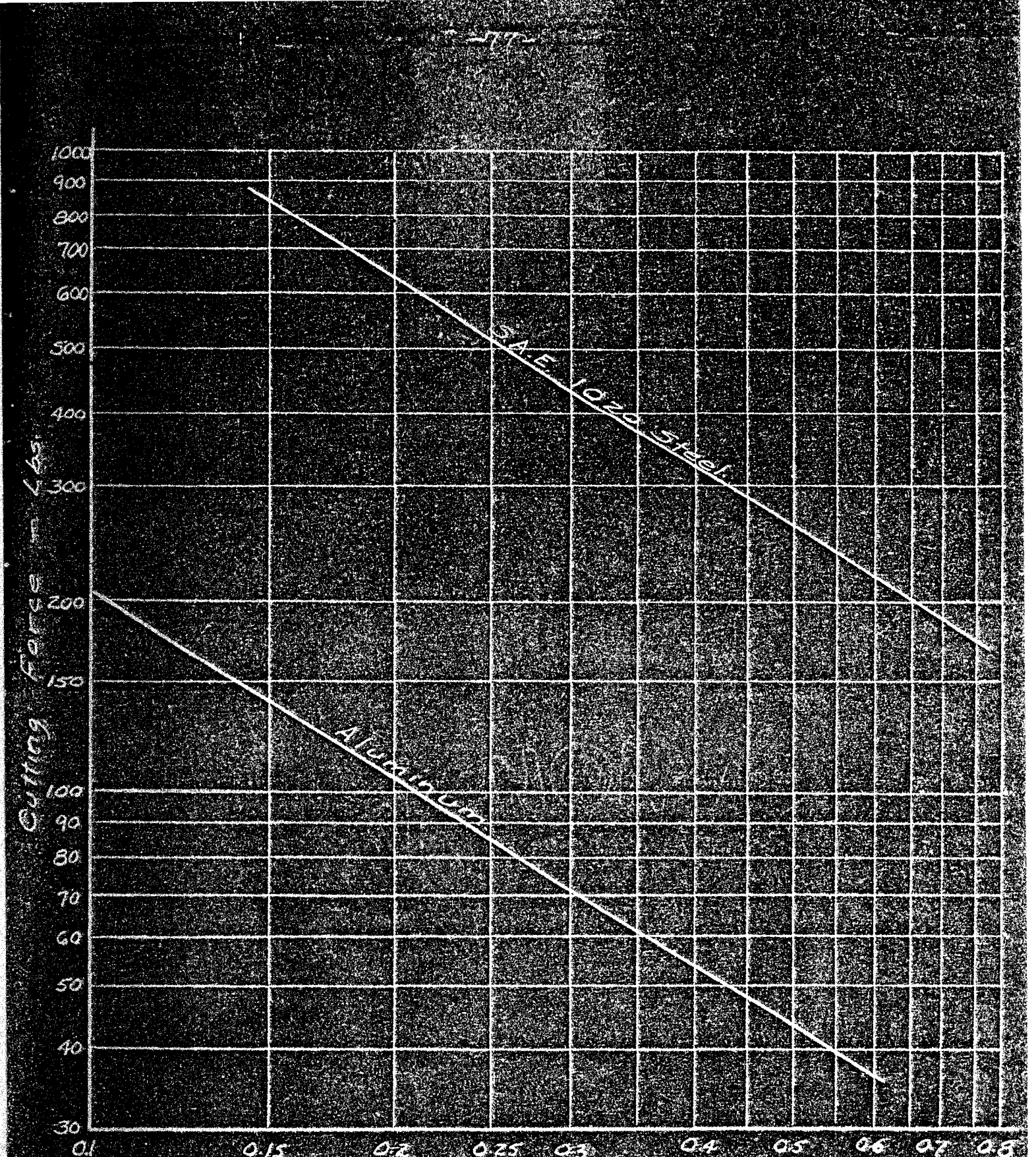


Fig. 23

Variation of Cutting Ratio With Cutting Force

Tests with Chlorinated Hydrocarbons

The chlorinated compounds were one of the groups of compounds most extensively studied in this investigation. Several different types of tests were made on these compounds, and an attempt was made to correlate the various independent results. The data obtained is shown in Table VII. The fluids tested are divided into three groups - the chlorinated derivatives of methane, ethane and ethylene.

The reflux tests were carried out by boiling 20 ml of the fluid with six one quarter inch diameter discs of aluminum for a long time. In all cases, the condenser was fitted with a drying tube and the joint between condenser and flask was made with a ground glass joint. The time given in column 5 of Table VII is the time of refluxing required before a noticeable reaction occurred. The slow speed cutting tests were made with the improved planer apparatus. In all cases, it can be seen that those fluids which reacted while being refluxed with the aluminum proved to be the better cutting fluids. None of the unsaturated compounds reacted in either the reflux test or in the fly milling apparatus, and these compounds proved to be very poor cutting fluids. The fact that the unsaturated ethylene derivatives were so poor has already been discussed.

Wilson (94) has said that there is no apparent relation between the total amount of halogen in a molecule and the re-

Table VII

Fluid	Formula	Boiling Point °C	Decomposes At B.P.	Reaction When Refluxed	Cutting Ratio	Coefficient of Friction	Chip Shape	Reaction in Fly Mill Ap.
Carbon Tetrachloride	CCl_4	76.7	No	Yes - 8½ min.	0.427	0.288		Yes
Chloroform	$CHCl_3$	61.2	No	Yes - 2½ Hr	0.401	0.312		Yes
Dichloromethane	CH_2Cl_2	39.8	No	No - 6 Hr	0.265	0.477		No
Pentachlorethane		161.9	Yes - 180 mm	Yes - 6 min/125	0.230	0.648		Yes
5 Tetrachlorethane		146.5	Yes - 360 mm	Yes - 2 min/200	0.320	0.419		Yes
3 Trichlorethane		113.5	Yes - 700 mm	Yes - 1½ min/150	0.344	0.407		
Methyl Chloroform		74.1	No	Yes at R.T.	0.340	0.422		
Ethylene Dichloride		83.7	No	No - 24 Hr	0.250	0.481		
Ethylidene Dichloride		57.3	No		0.330	0.406		
Ethyl Chloride		12.5	No		0.255	0.511		
Tetrachloroethylene		120.8	No	No - 24 Hr	0.195	0.603		
Trichloroethylene		86.7	No	No - 24 Hr	0.188	0.623		No
t Dichloroethylene		48.4	No	No - 24 Hr	0.185	0.612		No

activity of the halogen in the compound. This has been found to be the case in this investigation. No relationship is evident between the reactivity of a compound (or its effectiveness as a cutting fluid) and the amount of chlorine contained in the molecule.

Chemical Reactions Studied

The fly milling apparatus was used to study the chemical reactions taking place when metal was cut in the presence of a cutting fluid. Carbon tetrachloride was the first compound chosen for investigation. The nature of the reaction which occurred when aluminum was cut in the presence of carbon tetrachloride was entirely unexpected, the quantity of reaction product formed being very large.

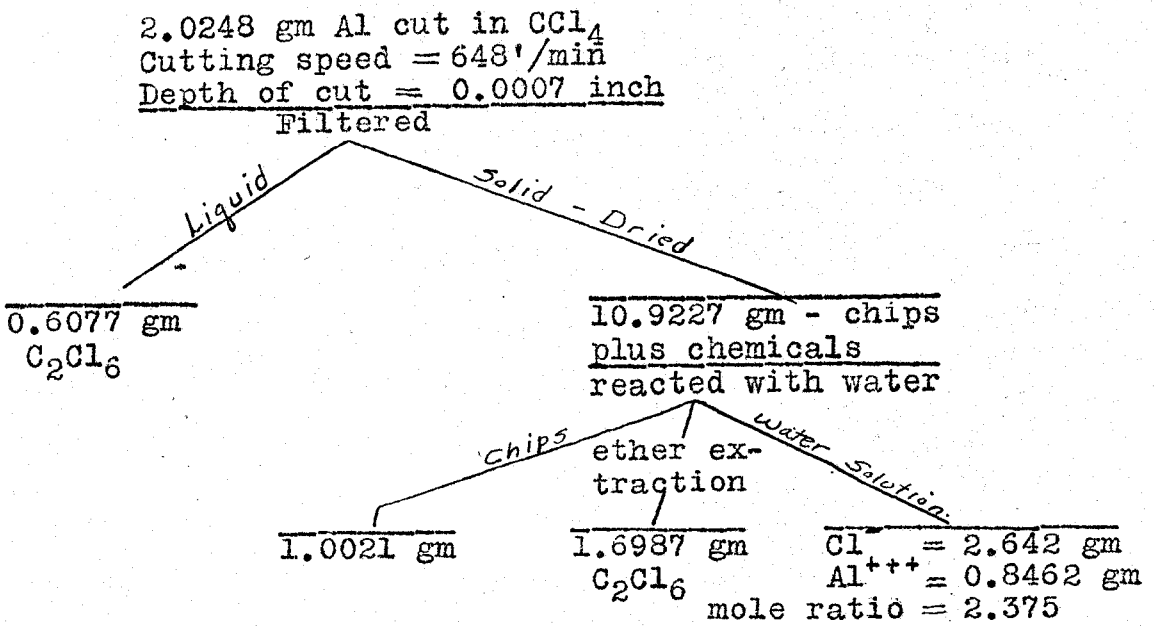
Zappi (95) has reported that aluminum is not attacked by carbon tetrachloride at room temperature even after standing for four months. However, when carbon tetrachloride is heated in a sealed tube with aluminum to 100 - 120°C, aluminum chloride, hexachlorethane, higher chlorides and a resinous product are formed. A contradictory statement is made by Sastry (80) to the effect that no reaction occurs between carbon tetrachloride vapor at its boiling point and aluminum. Rhodes and Carty (79) report no reaction at room temperature even after an exposure of six months. However, these authors say that when aluminum is exposed to dry carbon tetrachloride va-

pors, it is rapidly attacked with the formation of a dark gray powder. This powder has a very penetrating, resinous odor and hisses when thrown into water forming aluminum chloride and hexachlorethane. No other metal was found to form hexachlorethane when reacted with carbon tetrachloride.

After cutting had proceeded for about a half minute in the fly milling apparatus, a bright port-red color appeared in the solution and the chips had the same reddish hue. This color gradually darkened as the cutting was continued. Upon removal of both chips and carbon tetrachloride from the apparatus and allowing them to stand, a fluffy, dark red, floculent precipitate was observed.

When this floculent precipitate was separated from the other material by filtering and was dissolved in water, analysis indicated the presence of one atom of chlorine for each atom of aluminum. The red material initially formed on the chips was found to be very sensitive to moisture and to produce the red fluffy precipitate in the presence of water vapor. This red fluffy material is believed to be mainly aluminum hydroxychloride, colored by the presence of a small amount of a complex organo-metallic compound.

The results from a typical cutting test with carbon tetrachloride are shown diagramatically below:



Upon allowing the chips and carbon tetrachloride to stand in a loosely stoppered bottle at room temperature, it was found that the reaction continued and was endothermic to the extent that the solvent was soon brought to the boiling point. It appears that this reaction is autocatalytic, the red material first formed acting as a catalyst for the formation of additional reaction product.

The amount of hexachlorethane formed in the reaction of carbon tetrachloride is quite large. In one instance, 13 grams of aluminum were cut in the fly milling apparatus at room temperature, and the chips formed were allowed to stand in excess carbon tetrachloride at room temperature for a few hours. The result was the formation of 58 grams of hexachlorethane.

Several attempts were made to analyze the red material formed initially on the chips, but with no success. This red material was found to be very sensitive to moisture and heat. The fact that the material lost its deep red color upon hydrolysis, giving an aluminum chloride solution together with insoluble hexachlorethane, suggested the possibility of the existence of some sort of an organic chloride complex. This red substance behaved like very active aluminum chloride when brought into contact with water.

After considering the results of the various analyses made and all other available information, the following is presented as a possible reaction mechanism.

Happens while cutting:

$$3\ CCl_4 \longrightarrow 3\ Cl^- + 3\ CCl_3^+ \quad (1)$$

$$3\ Cl^- + Al \longrightarrow AlCl_3 \quad (2)$$

$$AlCl_3 + CCl_3^+ \longrightarrow AlCl_3.CCl_3 \quad (3)$$

$$2\ CCl_3^+ \longrightarrow C_2Cl_6 \quad (4)$$

Summary: $3CCl_4 + Al \longrightarrow AlCl_3.CCl_3 + C_2Cl_6$ (5)

Upon Taking from Apparatus and Standing in CCl_4:

$$AlCl_3.CCl_3 + 2H_2O \longrightarrow AlCl(OH)_2 + 2HCl + \tfrac{1}{2}C_2Cl_6 \quad (6)$$

$$AlCl_3.CCl_3 \xrightarrow{\text{in } CCl_4} AlCl_3 + \tfrac{1}{2}C_2Cl_6 \quad (7)$$

Summary: $AlCl_3.CCl_3 + C_2Cl_6 \xrightarrow[H_2O]{\text{trace}} AlCl_3.CCl_3 + C_2Cl_6 + AlCl(OH)_2 + AlCl_3 + HCl$ (8)

Upon Reacting with Water:

$$AlCl_3 + H_2O \longrightarrow Al^{+++} + 3\ Cl^- \quad (9)$$

$$AlCl_3.CCl_3 + 2H_2O \longrightarrow AlCl(OH)_2 + 2HCl + \tfrac{1}{2}C_2Cl_6 \quad (10)$$

$$AlCl(OH)_2 + H_2O \longrightarrow Al^{+++} + Cl^- + 2\ OH^- \quad (11)$$

Summary: $AlCl_3.CCl_3 + AlCl(OH)_2 + AlCl_3 \longrightarrow C_2Cl_6 + Cl^- + Al^{+++} + OH^- + HCl$. (12)

Final Summary: $CCl_4 + Al \xrightarrow{H_2O} C_2Cl_6 + Cl^- + Al^{+++}$ (13)

In order to determine whether or not the presence of the inert nitrogen atmosphere had any effect, a test was run and the chips and fluid were analyzed for nitrogen. A negligible

amount of nitrogen was indicated by the Kjeldahl method, thus indicating that the presence of the nitrogen atmosphere had no effect upon the products formed in the cutting chamber.

It was found that the same red complex material could be produced by refluxing pure carbon tetrachloride in the presence of pure aluminum. This red material first appeared after refluxing for about 8½ minutes, but it was necessary to reflux for several hours to produce the same amount formed in a few minutes in the cutting chamber with the bulk of the fluid at room temperature.

In order to make sure that no secondary reaction took place between aluminum and hexachlorethane, pure aluminum was subjected to hexachlorethane vapors at 160°C under high vacuum. No reaction was found to take place.

In order to find out what happens when chloroform reacts with aluminum, several small aluminum discs were refluxed with pure chloroform. There was no evidence of a reaction for the first 2¼ hours. After this period of time, the liquid at first turned pink and then rapidly grew black. The time required for the reaction to go to completion depends upon the size of the aluminum employed. For 1/4 inch diameter aluminum discs, the total reaction time is about ten hours. Upon making an analysis, only two products were found, namely carbon and aluminum chloride.

The carbon is formed in the ratio of two parts of carbon by weight to three parts of aluminum, thus indicating the following overall reaction

$$3CHCl_3 + 2Al \longrightarrow 2AlCl_3 + 3HCl + 3C$$

This reaction is very interesting because it is quantitative and the reaction products are extremely simple. Incidentally, this reaction offers an excellent method of preparing absolutely anhydrous aluminum chloride for use in a reaction such as the Friedel-Crafts.

In carrying out the above reaction, it is necessary that the chloroform used have no trace of ethanol (usually present in chloroform as a stabilizer), otherwise the reaction is very sluggish or will not even start. Ethanol is easily removed from the chloroform by washing it with water several times. The reaction described above occurred whether refluxing was carried out in an atmosphere of air or nitrogen.

dry with Na. wire

When aluminum was cut at 4.85 inches per minute using the improved planer apparatus and a heated tool, chloroform was found to leave a considerable black deposit. When chloroform vapor was used in place of the liquid, the entire cut surface was covered with a black deposit while the sides of the work piece did not change in appearance.

When aluminum was cut in the presence of s-tetrachlorethane in the fly milling apparatus, a considerable reaction

occurred. Upon analysis, only aluminum chloride and a black resinous gum were found as the products.

Pentachlorethane when refluxed with aluminum gave aluminum chloride and considerable tetrachlorethane. However, when pentachlorethane was employed in the fly milling apparatus, no tetrachlorethane was produced, the only products formed being aluminum chloride and a black tar-like gunk.

The Effect of Cutting Speed upon Quantity of Chemical Product

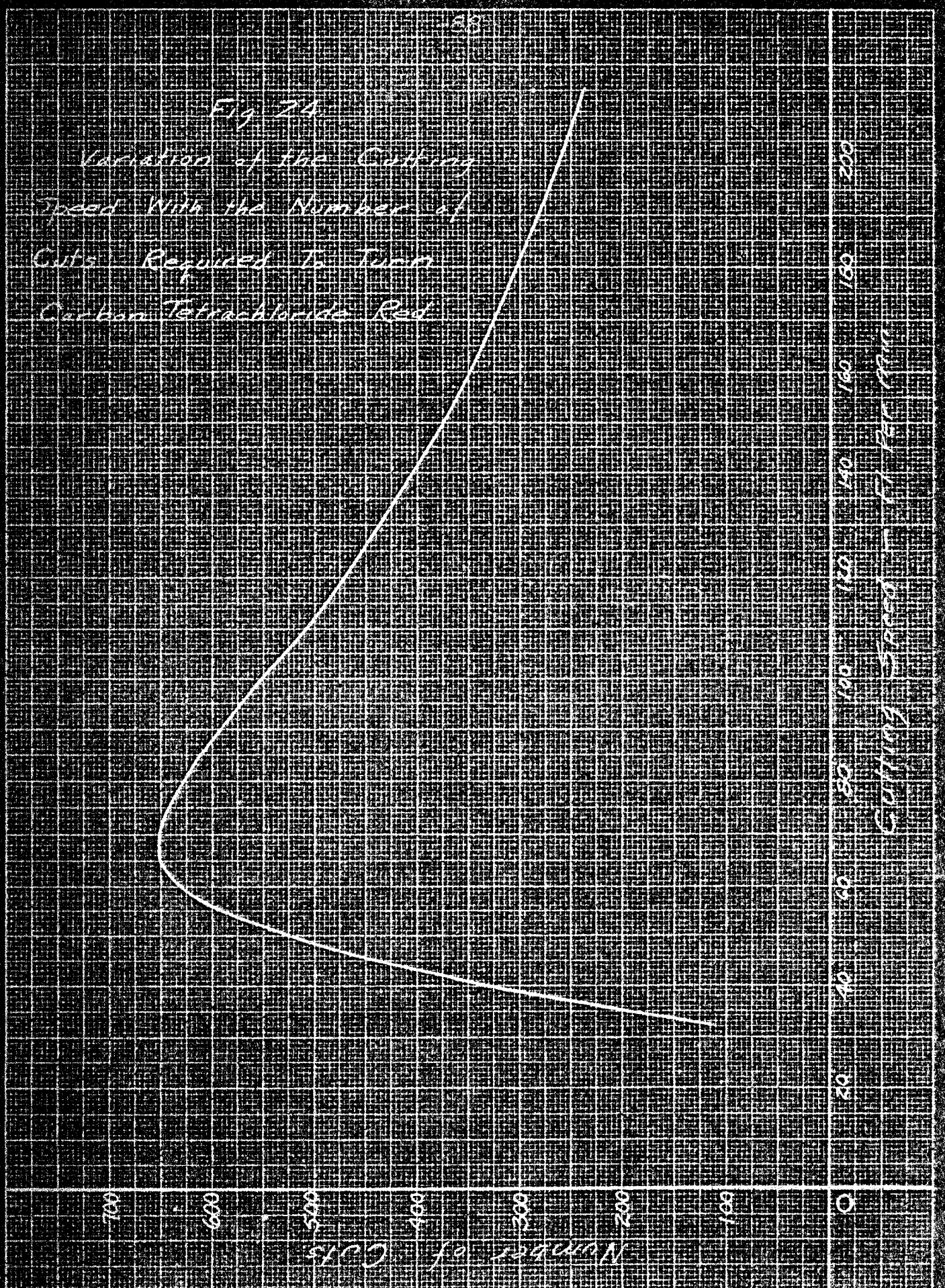
The variation in the efficiency of carbon tetrachloride as a cutting fluid (as measured by cutting ratio) with cutting speed has already been discussed. In fig. 18, these data are plotted and it can be seen that a minimum point occurs at a speed of approximately 60 feet per minute. The tests made with the fly milling apparatus included a series of runs in which the time required for the carbon tetrachloride to turn red was noted at different speeds. This table is given below in Table VIII and is plotted in fig. 24.

Table VIII

Cutting Speed '/min	Time for CCl_4 to turn red - seconds	No. of cuts to turn CCl_4 red
35	75	226
44	100	372
64	120	650
95	65	572
139	35	408
204	15	259
300	-	-

Fig 24

Variation of the Centering Speed With the Number of Cuts Required To Clean Carbon Tetrachloride Red

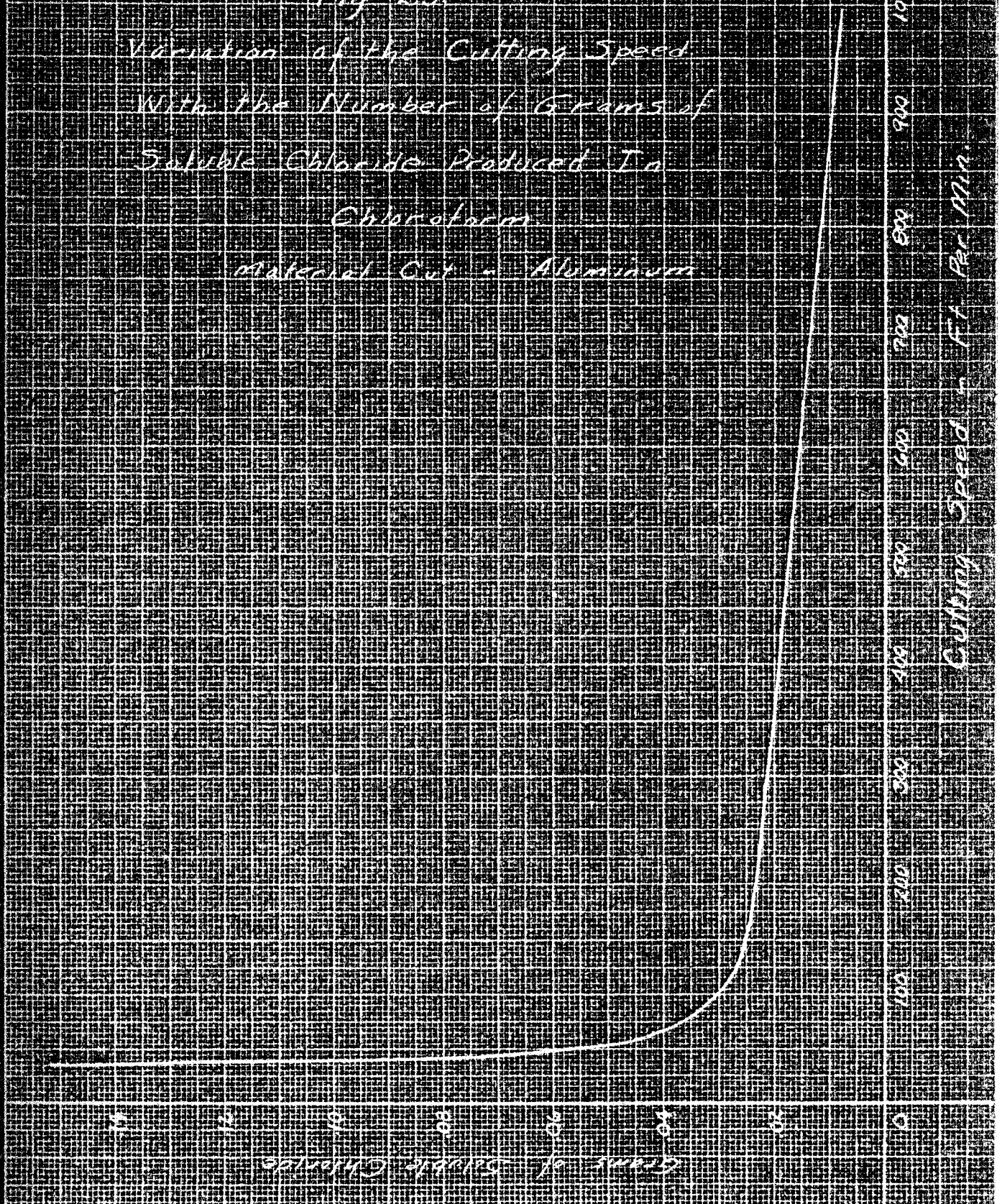


The table and curve above show that there is a maximum number of cuts required to make the carbon tetrachloride turn red. This maximum occurs at a cutting speed of about 60 feet per minute. If we assume that at all speeds, the same concentration of product is required to make the carbon tetrachloride appear red, then we can say that at about 60 feet per minute, the quantity of product formed per cut is a minimum. There is no doubt that the shape of fig. 24 is a chemical phenomenon. The similarity between fig. 24 and 18 therefore offers excellent evidence that the variation in cutting ratio and hence in cutting efficiency is governed by a chemical reaction.

A series of tests using chloroform in the fly milling apparatus indicated that this fluid behaved differently with change in speed than did carbon tetrachloride. In a number of tests, the same amount of aluminum was cut in the presence of the same amount of chloroform, but at different speeds. After each test, all chips and fluid were washed with water, and the water titrated for soluble chloride. This total amount of soluble chloride was taken to be a measure of the extent of chemical reaction at the various speeds. The data obtained is shown plotted in fig. 25. This curve shows that unlike carbon tetrachloride, chloroform does not reach a minimum of reaction product as the cutting speed is increased. Thus, it would be expected that chloroform would become poorer

Fig 25

Variation of the Cutting Speed With the Number of Milligrams of Soluble Chloride Produced In Chloroform Material Cut - Aluminum



and poorer as a cutting fluid as the cutting speed was increased.

As has been previously mentioned, chemical products were clearly visible in several cases after completing a low speed cut with the improved planer apparatus. A number of such 3 inch specimens holding deposits were preserved, and are shown photographed in fig. 26. This photograph does not reveal much, but the presence of a considerable deposit is evident in several cases. The surfaces and deposits produced using carbon tetrachloride and chloroform vapors are also shown. It should be noted that the uncut sides of these specimens remained bright and were absolutely unattacked by the vapors, while the freshly cut area reacted considerably with the vapors.

Tests with Alcohols

It has already been mentioned that the preliminary investigation showed that the cutting ratio increased with the chain length of the alcohols tested. While these compounds show little promise as practical cutting fluids, they have proved to be very beneficial in presenting several interesting cutting fluid phenomena. Very pure samples of the alcohols were used in the work to be described. It was found that the action of the alcohols was very sensitive to impurities.

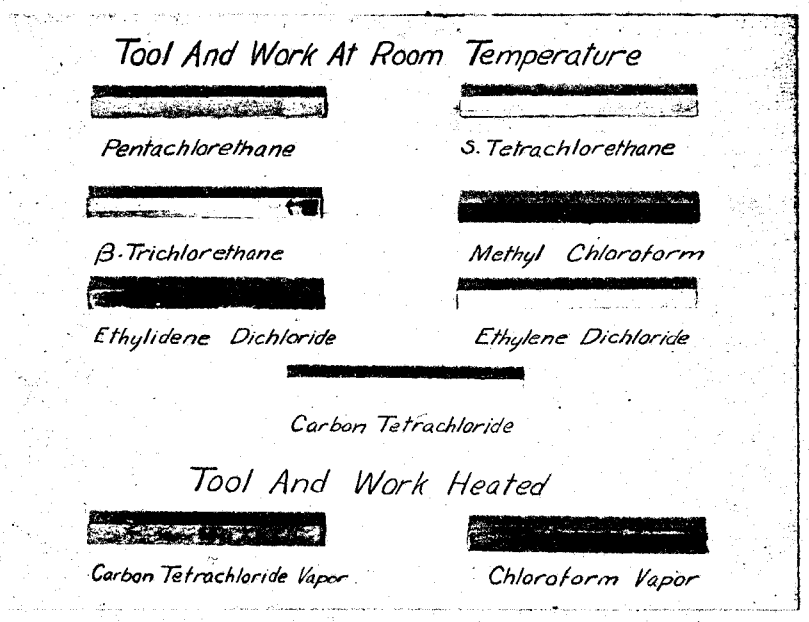


Fig. 26: Chemical Deposits Visible on Aluminum Surfaces Cut at Low Speed in the Presence of Several Organic Liquids and Vapors

For example, a sample of n.octanol, known to contain an impurity not separable by fractionation, gave results which did not check those predicted by previous results with other alcohols. When a new sample was obtained, prepared in a different manner and not containing the persistent impurity, this material gave a result quite in agreement with the other alcohols. Thus, the purity of the compound used in a cutting test is of vital importance.

An actual chemical product was never detected in any of the cutting tests using alcohols. This, however, does not prove that a chemical reaction could not have occurred. It is rather to be expected that in general, the reaction product will be detectable with great difficulty. The reaction will probably cease as soon as the cut is completed, either because the reaction is not autocatlytic, and stops as soon as the surface temperature and pressure return to normal, or because the reaction product takes the form of a continuous film which renders the metal surface inert to further chemical attack (just as the layer of aluminum oxide renders an aluminum surface relatively stable and inert to chemical attack). If such be the case, the total amount of product present on the chips will be quite small and may defy detection by means less sensitive than electron diffraction.

Seligman and Williams (82) have stated that anhydrous, normal, primary alcohols attack aluminum at high temperatures.

These authors claim that minute quantities of water are sufficient to prevent the attack or to stop it once it has started. The preparation of aluminum isopropylate has received considerable attention because of its use in the Meerwein-Ponndorf Reduction. It is often quite troublesome to start the reaction in the preparation of aluminum isopropylate. This reaction is autocatalytic and once started, proceeds without difficulty. It may be that the presence of small amountsof moisture in the alcohol stop the reaction by oxidizing the freshly cut aluminum surface. The fact that the alcohaltes have dehydrating properties may then account for the autocatalytic feature of the reaction of aluminum with alcohol.

Alternation of Chemical Properties of Members of Homologous Series Having Even and Odd Numbers of Carbon Atoms

When pure, normal monohydric alcohols were tested in the simple planer apparatus, the cutting force was found to alternate with the use of successive members of the alcohol series. Fig. 27 was obtained by plotting the cutting force against the number of carbon atoms in the alcohol chain.

While there are many references in the literature to the periodic variation of such properties as melting point, viscosity, heat and entropy of crystallization, molecular volume and other physical properties of successive members of homologous series, little has been reported concerning similar periodic alternations of chemical properties (47).

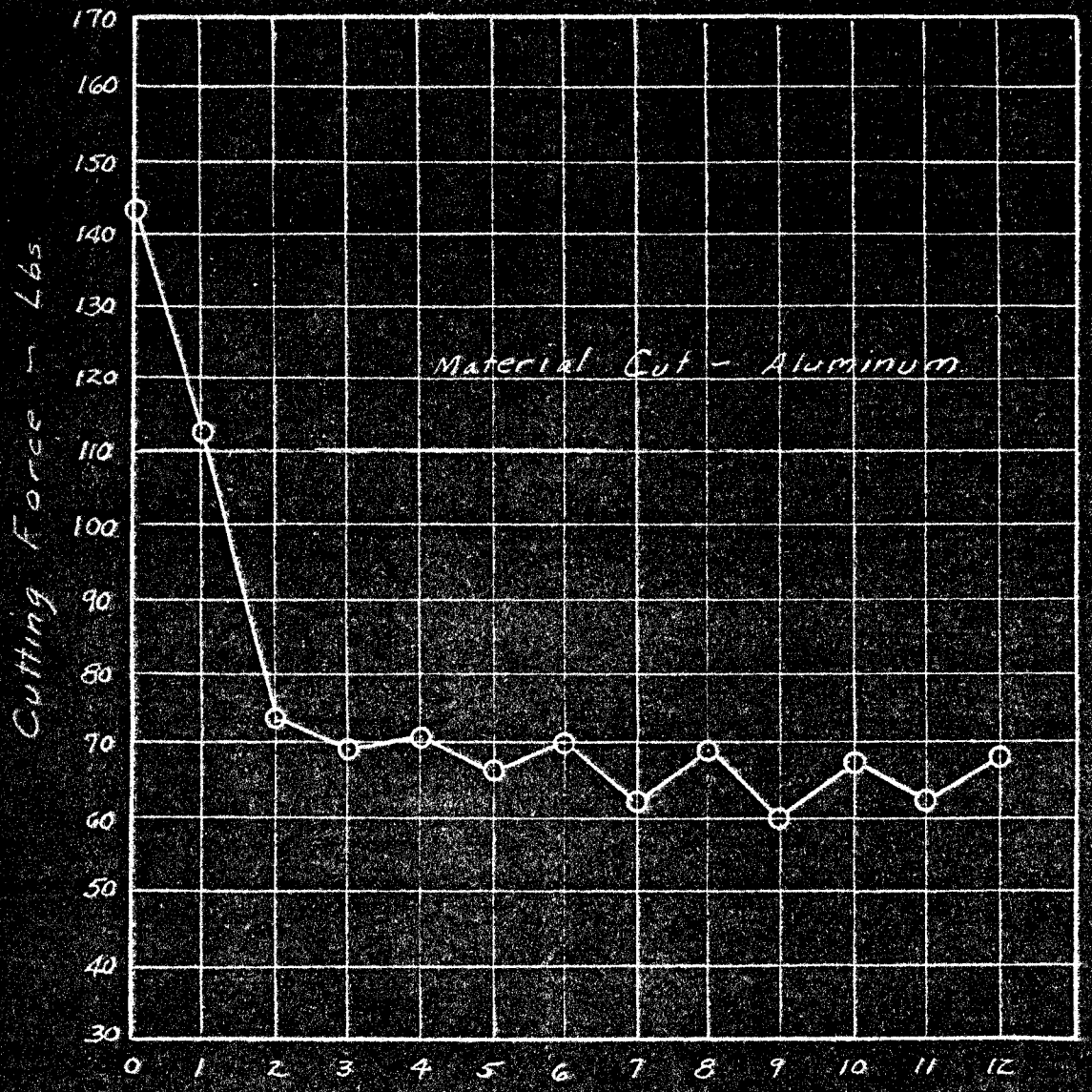


Fig 27

Variation of Cutting Force With Chain Length For Alcohols

Challenor and Thorpe (33) have mentioned that they observed a difference in the ease with which even and odd members of the dibasic acid series were oxidized. A borderling case, which may be considered either physical or chemical in nature, is reported by Biltz and Balz (14), who measured the dissociation pressure of various ammonia salts and found that these pressures alternated as the series was ascended.

An excellent example of the alternation of chemical properties in a series is given by the yields of some Grignard reagents produced from alkyl iodides as reported by Gilman and McCracken (48). These authors draw attention to the apparent irregularity of their data. They consider the phenomenon of alternating properties of even and odd numbered members of an homologous series as a possible explanation of this irregularity, but seemingly discard it because the yield of ethylmagnesium iodide is not in agreement with the general even - odd variation. This anomaly should not be greatly stressed since the first and second members of such series often behave differently than the subsequent members would indicate. In fig. 28, these yields are plotted against the number of carbon atoms in the alkyl chain. The value for ethylmagnesium iodide was obtained from an article by Gilman and Meyers (49).

Applying the chemico-physical theory of cutting fluid action to explain this alternation, we find that the alcohols having an odd number of carbon atoms in their chain must be the more chemically reactive since they are the more efficient in

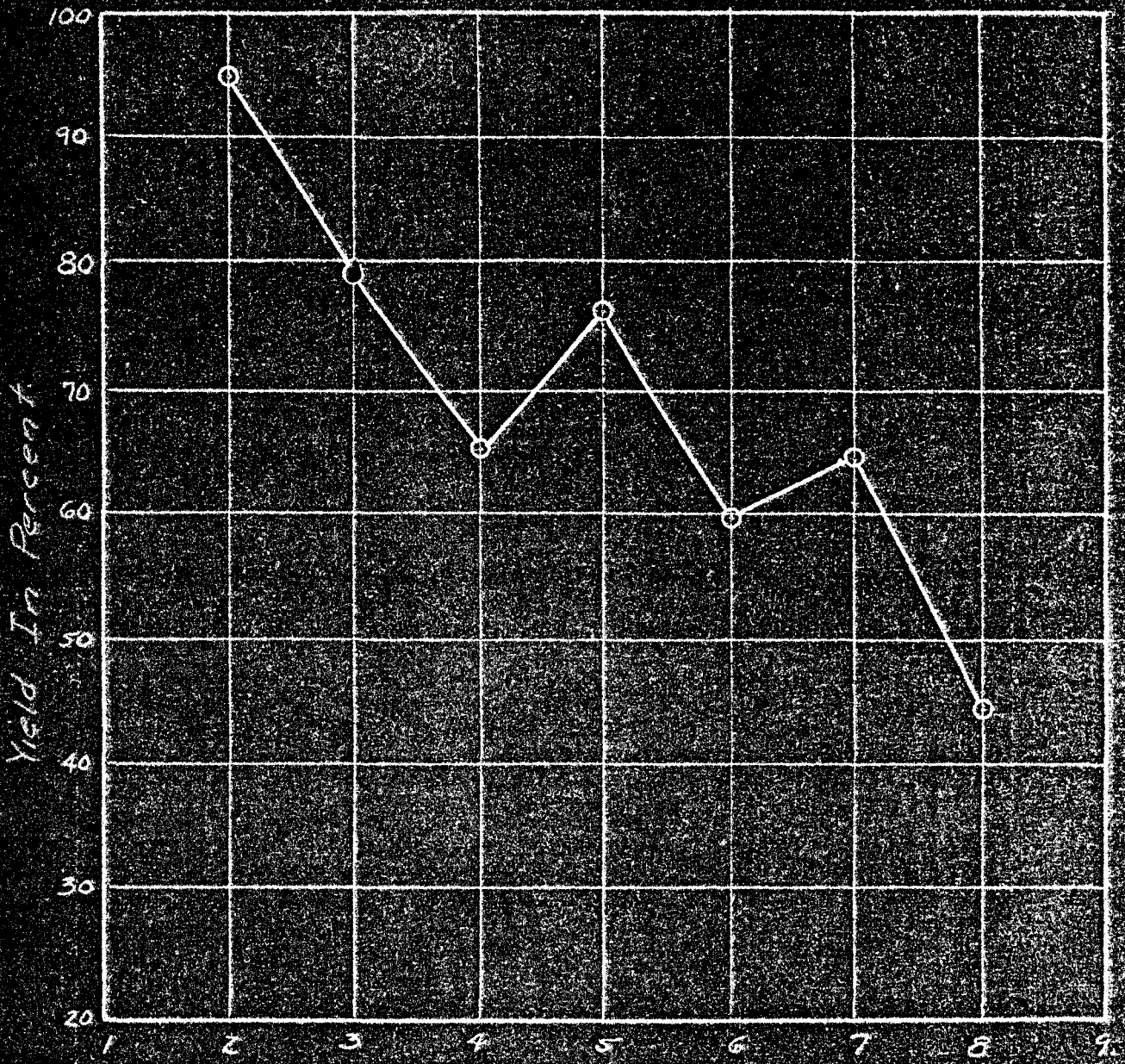


Fig. 28.

Yield of Grignard Reagents From Normal Alkyl Iodides.

this particular metal cutting operation. The fact that the alkyl iodides having an odd number of carbon atoms in their chain give better yields than those having an even number of carbon atoms, indicates that here, too, the compounds having an odd number of carbon atoms are more reactive chemically.

Photomicrographs of the aluminum surfaces produced with several alcohols are shown in fig. 29. These photomicrographs are all at a magnification of forty times, and in producing the surfaces, all variables were kept constant except the fluid used. The manner in which the built-up edge fragments on the surface decrease in both size and number as the chain length is ascended is readily apparent.

Tests were also made with several pure isomers of the normal primary alcohols. These isomers all gave cutting ratios less than the value corresponding to the normal compound of the same molecular weight. The length of the longest side chain seemed to be the important consideration in attempting to correlate the action of the various isomers.

Benzene - Alcohol Mixtures

In the course of the alcohol investigation, various mixtures of alcohols and benzene were employed. The mixtures of n.decanol and benzene proved to be the most interesting. Fig. 30 shows the variation in cutting ratio observed with mixtures of n.decanol in benzene ranging from 0 to 100% decanol. The

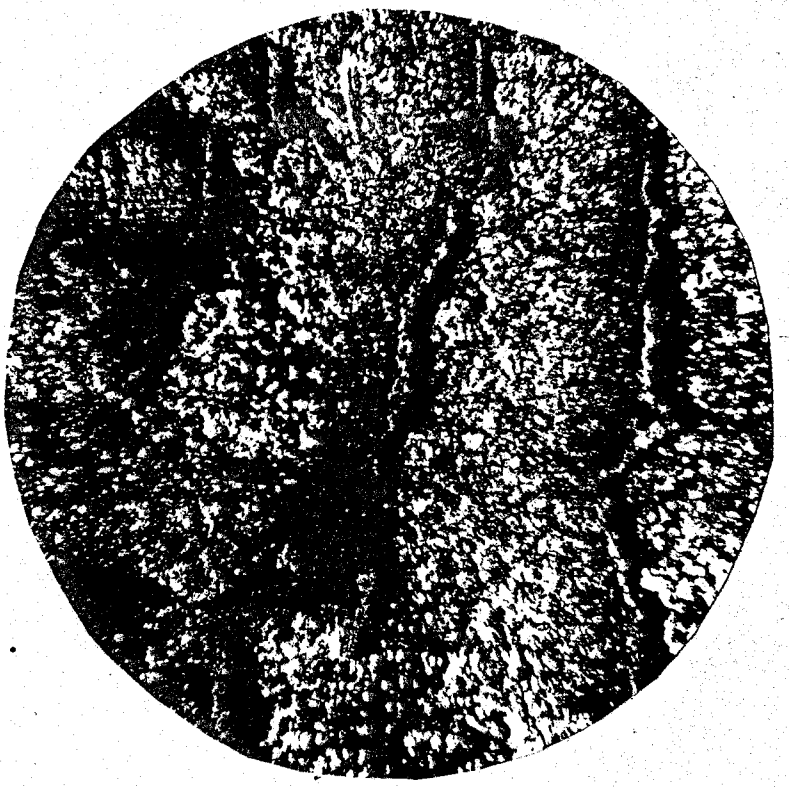


Fig. 29-a: Aluminum Surface Formed Using Distilled Water as the Cutting Fluid

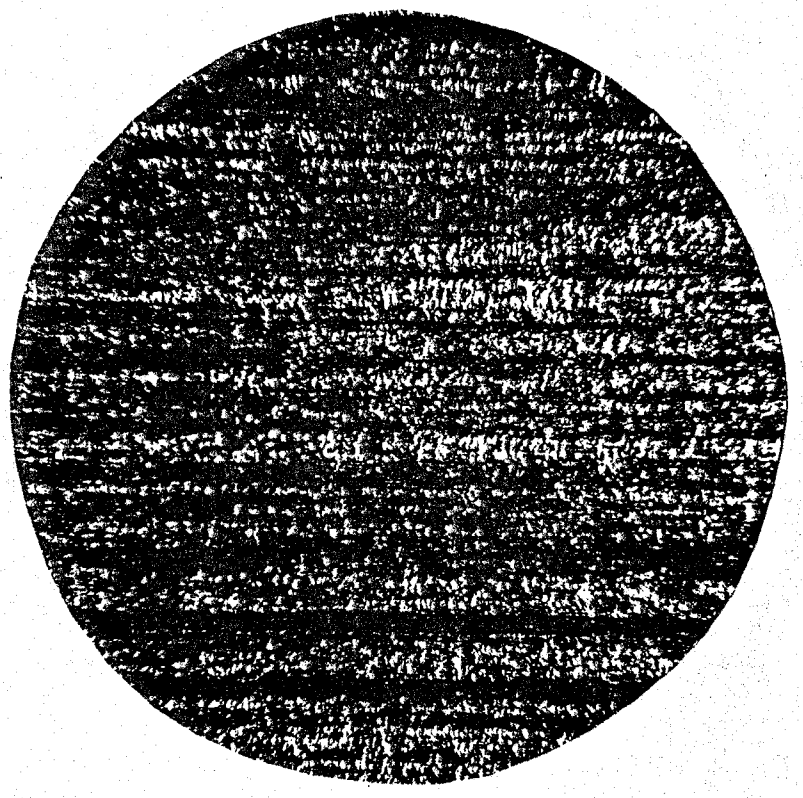


Fig. 29-b: Aluminum Surface Formed Using Ethanol as the Cutting Fluid

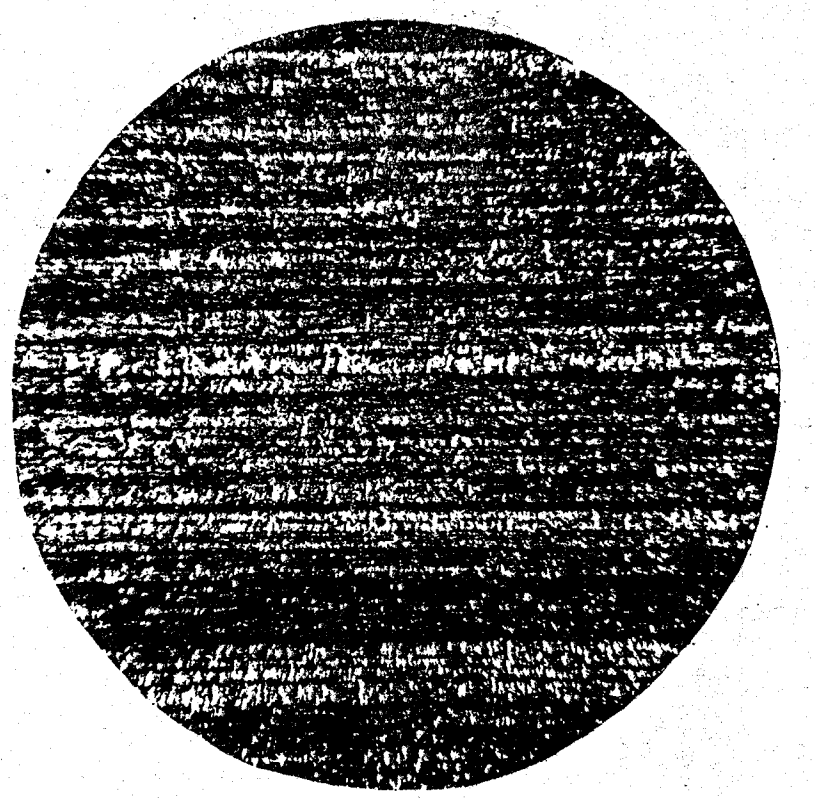


Fig. 29-c: Aluminum Surface Formed Using n.Butanol as the Cutting Fluid

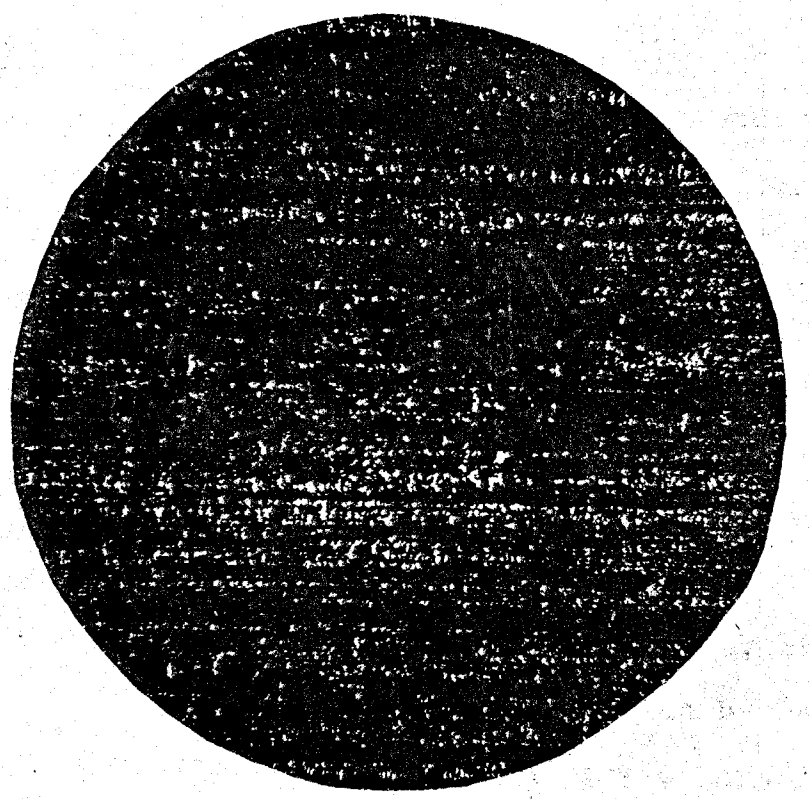


Fig. 29-d: Aluminum Surface Formed Using n.Decanol as the Cutting Fluid

chips produced in each case are shown opposite the concentration of the mixture used.

Below a concentration of 7% n.decanol in benzene, it was found that the chip produced was not at all uniform. The thickness of the chip varied periodically and on closer examination, the finished surface was found to be alternately rough and smooth with a period the same as that of the thickness variation. The cutting force likewise fluctuated periodically. This phenomenon first appeared at a concentration of 7% n.decanol in benzene, was most pronounced at 3%, and finally disappeared at a concentration of 1%.

An enlarged drawing of one of the chips and of the corresponding surface produced with a concentration of 3% n.decanol in benzene is shown in fig. 31. The cutting force maxima and minima are indicated at the points where they were observed, and the periodic rough spots on the surface are also indicated. A time scale is included and it can be seen that the period of the fluctuation is about six seconds. Photomicrographs of the rough and smooth portions of the surface are shown in fig. 32. Tests were also made in which o.xylene was used in place of benzene; a similar fluctuation of cutting force was observed.

The periodic variation of cutting force, chip thickness, and surface smoothness described above can be readily explained in terms of the chemico-physical theory of cutting fluid action.

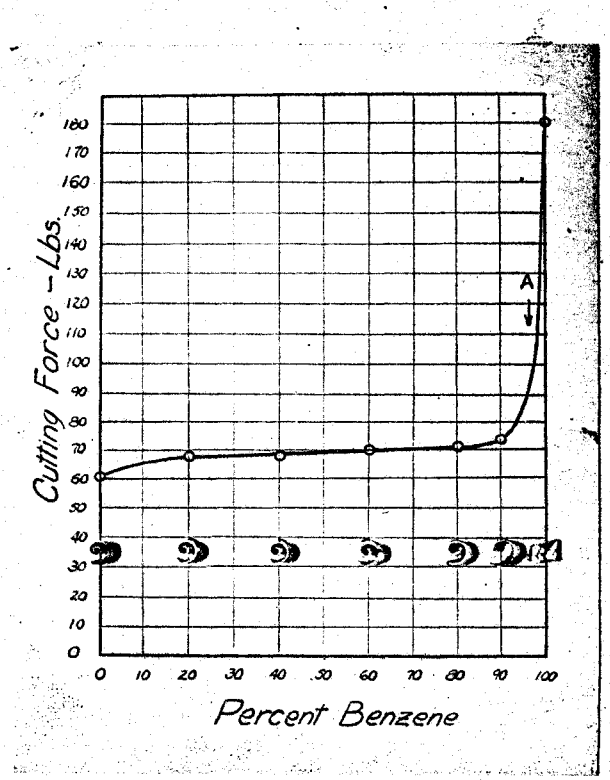


Fig. 30: Variation of Cutting Ratio with % n.Decanol in Benzene - Decanol Mixtures

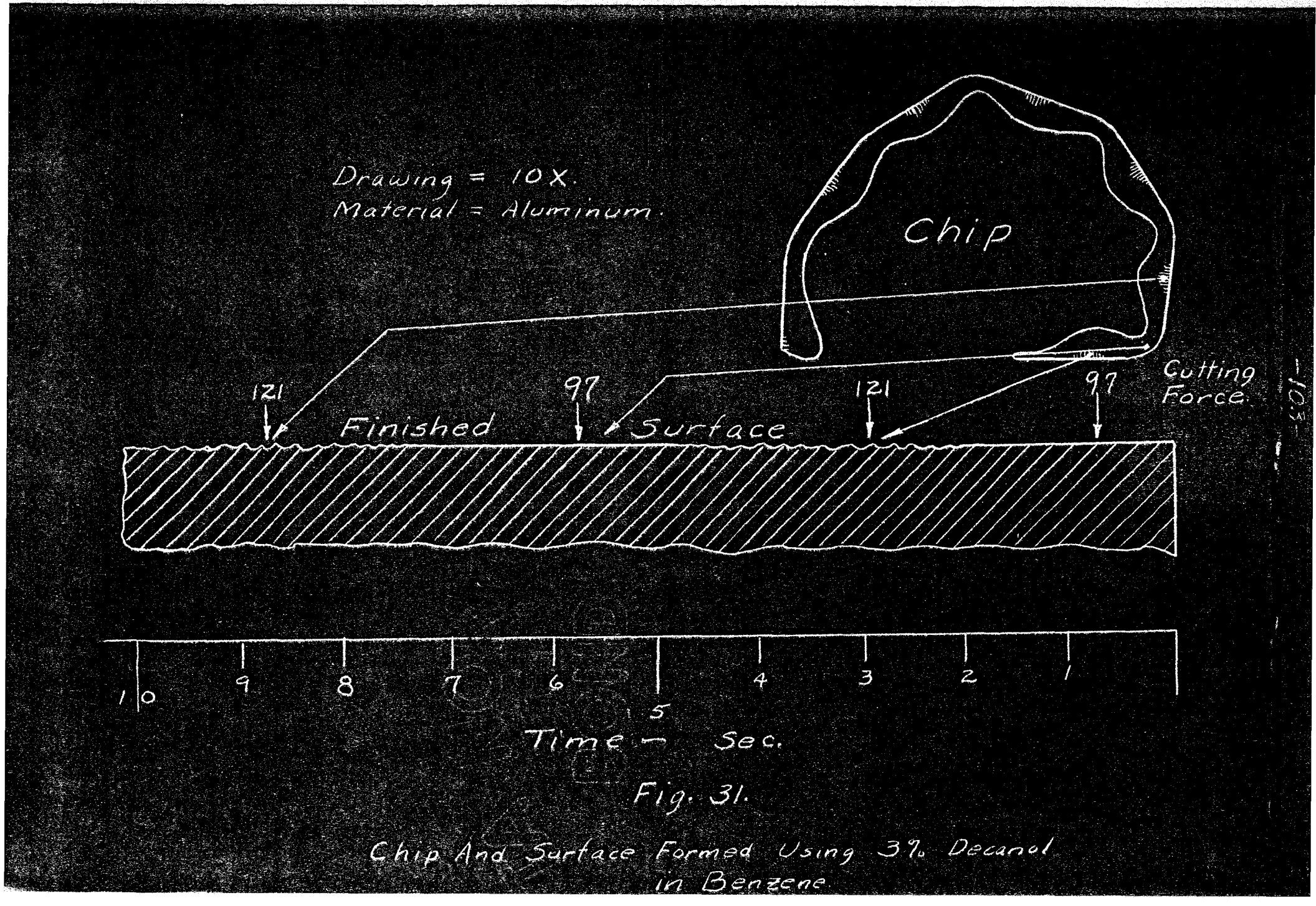


Fig. 31.

Chip And Surface Formed Using 3% Decanol in Benzene

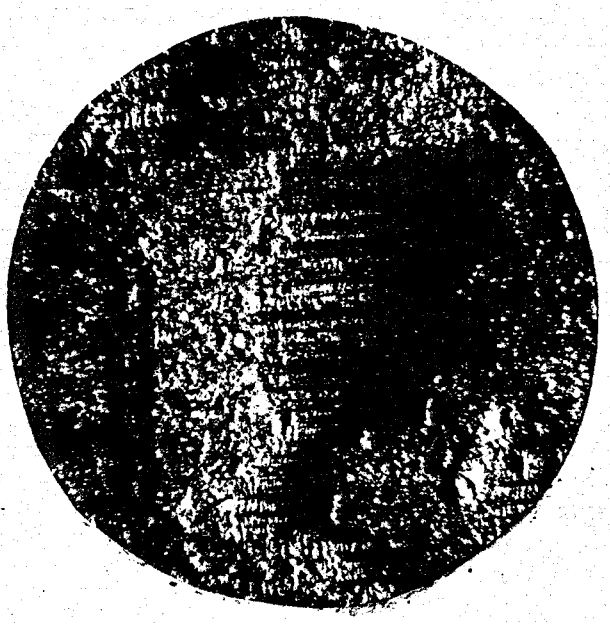


Fig. 32-a: Rough Portion of Surface Formed Using 3% n.Decanol in Benzene

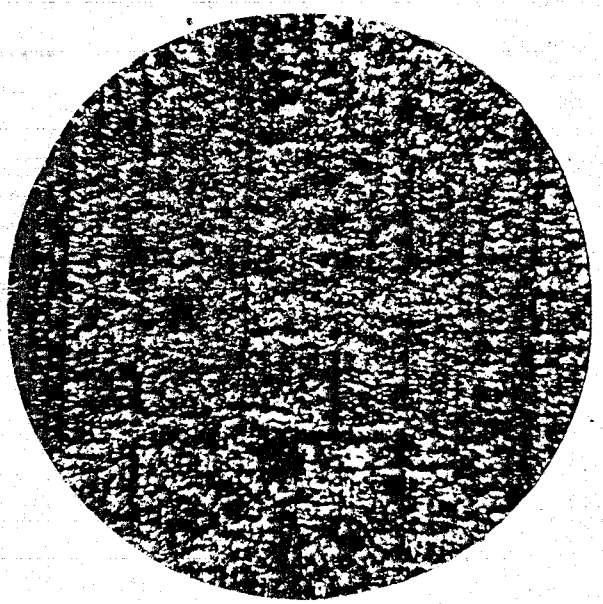


Fig. 32-b: Smooth Portion of Surface Formed Using 3% n.Decanol in Benzene

It is believed that this phenomenon arises from a critical relationship existing between the surface temperature, the pressure, the concentration of the active ingredient in the mixture and the amount of reaction product. It is reasonable to expect that a certain minimum quantity of low shear strength reaction product will be required to produce an appreciable reduction in coefficient of friction between chip and tool, and consequently produce a noticeable improvement in finish and reduction in cutting force. At the beginning of a cut, the surface temperature and the pressure increase as the tool moves ahead, and in general, reach a state of equilibrium with the rate of production of the reaction product. However, at a critical dilution of the active ingredient, the rate of production of the reaction product falls off rapidly; consequently, the cutting force rises sharply as at point "A" in fig. 30, where the cutting force increases suddenly with a slight decrease in the concentration of n.decanol. In such a critical region where a slight change in concentration causes such a large change in cutting force, one may expect to find a state of instability.

At the beginning of a cut, the surface temperature and the pressure increase gradually to a high value. In the critical region of 3% n.decanol in benzene, the concentration is just sufficient to produce enough reaction product for effective cutting fluid action, when this high surface temperature and pres-

sure are attained, thus decreasing the frictional resistance and the cutting force. At this reduced cutting force, the temperature and pressure are decreased and thus the quantity of the chemical product formed is insufficient for effective cutting fluid action to continue; therefore, the pressure and surface temperature once more increase. This cycle will be repeated periodically.

The fact that the period of the fluctuations described above is as long as six seconds, eliminates any possibility of this phenomenon being due to chatter or to any other periodic variation of the mechanical system.

A few tests were made with o-xylene as the solvent in order to ascertain whether the rate of evaporation of the solvent would have any effect upon the observed fluctuation. Like benzene, o-xylene is a poor cutting fluid, but it is much less volatile. The fact that the same period of fluctuation was observed when o-xylene was used in place of the benzene, shows that this effect is independent of the volatility of the solvent employed.

Benzene gives worse results in cutting steel or aluminum than those produced by cutting with a dry tool. This observation may at first seem unusual but can be readily explained. A dry tool or one operating in an atmosphere of air has present on its surface an organic film condensed from the air. This film prevents the tool from adhering as strongly to the chip as

might be the case if no such film were present. Benzene, being a good solvent for organic matter, helps to produce a clean tool when it is used as a cutting fluid and thus a surface produced in the presence of benzene will be worse than one made with a dry tool. Benzene will exclude air from the chip tool interface and likewise, any air-borne vapors. Such vapors may be capable of reacting with the chip or tool, thus producing a certain reduction in frictional resistance. By comparing the photomicrographs shown in figs. 16 and 17, together with the cutting forces given, it can be seen that a poorer steel surface is formed when benzene is present than when a dry tool is employed.

Tests with Sulfur Compounds

In general, the organic sulfur compounds were found to be excellent cutting fluids. Only those compounds which are known to be very stable toward aluminum, such as carbon disulfide, dimethyl sulfate and benzene sulfonyl chloride, proved to give poor results. As in the case of the alcohols, no reaction products were detected when aluminum was cut in the presence of mercaptan and disulfide in the fly milling apparatus.

A very interesting group of tests were made with commercial diamyl sulfide. This material is available from the Sharples Solvents Company and consists of a mixture of several isomers. Diamyl sulfide proved to be such a good cutting fluid that it was decided to fractionate some and test the highly purified ma-

terial. A sample was first rectified into five fractions as indicated in Table IX. The values of cutting force and cutting ratio given were obtained with the simple planer apparatus.

Table IX

Fraction No.	Percent Distilled	Boiling Point °C at 760 mm.	Cutting Force -lbs	Cutting Ratio
I	23.2	190.3 - 201	109	.227
II	36.4	201 - 208	117	.210
III	52.7	208 - 244	73	.330
IV	84.4	244 - 257	57	.397
V	100	above 257	57	.403
Commercial Sample		190 - 260+	61	.385

Each of the last three portions were then refractionated with the results given in Table X. The distillation curve for diamyl sulfide is shown in fig. 33. This curve indicates that at least three substances are present. The cutting data given in Table X was obtained from the improved planer apparatus.

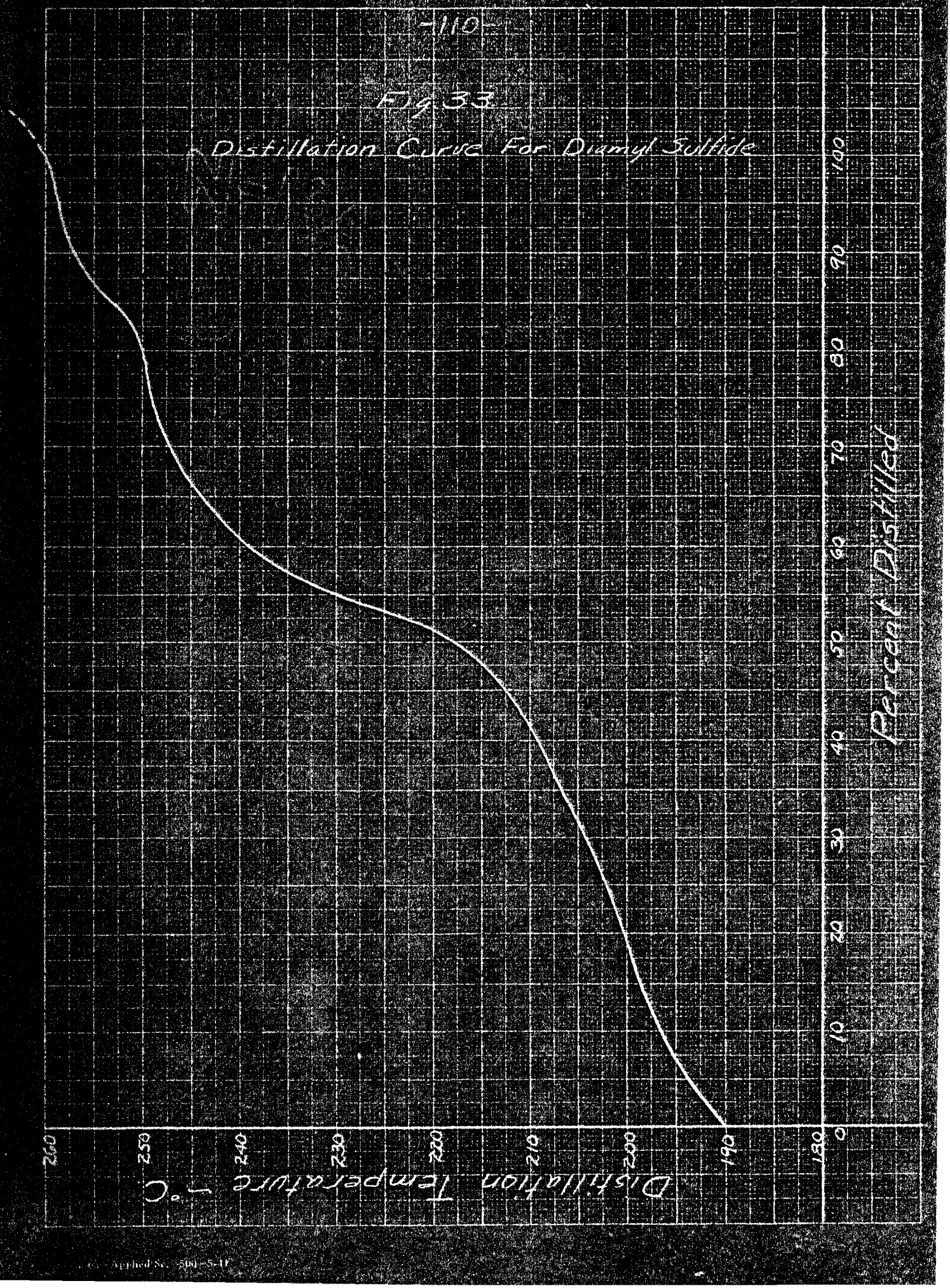
Table X

Fraction No.	Percent Distilled	Boiling Point °C at 760 mm	Cutting Ratio	Coefficient of friction
I	23.2	190.3 - 201	0.273	0.482
II	36.4	201 - 208	0.257	0.498
III	52.7	208 - 244	0.423	0.269
IV	84.4	244 - 257	0.447	0.232
V	100	above 257	-	-
III-1	41.6	205 - 210	0.287	0.442
III-2	46.1	210 - 213	0.270	0.458
III-3	51.6	213 - 219	0.323	0.423
III-4	52.7	219 - 227	0.423	0.274
IV-1	59.6	219 - 238	0.447	0.243
IV-2	67.5	238 - 246	0.450	0.235
IV-3	70.6	246 - 247	0.450	0.235
IV-4	77.0	247 - 249	0.447	0.235
IV-5	84.4	249 - 252	0.450	0.235
V-1	87.0	251 - 256.5	0.440	0.232
V-2	93.8	256.5 - 258	0.440	0.225
V-3	98.3	258 - 262	0.447	0.216

The coefficients of friction and cutting ratio values, from tests with several of the fractions are plotted against the mean boiling point of the fraction in fig. 34. It is evident also from this figure that the coefficient of friction

Fig 33

Distillation Curve For Diamyl Sulfide

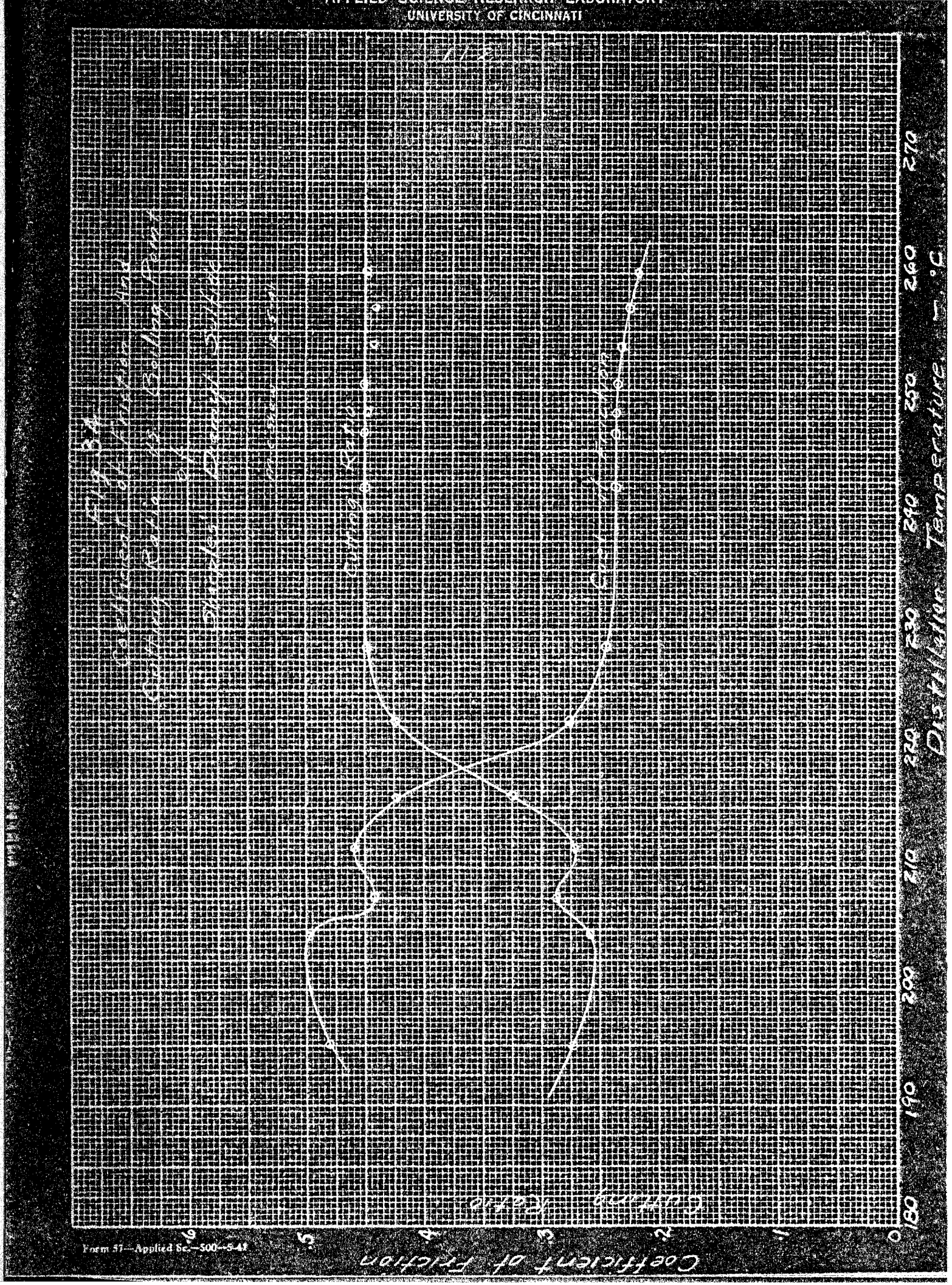


varies inversely as the cutting ratio and that the same slight changes in the properties of a fluid are shown by each of these variables. The figure also shows that little is gained in the performance of this cutting fluid above a boiling point of 225°C. The lower boiling half of the material is quite ineffective as a cutting fluid while the higher boiling half is good. Little more can be said about these tests since little is known of the exact chemical structure of the fluid. However, these tests do show the sensitivity of this test procedure to slight changes in the structure of a compound.

Mechanical Synthesis

The first indication that unusual chemical reactions occur when metal is cut in the presence of certain cutting fluids was supplied by the slow speed cutting tests with carbon tetrachloride, chloroform and pentachlorethane. In these tests, visible amounts of chemical products were formed. While the existence of unusual reactions was observed as stated above, the power and uniqueness of these reactions were not fully realized until after the first few runs had been made with the fly milling apparatus. At this time, the writer conceived the idea that a device similar to this test equipment might feasibly be used in the synthesis of chemical compounds.

There are many organo-metallic reactions in which the use



of a mechanical device similar to the fly milling apparatus could be used to advantage. Such a chemical process in which a nascent metallic or non-metallic surface is created, accompanied by high localized temperature and pressure, may be called "Mechanical Synthesis".

The power and uniqueness of mechanical syntheses may be attributed to several causes.

1. This method provides a means for producing very high pressures up to the hardness of the material being cut. These pressures can locally far exceed any now available to carry out chemical processes (such as in an autoclave).

2. The temperature available for a reaction is controllable over a large range by the easy variation of cutting speed. This local temperature at or near the cutting point is limited only by the melting point of the metal being cut.

3. Another important feature of this new type of chemical device is the production of clean, freshly cut metal surfaces which can contact only the material with which they are intended to react. These nascent surfaces are in a highly reactive state at the moment in which they are produced and thus are capable of many reactions which will not take place under other conditions where the cutting process is separated from the reacting process.

Materials which enter into organo-metallic reactions and which may lend themselves advantageously to mechanical synthesis include: magnesium, zinc, calcium, aluminum, lithium, copper and silver. The best known of the organo-metallic reactions is the Grignard reaction. This reaction has made accessible to the chemist a large number of compounds hitherto available only through the use of very tedious methods and costly chemicals and, in some cases, the Grignard reaction has made possible compounds which could not be prepared at all by the methods previously known.

At present, in carrying out the Grignard reaction, it is very important to keep all apparatus and reagents strictly anhydrous. A trace of water will prevent nearly all Grignard reactions from starting. Using the fly milling apparatus, a test has been made in which magnesium was cut in the presence of a mixture of phenyl bromide and diethyl ether. The ether used was not specially dried but was of ordinary commercial grade. At first, the fluid mixture turned milky as the initial phenyl magnesium bromide was hydrolized but when all water had been used up, the reaction proceeded just as though dry ether had been employed.

A good grade of magnesium, freshly cut, is generally used. For many of the more difficult reactions, alloys of specially catalyzed magnesium are employed. Catalysts, which may contaminate the product must often be added in order to get the reaction started.

Concerning the industrial use of the Grignard reaction, West and Gilman (92) have written, "Shortly after the discovery of the reaction (1900) several patents were taken out, covering its application to the synthesis of compounds of possible technical importance. It is not known how useful the reaction has been found in industry, but from its nature, it would appear that it must always be used in comparatively small scale operations." The above statement is quite true as far as the present method of synthesis is concerned, for here a batch process is employed. The size of the batch is also limited by the dan-

ger involved in handling large quantities of highly inflammable ether. However, by using a device such as the fly milling apparatus, the reaction may be made continuous.

In getting the ordinary reaction to start, the mixture must be heated appreciably. Once started, the autocatalytic reaction is endothermic and the flask must be cooled in order to keep the reaction under control. This problem of control is another point of inconvenience of the conventional Grignard reaction. When magnesium was cut in the fly milling apparatus, in the presence of phenyl bromide in ether solution, the control was excellent. As fast as the chips were formed, they were completely consumed by the reaction. Few chips reached the bottom of the cutting chamber, so rapid was their rate of reaction. However, despite this rapid reaction rate, the temperature of the body of the fluid never rose to more than a few degrees above room temperature. At no time did the reaction become violent. A positive test was obtained for the Grignard reagent when magnesium was cut in a phenyl chloride - ether solution. This reaction is practically impossible to carry out by ordinary means using the chloride, and thus it is seen that it is feasible that reactions not possible by ordinary methods may be accomplished by mechanical synthesis.

There are thus seen to be many apparent advantages for employing a mechanical method of synthesis. These advantages

may be summarized as follows:

1. The process may be made continuous.
2. Cheaper reagents can be used.
3. Reaction time may be reduced.
4. Special magnesium alloys and catalysts need not be used.
5. Ease of control - the temperature of the bulk of the material does not rise appreciably during the reaction.
6. Reactions may be carried out which cannot be accomplished by ordinary means.

Upon closer examination and investigation, many more advantages may be uncovered. The above discussion has been centered chiefly around the Grignard reaction. Many other different types of reactions involving metals should be investigated. The investigation of the possibility of mechanical synthesis is an extremely interesting and promising field, and it should be investigated further.

Summary

The purpose of this investigation was to study many phases of cutting fluid action and to establish a more rational and more fundamental theory than had previously existed. The experimental method was employed, and the theory was continuously altered so as to explain all observed phenomena. Aluminum was used in the greater part of this work because it gave widely different results for good and poor fluids and because it is a chemical element. Less extensive tests were made using various steels, brasses, lead, copper and iron. Numerous organic chemicals were tested as cutting fluids, giving widely different results.

Two types of tests were employed. In the first type, metal was cut in the presence of a fluid, the cutting force, chip length and shape, and surface quality being the variables studied. The chip length was found to be a good measure of the efficiency of cutting, a long chip being desirable. In the second type of test, the metal was cut in a closed chamber in such a way that the small amount of fluid employed could be recovered for chemical analysis.

Several experiments are described which are readily explained in terms of the proposed chemico-physical theory of cutting fluid action. Some of these phenomena can be satisfactorily explained only in terms of this theory. Several generalizations are given concerning the relative abilities

of different homologous series when used as cutting agents. The cutting speed, surface condition (amount of work hardening and the effect of directional properties), and the kind of metal cut all influence the action of a specific cutting fluid. The role of these three variables is discussed from the chemical point of view.

Direct evidence of chemical reactions occurring between the newly cut metal and the cutting fluid was observed in several instances during this investigation. Some of these reactions were studied in detail.

The presence of a low shear strength aluminum halide between the chip and the tool is advantageous. The behaviour of the chlorinated hydrocarbons when refluxed with aluminum, together with the results of the two kinds of cutting tests in which aluminum is cut in the presence of the fluid, have been successfully correlated. It is seen that those compounds which react with the metal are better cutting fluids than those which do not react.

Vaporized fluids were found to be effective, and in the case of carbon tetrachloride the vapor was more effective than the liquid. The fact that a cutting fluid need not be a liquid may prove to be of great practical importance. It is feasible that all cutting fluids are vaporized before reaching the zone of action.

A zig-zag curve was obtained when the force required to cut aluminum was plotted against the chain length of normal pri-

mary monohydric alcohols. This phenomenon has been compared with data, published by Gilman and Others, for yields of Grignard reagents prepared from normal alkyl iodides. The writer observed in both cases that the compounds having an odd number of carbon atoms are more reactive than those having an even number of carbon atoms.

There is not much in the literature concerning the fundamental nature of cutting fluid action. The general belief has been that cutting fluids act to advantage because of the lubricating ability they possess. In the opinion of the writer, the extremely high pressures reached in metal cutting, together with the geometry of the metal cutting process, preclude any chance of the existence of a hydrodynamic film. The conditions existing in a metal cutting process are rather those of very extreme "boundary lubrication".

H. Blok has divided the huge field of boundary lubrication into four regions, corresponding to the four possible combinations of high and low temperature and pressure. The chief requisite for an effective fluid in the two low pressure regions is that the compound be highly polar and capable of being strongly bonded to the sliding surfaces. The writer considers a different mechanism to hold for the two high pressure regions. Under high local pressure and temperature, it is quite feasible that certain fluids will react with the metal, giving a reaction product between the sliding surfaces. Organo-metallic compounds

or metal salts are generally solids and are thus capable of withstanding higher pressures than liquids. In this theory, the criterion of importance is the shear strength of the metal salt relative to that of the metal. In general, metal compounds have lower shear strengths than the corresponding metals, and hence, the cutting force will be reduced if metal to metal contact is decreased by the presence of a metal compound between the sliding surfaces.

It has now been found that in addition to temperature and pressure, a third variable should be considered in the classification of boundary lubricants. This third variable is the amount of fresh surface produced. The amount of nascent surface present has an important bearing upon the chemical reaction taking place between the metal and the fluid. In ordinary boundary lubrication, the amount of fresh surface formed is a minimum since the actual area of contact is small. In metal cutting, the amount of nascent surface produced is a maximum since the entire under side of the chip is newly formed.

It is now clear that cutting fluid action occupies a small portion of the huge field of boundary lubrication. Metal cutting involves pressures up to the hardness of the metal cut, surface temperatures up to the melting point of the metal, and maxima of newly formed and highly active metal surface. The mechanism of cutting fluid action described above is termed chemico-physical because the action is initiated by a chemical reaction between the fluid and the nascent surface and is fol-

lowed by a decrease in frictional resistance accounted for by the relative shear strengths of the metal compound and the metal.

A very important outgrowth of the cutting fluid investigation is the possibility of employing a cutting apparatus to produce organo-metallic compounds by cutting the metal under the liquid reactant. This new method of carrying out chemical reactions is called "mechanical synthesis". The several advantages of mechanical synthesis have been discussed, and its possibilities are promising.

Acknowledgment

Acknowledgment is due the Cincinnati Milling Machine Company for its sponsorship of the Graduate Cooperative Research Fellowship which has made this investigation possible.

The writer is grateful for the counsel of Dr. Walter Soller and staff members of the Applied Science Research Laboratory and other departments of the University of Cincinnati. He is particularly indebted to Dr. Willy Lange, under whose supervision a large portion of the chemical work has been done. He likewise wishes to acknowledge the advice and cooperation of Mr. Hans Ernst, Dr. M. E. Merchant and other members of the Research Department of the Cincinnati Milling Machine Company; also, the assistance of Mr. Ian MacGregor in carrying out chemical analyses and of Mr. Emil Suhr in the construction of the mechanical apparatus.

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