INVESTIGATION OF THE SHEAR ZONE AS BASIC PARAMETER IN CHIP FORMATION

by

Eric P. Schuld

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SIGNED: Eric P. Schuld

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This thesis has been approved on the date shown below:

B. S. Mesick
B. S. MESICK
Professor of Mechanical Engineering

12 October 1961
Date

ABSTRACT

This thesis investigates the influence of the metallurgical properties of certain low carbon and alloy steels on the metalcutting characteristics, specifically the power consumption. A dimensional analysis of the process of chip separation reveals that the present state of knowledge of this process is not far enough advanced to make a comprehensive mathematical theory valid.

By constructing a special quick-release tool it was possible to study the cutting action for certain cutting conditions. The study shows that for ductile materials the cutting force required decreases as the hardness increases. An explanation of this phenomenon can be given by considering the work-hardenability of the material and the chip-tool friction. Even though no definite relationship between grain size and power required is apparent, it is observed that the small grained materials require less force. The effect of dislocations, as predicted by the current dislocation theories, is pointed out. An analysis of vibrational frequency as related to grain is given.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

The great impact of metalcutting upon this nation's economy can be realized readily if one considers that the fabrication of almost everything with which we come in contact today is directly or indirectly connected with machining. It is rather strange to realize this and find that the metalcutting process is one of the least understood processes in the present state of our sciences. In most cases it is known how to machine a certain metal but the "why" has not been answered. This is a clear case of the art preceding the science.

The knowledge of the chip separation process becomes more and more important as the demand placed upon today's metals increases very rapidly. This implies, of course, that new alloys come into being which exhibit extreme toughness and high strength. These new alloys are not only strong and tough in their use but present many machining problems. Much time and money is spent each day by industry and research establishments to overcome these problems and find ways of cutting the metals most economically. This most tedious and expensive job could be eliminated or at least reduced were it known in advance how a particular metal will behave under cutting conditions.

The research carried on at many universities and in industry in the field of metalcutting is designed to shed more light on the cutting process, with the goal that the cutting requirements of any metal may be determined from easily measured properties of the metal. If this were achieved the cost of metalcutting would be greatly reduced and consequently the price of many consumer products would go down.

The investigation described in this report covers only a very small part of this vast and complicated field of metalcutting. It is hoped that eventually all the small parts contributed by the many scientists and researchers in this field may be pieced together to come up with a solution to the metalcutting problems.

The purpose of this report is to investigate the effect of the metallurgical properties of certain steels on their cutting characteristics. Of specific interest is the effect of the microstructure on the power requirements. Some consideration is also given to the surface finish and vibrations due to the various metallurgical properties.

The investigation of the shear zone from this standpoint seems very important since it is well known that different materials exhibit different cutting characteristics, the variation being solely due to the inherent properties of the material. If the influence of the material's properties is known and understood, perhaps the other variables can be adjusted to yield proper cutting results.

CHAPTER 2

BACKGROUND

A literature survey reveals that a considerable amount of research has been done in the past twenty years concerning the effect of the microstructure of metals on their cutting characteristics. Many theories have been advanced on this subject, but none of them are in full accord with the existing data, indicating that more experimental work needs to be done to come up with a satisfactory theory. Although the failure of a given material under certain cutting conditions can be very plausibly explained by the theories of dislocations and imperfections, these theories are not far enough advanced to be used in predicting the deformation and failure phenomena of most materials.

Before presenting some of the theories, the major constituents of the iron base metal will be described from a metallurgical standpoint. Since most of the metals used in machining today are of the iron base type, primary consideration will be given to them.

Dreves (2) in his article on machinability of carbon and alloy steels points out that the three major metallurgican characteristics which affect machinability are "ferrite", "inclusions" and "iron carbide". Ferrite, which forms the matrix of the structure is basically impure alpha iron with varying amounts of other elements dissolved in it. In its pure form it is a very soft and ductile material. Its low strength would be advantageous for machining but the high ductility results in the so-called "built-up edge" and causes a very rough surface finish. The chip is long and stringy and consequently hard to handle.

Some of the common elements that readily go into solution with ferrite are manganese, phosphorus, nitrogen, silicon, nickel, chromium, molybdenum and aluminum (2). The hardness of the ferrite depends on the proportionate amount of elements dissolved in it. Phosphorus and sulphur are commonly used to improve the machinability of low carbon steels since they reduce the ductility and increase the hardness of the ferrite somewhat; they also act as a lubricant. Of course, too much addition (1.00% or more) of these elements to the steel will cause its characteristics to change significantly and result in a variety of alloy steels. Also, the addition of most elements will result in carbides or oxides which are very hard and consequently abrasive, so that too many additions would be detrimental to tool wear.

Inclusions represent another characteristic affecting machinability. Some inclusions, such as various oxides, silicates and slag, have little effect on the machinability if they are present in very small amounts. In larger amounts they cause excessive tool wear. Some inclusions, such as manganese sulfide, are added intentionally to the steel since they are very brittle and cause the chip to break up and prevent a built-up edge. The addition of sulphur is very desirable since it causes the material to remain soft, but become less ductile, thus increases its machinability. With the proper heat-treatment the manganese sulfide inclusions take on a globular shape and aid the machining process greatly. Other inclusions used to reduce the ductility of the ferrite are manganese, phosphorus and nitrogen.

Iron carbide also has a definite effect on the machinability. The shape and distribution of this phase is of vital importance. Iron carbide is a very hard, brittle material, which in excess, causes rapid tool wear but helps to reduce the ductility of the material by breaking up the continuity of the ferrite. It also prevents the formation of the built-up edge by continually sweeping it away. Iron carbide is formed by the combination of the carbon present in the steel and some of the iron. It can take on many shapes depending on the thermal treatment. Probably the most common structure in plain carbon, easily machinable steel is lamellar pearlite which consists of alternate layers of ferrite and cementite (iron carbide). Other forms of iron carbide are martensite, spheroidite, sorbite and troostite (2).

All of these can be obtained by various heat treatments and result in various degrees of hardness.

The term "built-up edge" has been used quite frequently in the foregoing description so that an explanation of this phenomenon might be in order. Under certain conditions of machining, such as machining a ductile material which has a relatively high frictional resistance, small parts of the parent metal deposit on the tool face. This formation continues until the "built-up edge", as this extremely deformed deposit is called, reaches a certain size and breaks off, part of it going off with the chip and part of it sticking to the workpiece, causing the surface to be very rough. The extreme plastic deformation that the built-up edge undergoes

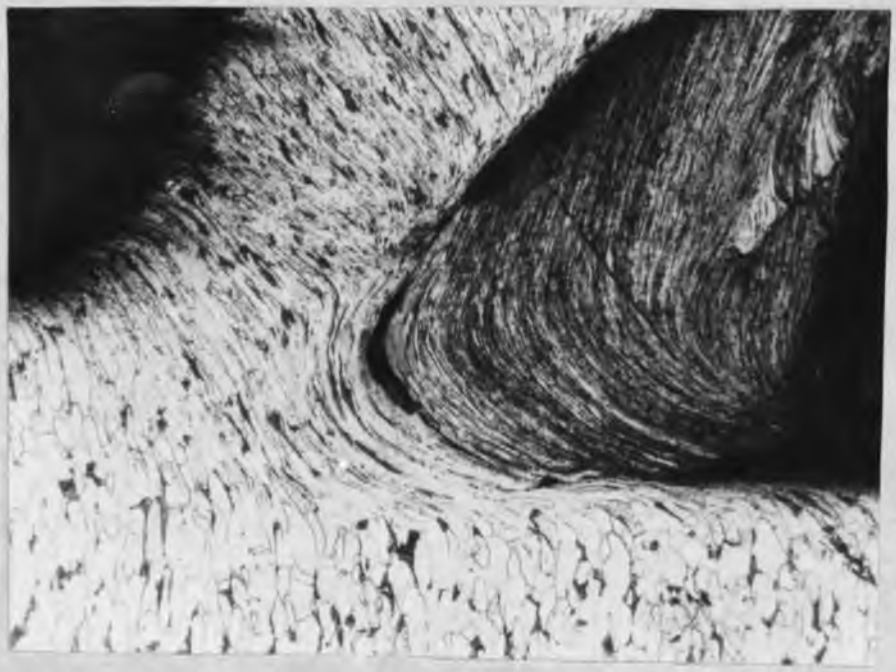

Figure 2.1 Photomicrograph of cutting zone with large built-up edge (100x)

causes it to become very hard - about three to four times as hard as the parent metal - and consequently to do much of the cutting. To a certain degree it protects the cutting edge but is very detrimental to the surface finish and power consumption. Fig. 2.1 shows a built-up edge.

Of the theories of failure considering the microstructure, possibly the most basic is the theory of slip and/or mechanical twinning outlined by Clark and Varney (3). Upon the application of a force on a crystal structure slip takes place along a crystallographic plane. This usually takes place on a plane containing the greatest number of atoms, since these atoms are separated by the greatest interplaner distances and consequently have the least attraction. The crystal lattice of the particular material determines the number and direction of the slip planes. As plastic flow continues slip is continuously shifted to other planes and consequently increases the resistance to slip. The slipping causes crystal distortion and if the forces continue to act the material will ultimately fracture.

In polycrystalline structures - most metals - the process of slip is made somewhat more complicated by the fact that a large number of grains of different orientation are present. The different orientation of the natural slip planes causes interference and makes plastic flow more difficult. Additional difficulties are introduced by the fact that in all alloyed metals the neighboring crystals are not only differently oriented but have different metallurgical properties.

From the advancements made recently in the field of dislocations it is known that slip occurs on the crystallographic planes indicated above, but it will only occur if there are dislocations present. Before the dislocation theories were introduced it was very difficult to explain completely the slip phenomenon.

The theory advanced by Vogt (4) is very similar to the sliding theory proposed above, but with certain additions. He states that the process of deformation in a crystal occurs as a translatory sliding. The translation happens stepwise and starts at the grain boundaries. In an iron-carbon alloy the carbon atoms are located at the midpoints of the edges and the centers of the faces of the crystal cube. If deformation or slip takes place the carbon atoms are displaced, collect and stabilize. This collection of carbon atoms Vogt calls "clouds"[1]. As sliding continues these "clouds" resist the movement but are pushed along. This resistance causes an increase in the external force that must be applied in order to continue the deformation. This diffusion of the

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[1] In this country this collection of carbon atoms is called "atmosphere" rather than "cloud".

carbon atoms requires a certain length of time, short as it may be. For higher cutting speeds there is no time for this diffusion and consequently the cutting force required decreases.

Although Vogt described the process of diffusion and collection of the carbon atoms, he mentioned nothing about dislocations. This fact is better explained by the dislocation theories. Cottrell (6) points out that when deformation takes place the carbon atoms are displaced and collect around dislocations. These "atmospheres" inhibit the movement of the dislocations and result in an increase in the force required to cause further deformation.

In order to understand this occurrence a short discussion of the theory of dislocations will be given. In simple language, a dislocation can be defined as a wrinkle in the atomic layers of a crystal (5). Fig. 2.2 shows a sketch of a single edge dislocation. It should be realized

Figure 2.2 Sketch of an edge dislocation in a crystal

that dislocations exist on a submicroscopic level and can be viewed only by applying special techniques the description of which is beyond the scope of this report.

The dislocations or structural irregularities represent a weak spot within the crystal and reduce the resistance to sliding. The relatively low actual yield strength of materials is to a large extent attributed to the presence of the dislocations. Brenner (8) and other investigators were able to grow whisker-like single crystals that contained no dislocation and found that these crystals exhibited strengths up to a million times the strength of the same crystal with imperfections. For example, an iron crystal required well over a million pounds per square inch to fracture. Many of these crystals remain elastic up to deformations as large as 2 to 5 percent.

With the recent advancements made in the theory of dislocations, investigators are attempting to reduce or control the number and types of dislocations. This would mean, of course, that a considerable increase in strength of the materials would be achieved. From the standpoint of engineering use of these materials, this would be very desirable. From the standpoint of metalcutting, however, this would be a bad quality, since a low strength material is desirable for good, easy machining. Of possible advantage to machining might be the fact that because of the control and the consequent knowledge of the dislocations certain predictions of the characteristics of failure might be possible. It is known that failure or slip will occur on planes containing dislocation so that a knowledge or the type, location and quantity of dislocations present would indicate to the scientist how the material will behave under external loading.

To understand the influence of dislocations on the mechanical behavior of materials certain pertinent facts must be realized. First, dislocations move under the application of force. The speed increases as the stress increases. The stress required to cause movement of the dislocations is close to the macroscopic yield stress, so that the yield strength of a material greatly influences the beginning of movement of the dislocations. Second, a single dislocation can multiply into many. Plastic deformation, for example, causes a vast increase in the number of dislocations in a crystal. Fisher (5) points out that a carefully annealed crystal may contain only a few hundred or a few thousand[1] dislocations per square centimeter whereas a heavily cold-worked material may contain as many as 10^{10} or 10^{12} dislocations per square cm. It could be expected that the resulting increase in internal energy would be quite appreciable, thus explaining the increased hardness of cold

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[1] According to Cottrell the usual number of dislocations is 10^8 per square cm.

worked materials.

There are several methods of inhibiting the motion of dislocations. The presence of parts of well-ordered atom arrangements prevents dislocations from moving due to the inherent high interatomic attractions. Second phase or precipitate particles tend to block the slip planes and introduce high local stress fields thus reducing dislocation movement. The segregation of carbon atoms, referred to as atmospheres above, tend to pin the dislocations in place, thus inhibiting their motion.

By the use of the above mentioned facts many of the behaviors of metals in cutting can be explained. Previously it was mentioned that the inclusions in ferrite cause it to become less ductile. These inclusions act as dislocation movement inhibitors by pinning the slip planes, thus reducing the ductility and in turn affecting the machinability. Thus, by the application of the theory of dislocations the metal-cutting characteristics can be explained but as yet may not be predicted. For a very detailed and comprehensive discussion of the basic theory of dislocations the reader is referred to references (5), (6) and (7).

Of relatively large influence on metalcutting is the process of cold working prior to machining and warrants some discussion. The three major practical reasons for cold working are the achievement of straightness, better surface finish, and closer accuracy. To the user of the steel these factors represent big advantages since little machining has to be done if the piece can be used "as is". As far as machinability is concerned probably a bigger advantage than those mentioned above becomes apparent. From a metallurgical standpoint cold working increases the strength and reduces the ductility. The increase in strength is sometimes detrimental to machining but the decreased ductility is favorable. For good machinability these two factors must be adjusted properly.

Armour (9) points out that cold working affects only the ferrite in ferritic steels and the austenite in austenitic types. This means that only soft, ductile phases are affected. For that reason medium or high carbon steels are very seldom cold worked. The hard brittle carbide adds enough strength and brittleness so that not much would be gained by cold working.

When steel is hardened by cold working slip occurs along the slip planes of the ferrite (9). The ferrite crystals are now essentially composed of soft ferrite separated by strong (deformed) layers of ferrite. This breaks up the continuity of the ductile ferrite, much as lamellar pearlite, and improves machinability. In the metalcutting process the built-up edge is a function of the strain-hardenability of the material, so that in a cold worked material the layers of deformed ferrite tend to minimize the built-up edge.

The effect of the grain size was mentioned in various reports. Lewis (10) points out that by decreasing the grain size the hardness is increased. It seems that it would be difficult to generalize this statement, since too many other factors that control hardness are involved. This will be explained in Chapter 5. Lewis further points out that a wide dispersion of carbide particles (small grain size) reduces the built-up edge since the mean ferrite path is thus reduced. This would impare tool life since more hard carbide particles come in contact with the tool edge, but it would improve the surface finish. A large-grained material reduces the power consumption, since it would tend to split more readily along crystallographic planes. In another report Lewis (11) points out that hardness should not be considered as an indication of machinability since more important factors outweigh the effect of hardness.

The application and analysis of some of the theories and facts outlined in this chapter will be presented in Chapter 5. Many of the apparent disagreements and deviations from these again merely illustrate the large volume of work that has to be done in the field of metalcutting to arrive at a comprehensive theory.

CHAPTER 3

DIMENSIONAL ANALYSIS

In many cases the theory of dimensional analysis can be applied very profitably to a problem that is so complicated that a sufficiently comprehensive theory cannot be developed at the time. A very useful approach to a solution is to write down all independent variables of the problem and form their dimensionless groups. In this way the number of variables with which to work is not only reduced, but the dimensionless groups thus formed take on special physical significance and help in visualizing the problem. Upon forming the dimensionless combinations, the significance of each variable can be determined from prior knowledge, reasoning or experiment. In many cases the number of variables can be reduced still further since some of the dimensionless groups have no noticable effect on the result and can be neglected.

In their article on dimensional analysis Drücker and Ekstein (1) pointed out that by dimensional reasoning new variables are often found and their meaning made clear. As an example they cite the necessity of introducing a time dependent variable T, which might be interpreted as the time required to fracture the material during cutting. It is known that as the cutting speed decreases or the depth of cut increases the chip will gradually change from the continuous to the segmental type. The problem of finding the conditions under which this change occurs necessitates a variable with dimensions of time, since any combination of V (cutting speed, ipm) and t (depth of cut, in) will not result in a dimensionless group. With the introduction of T such a group can be constructed and will result in $\frac{VT}{t}$, which is an independent variable with definite physical meaning.

The list of independent variables believed to be important in the study of metalcutting is given in Table I. Because of the lack of complete understanding of the metal-cutting process and the enormous complexity of the problem, this list may not be complete or the variables may not be completely independent. This is evidenced by the disagreement among various researchers on this point and apparent inability to correlate many of the combinations. The author believes, however, that a good start is made by the use of these variables.

The Buckingham Pi Theorem is utilized to arrive at the dimensionless groups listed in Table III. Since there are 17 quantities and four fundamental units the number of dimensionless groups is 13. The basic equation $\Pi = P^a V^x t^y C^z$

TABLE I

Independent Variables of Metalcutting

Variable	Units	Description
V	LT^{-1}	cutting speed
t	L	depth of cut
α	-	true rake angle
G	$ML^{-1}T^{-2}$	shear modulus of elasticity
γ_L	-	ductility (limiting value of shearing strain)
T	T	time required for fracture
h	-	hardness
S	L^{-2}	grain size
d	L	spacing of disturbances in crystal structure
τ_o	$ML^{-1}T^{-2}$	yield stress in shear
ρ	$ML^{-2}T^{-2}$	mass density
u	-	coefficient of friction
r	L	nose radius
k	-	slope of curve of yield point in shear vs. normal stress
c	$L^2T^{-2}\theta^{-1}$	specific heat
K	$MT^{-3}L\theta^{-1}$	thermal conductivity
ψ_w	θ	workpiece temperature

was used to arrive at the various Π-quantities. It is realized, of course, that these groups are not unique and therefore can be arranged in any desired combination. A rearrangement will often make the physical significance more obvious.

TABLE II

Basic Dimensions

Description	Units
Force	MLT^{-2} (mass)
Length	L
Time	T
Temperature	θ

TABLE III

Dimensionless Combinations in Metalcutting

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
k	α	γ_L	u	h	$\frac{G}{\rho V^2}$	$\frac{\tau_o}{\rho V^2}$	$\frac{d}{t}$	$\frac{K}{\rho Vct}$	$\frac{r}{t}$	$\frac{T\ V}{t}$	$\frac{\Psi_w C}{V^2}$	t^2S

The first five quantities in Table III are dimensionless to begin with and are consequently π-values by themselves and self-explanatory.

The quantity $\frac{\tau_o}{\rho V^2}$ might be interpreted as the ratio of the yield stress in shear to the inertia stress. A similar ratio is $\frac{G}{\rho V^2}$. The combination of these two groups $\frac{\tau_o}{G}$ represents the maximum elastic shear strain. The ratio $\frac{r}{t}$ would indicate the relationship between the tool sharpness and the depth of cut. It is well known that a sharp tool radius and a shallow cut does not give the same cutting characteristics as a round nosed tool and a deep cut. Other quantities, such as imperfections in the material or grain structure would have to be coupled with this quantity to explain this phenomenon. In most cases $\frac{r}{t}$ can be neglected if the tool is kept properly sharpened. $\frac{TK}{\rho Vct}$ and $\frac{\Psi wc}{V^2}$ describe some of the temperature relationships in metalcutting. The quantity $\frac{TV}{t}$, as mentioned previously, would give an indication of the time available for a chip to fracture. This governs the continuity or discontinuity of the chip.

The tangential force between tool and chip is certainly dependent on temperature, cutting speed, depth of cut, and rake angle. Using this type of reasoning the dependent variables can be expressed as functions of the independent dimensionless quantities. The exact relationships can then be determined experimentally.

Some of the difficulties that arise in dimensionally analyzing a problem as complex as metalcutting, stem from the fact that it does not guarantee the completeness or the true independency of the variables. In this particular problem additional difficulties arise since quantities such as specific heat, ductility, yield stress and disturbances in the material vary not only from one material to the other, but vary within the material as the cutting conditions change. It is true that approximations can be made, such as to use fixed values of the above mentioned quantities, but just how reliable would such assumptions be? Much experimental work is therefore necessary to find the extent of the influence of the various quantities upon cutting characteristics.

In this analysis the tool geometry and coolant were not considered. These would certainly add many more constants and variables and make the problem even more difficult.

Some of the difficulties mentioned above merely emphasize the impossibility of developing a comprehensive mathematical theory at the present level of knowledge of the cutting process. Many "small pieces" will have to be contributed through arduous experimental work and careful examination to complete the picture of the process of chip formation.

CHAPTER 4

EXPERIMENTAL PROCEDURE

The basic mechanism of chip formation has now been well established. It has been shown by numerous investigators that the geometry of the chip forming process is similar in all metalcutting operations, e.g., milling, turning, broaching, planing, drilling, etc. In every case the cros-section through chip, tool and workpiece perpendicular to the direction of cutting, commonly called the cutting region, will look somewhat like that shown in Fig. 4.1 The basic

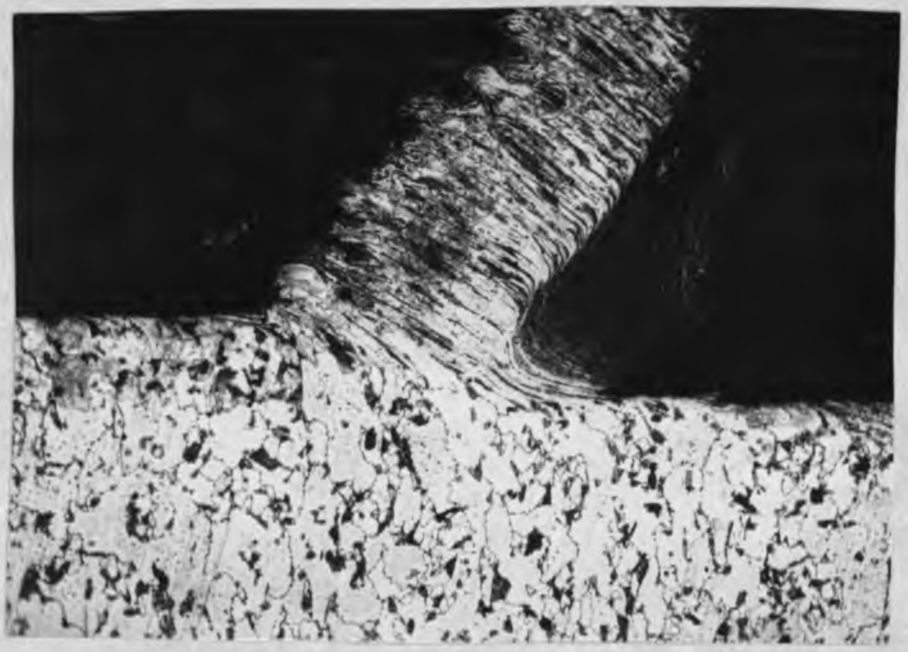


Figure 4.1 Crossection through chip and work piece (100x)

fundamentals, as found from the study of any one metalcutting operation, can therefore be quite readily applied to any other.

In order to get a proper understanding of the basic fundamentals, the investigator attempts to simplify the experiment as much as possible. For that reason tests for the study of the basic metalcutting process are usually conducted on a lathe. There, some of the many variables involved can be controlled very effectively. In order to simplify the metalcutting process further, a method called orthogonal cutting is employed. Orthogonal cutting is achieved by adjusting the tool in such a way as to have the cutting edge perpendicular to the direction of cutting. By endcutting a piece of tubing orthogonal cutting is obtained. This type of cutting was used for all experiments described in this report.

In order to study the metalcutting process it is imperative to know what happens in the cutting region while the metal is being cut. By the use of high speed photography instantaneous cutting conditions can be observed, but this method is limited by the magnification that can be observed and by the fact that the camera cannot take a picture of the inside of a material. Another method, used by the author, was to "freeze" the cutting action by the use of a special toolholder. This toolholder, illustrated in

Figs. 4.2 and 4.3, made it possible to release the tool instantaneously and move it away from the cutting region. The deceleration of cutting, upon release of the tool, was reduced to fractions of thousands inches/sec^2, which for practical purposes can be considered instantaneous. The tools used in the experiment were standard half-inch high-speed steel tool bits. The tool (A) (see Fig. 4.2) was clamped in a carriage (B) which pivoted freely about a pin (C). The carriage is held in place by a notched sear pin (D). This pin is turned by means of a lever (E) until the notch allows the tool to swing away from the cutting zone. In order to move the tool away from the workpiece (F) a spring (G) was

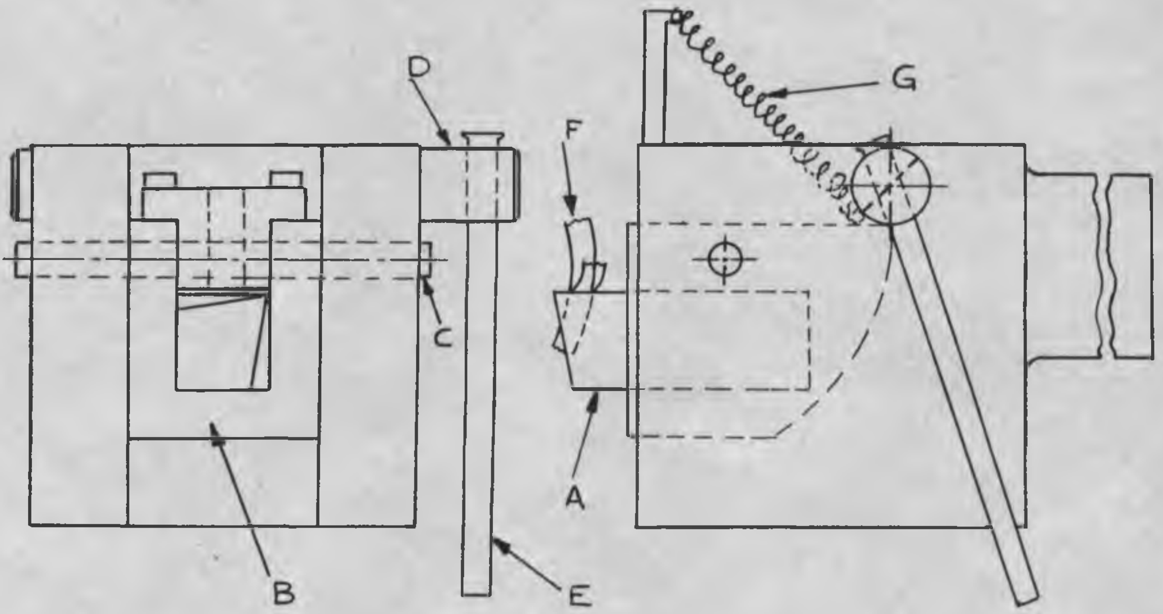


Figure 4.2 Sketch of chip "freezing" tool and holder

Figure 4.3 Photograph of special tool holder

attached to the carriage. The spring plus the static force on the tool cutting edge - which is due to cutting - causes the tool to move away from the chip at a greater rate than the speed of chip travel, thus providing the "instantaneous" tool release. By using high speed photography and a strain recorder this fact was demonstrated. Since the tool was released while cutting the workpiece, the chip remained part of the workpiece. A small section of the workpiece (Fig.4.4) containing the chip was cut out, labeled and mounted in either bakelite or lucite in a one inch mold. Some of the mounted samples are shown in Fig. 4.5. The samples were mounted such that they presented a surface perpendicular to the cutting edge of the tool. They were then polished by standard metallurgical polishing procedures and etched with

with the appropriate etchant. 10% Nital was used on all steel samples. After etching, a metallograph was used to take a photograph of the microstructure in the cutting region at the desired magnification.

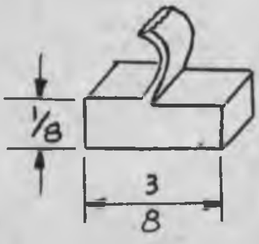


Figure 4.4 Metalcutting sample

Figure 4.5 Mounted samples

In order to measure the forces involved in cutting the various metal samples, a beam type tool dynamometer was used. The dynamometer was designed, built and improved by Prof. A. G. Foster at the University of Arizona. It is illustrated in Fig. 4.6. The force on the tool causes the shaft to deflect, the deflection being directly proportional to the force applied. This can be seen on the calibration curve, Fig. 4.7. From this graph it can be concluded that for each .001" deflection of the shaft at the point of measuring, a force of 71.5 pounds was applied at the tool. The dynamometer was calibrated on a standard Tinius Olsen tensile testing machine.

Figure 4.6 Photograph of tool dynamometer

The deflections due to the horizontal and vertical components of the force were at first read on dial indicators mounted on the dynamometer so that they would contact the shaft at the extreme top and side. Even though a hydraulic damping device was mounted on the shaft, the vibrations from cutting were too large to obtain accurate readings, since it

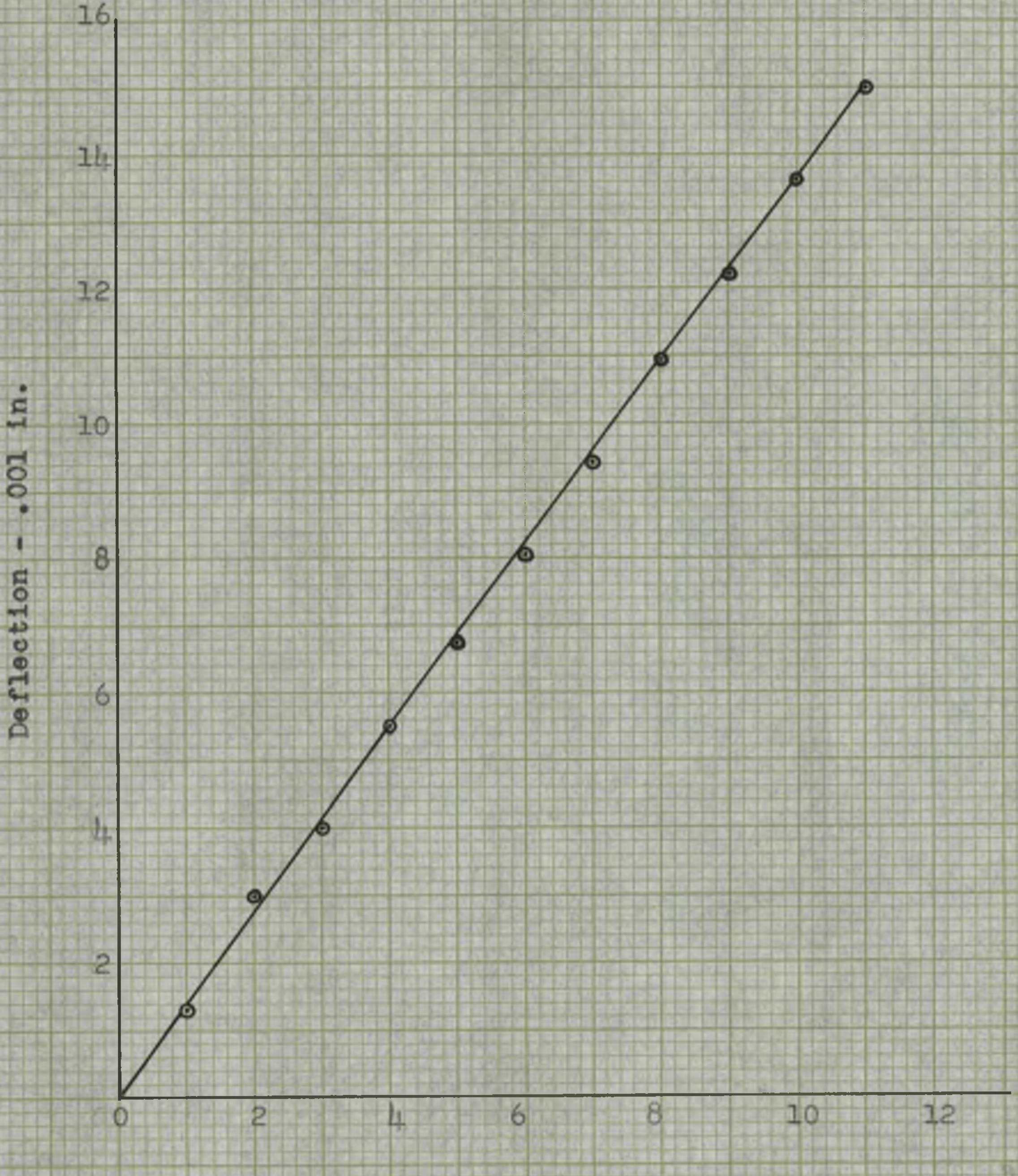


Figure 4.7 - Calibration Graph for

Tool Dynamometer

was difficult to see where the mean of the fluctuating indicator needle was. For that reason the dial indicators were replaced by strain gages. SR-4 Type C-5 strain gages were used. The strain gages were mounted on opposite sides of the shaft so that twice the deflection was recorded but the temperature compensating gage was thus eliminated.

Figure 4.8 Photograph of experimental equipment

The strains in the deflected shaft were picked up and recorded by the use of a Sanborn Carrier Preamplifier, Model 150-1100 and a Sanborn 151 Recorder. Both are shown in Fig. 4.8. The sensitivity of these instruments made it possible to obtain very accurate readings of force as well a as amplitude and frequency of the vibrations involved in cutting.

All tests were conducted on a new 15x54 inch

Cincinnati engine lathe, which was located in the Metals Processing Laboratory in the Mechanic Arts building at the University of Arizona. No coolant was used throughout the experiment.

Because of the excellent equipment used in testing and the care taken in obtaining each sample it is believed that the experimental errors are at a minimum. The lathe used was a new machine, manufactured by a reputable machine-tool builder and consequently no looseness or "run-out" could be detected in working with this machine. The Sanborn Carrier Preamplifier and Recorder were carefully calibrated and frequently checked so that no errors were probable. It was found that the dynamometer shaft did not return to the zero position immediately after releasing the load on the tool, but this fact was taken into consideration and the necessary corrections were made.

All cutting tests were run for a sufficient length of time to allow equilibrium conditions to be reached, e.g., until the tool was well into the workpiece and the full cutting load was acting.

The tool was reground at frequent intervals to eliminate the additional power requirement due to a dull tool. This was necessary since a High Speed Steel tool was used throughout the tests.

All metal samples were machined after each heat treatment to eliminate errors that might arise from the scale on the metal and to present a constant width of cut throughout the tests. Before running the test the material was allowed to attain room temperature and thus eliminate errors due to differences in workpiece temperature.

All tests were conducted in the following sequence:

1. Machine the metal specimen to have an O. D. of 1.750 inches and wall thickness of .150 inches.
2. Clamp piece in the chuck, cock the tool and bring it close to the metal to be machined.
3. Turn on machine and recorder.
4. After reaching steady cutting conditions, release the tool, shut off machine and recorder.
5. Cut out sample containing cutting zone and chip.
6. Mount sample or samples, polish, etch, and photomicrograph.

The force applied at the tool was calculated from the measured strains by the use of the two equations $S=eE$ and $S=\frac{Mc}{I}$. After substituting all known values in the above equations the force was calculated directly from $F=(cm)(67.5)$ where cm = number of centimeters read from the recorder graph.

CHAPTER 5

CORRELATION AND ANALYSIS

From a practical viewpoint the three major factors of interest in the study of metalcutting are power consumption, tool wear and surface finish. Metalcutting research is therefore conducted in such a way that the results will indicate one or all of the three factors. The discussion of results in this chapter will be limited to the effect of the metallurgical properties of various materials on the power consumption or the forces required to cut various samples. Only slight mention will be made of the other two metalcutting characteristics. It is felt that a complete investigation of each factor is a research problem in itself. Throughout the experiment attempts were made to isolate the important variables, such as the metallurgical properties, by keeping all controllable variables constant. Cutting speed, feed, coolant, tool geometry, etc. were kept constant throughout so that their influence would not impare the results.

One of the most unexpected results was observed when plotting the tangential cutting force against the hardness of the material. This result was unexpected in two ways. First, it indicates that the harder the material the easier it is to cut. Second, other investigators (2), (10), (13) have pointed out that hardness has no appreciable effect on the cutting characteristics. In general, this may be true, but for the specific materials that were tested the hardness did affect the cutting force. (It should be pointed out that the power required is directly proportional to the tangential force and is frequently (14) presented as a unit quantity u in-lb/in^3. It is obtained from the equation $u=\frac{F_t}{bt}$, where F_t is the tangential force, b is the width of cut, t is the depth of cut and u is the specific cutting energy or the energy required to remove one cubic inch of metal.) Fig. 5.1 shows the relationship between the hardness and the tangential force. This graph demonstrates a quite obvious trend, namely, the softer the material the harder it is to cut. This, of course, goes against any commonly expected observation and needs some explanation.

There are two factors that will explain the apparently unorthodox behavior. The first concerns itself with the work-hardenability of materials. It was stated in Chapter 2 that upon cold working a low carbon steel only the ferrite, which is the soft, ductile phase, will be affected. The degree to which the material will lose ductility and gain hardness depends on the softness of the ferrite in the original state, so that the softer the steel the more susceptible it is to work hardening. It was also stated that the

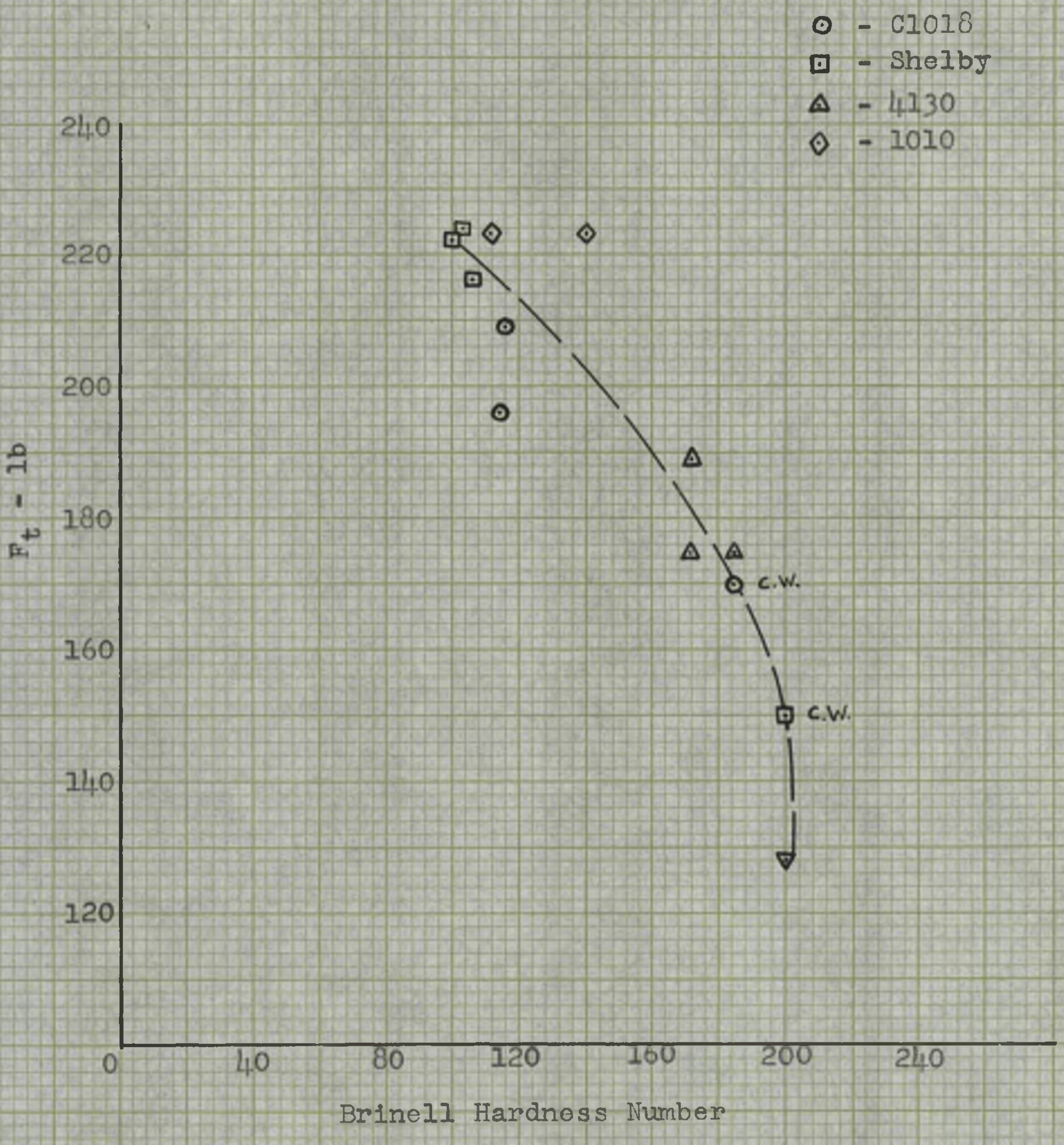


Figure 5.1 - Correlation, Hardness vs. Cutting Force

built-up edge is a function of the ductility and in turn of the work-hardenability of the material. The built-up edge clings to the tool at the extreme edge and actually "ploughs" the chip from the parent metal. With this in mind Fig. 5.1 can be explained quite readily. As the hardness of the machined materials increased the size and amount of the built-up edge decreased, since the harder material was less susceptible to deformation. Consequently, as the built-up edge decreased the cutting edge radius decreased, and cutting was done with a much less blunt tool edge, with a consequent decrease in power required for cutting. Fig. 5.2 illustrates this fact. The radius of the built-up edge was measured on the photomicrographs appearing on pages 48-55, and was plotted against the cutting force. As the radius increases an increase in cutting force can be observed. Even though the points do not fall on one line they do indicate a trend. Since it is almost impossible to release the tool at a moment so that all built-up edges are in the same stage of build up the sizes vary, but the tendency for the size of the radius is present. From this we can conclude then that the built-up edge not only impares the surface finish, as mentioned by many investigators, but it also has an effect on the power consumption. In connection with the size of the built-up edge it can also be said that the harder material is not only less susceptible to cold working but, because of

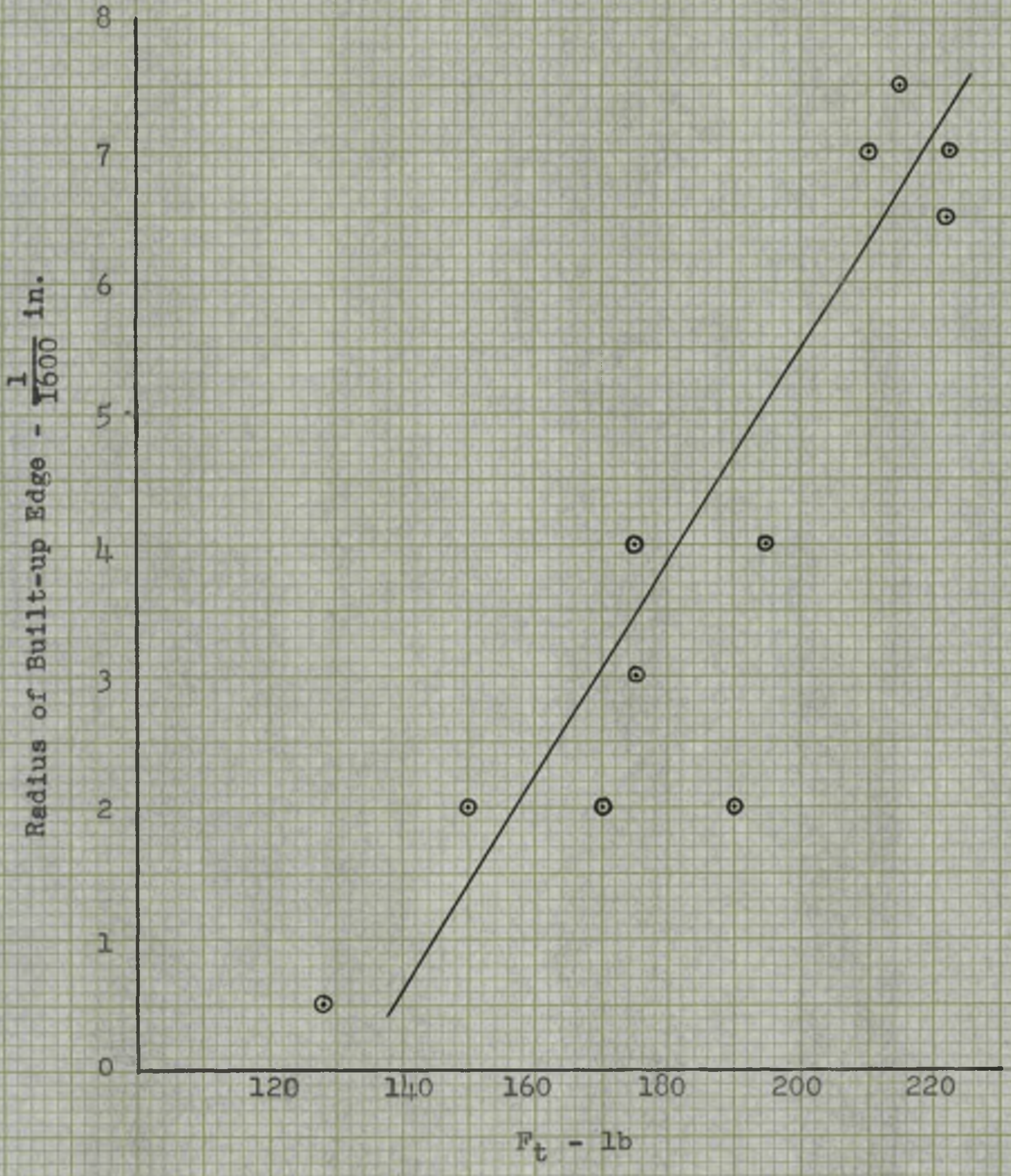


Figure 5.2 - Plot of Size of Built-up Edge against Cutting Force

its higher hardness, tends to sweep the built-up edge away more readily and thus prevents its increase in size. The proof of this could be seen on the graphs from the Sanborn Recorder. The harder materials showed considerably less difference between peak to low point distance, indicating that the build up and break down of the built-up edge occurred more frequently.

The second reason for the strange behavior of the relationship of hardness to cutting force deals with the chip-tool friction. Even though no proof of this is included in this report it can be said that the frictional force is related to the ductility. This was pointed out by Dr. H. Ernst (15) and Dr. E. Merchant (16) in their earlier investigations of metalcutting. Since the frictional force increases with the ductility it can be seen that this fact would contribute to the appearance of Fig. 5.1. It is believed that this condition was of a relatively minor significance and would hardly have been detected if it were the only contributing factor.

The role of the dislocations was quite well observable. Two of the samples tested were cold worked and appear as the second and third points in Fig. 5.1. It was stated previously that cold worked materials contain a much larger amount of dislocations than the annealed materials. Since they contain more dislocations the resistance to deformation and failure should be less. The two points in Fig. 5.1 illustrate this fact.

At the beginning of research for this thesis it was hoped that a definite empirical relationship of grain size, grain hardness and distribution with cutting characteristics could be found. Unfortunately, however, no definite relationship could be detected. Fig. 5.3 shows a graph of grain size vs. cutting force. From this it can be seen that the points have a completely random location from which no definite conclusions can be drawn. There seems to be a vague indication that for a larger grain size less cutting force is required. This is in line with the theory expressed earlier in this report that for a larger grain size the mean path of the matrix, which was ferrite in most cases, is less obstructed and consequently offers less resistance to cutting. This can be pointed out in a general manner but no definite relationship can be constructed. It seems that more important parameters overshadow the effect of the grain size.

Fig. 5.4 shows a plot of hardness vs. grain size and there again, no definite relationship seems to exist. Microhardness tests were conducted to determine the hardness of the various constituents of the materials but they too did not seem to have much effect. This, of course, does not mean that grain size and microhardness have no effect on tool wear. No tool wear tests were conducted but it seems

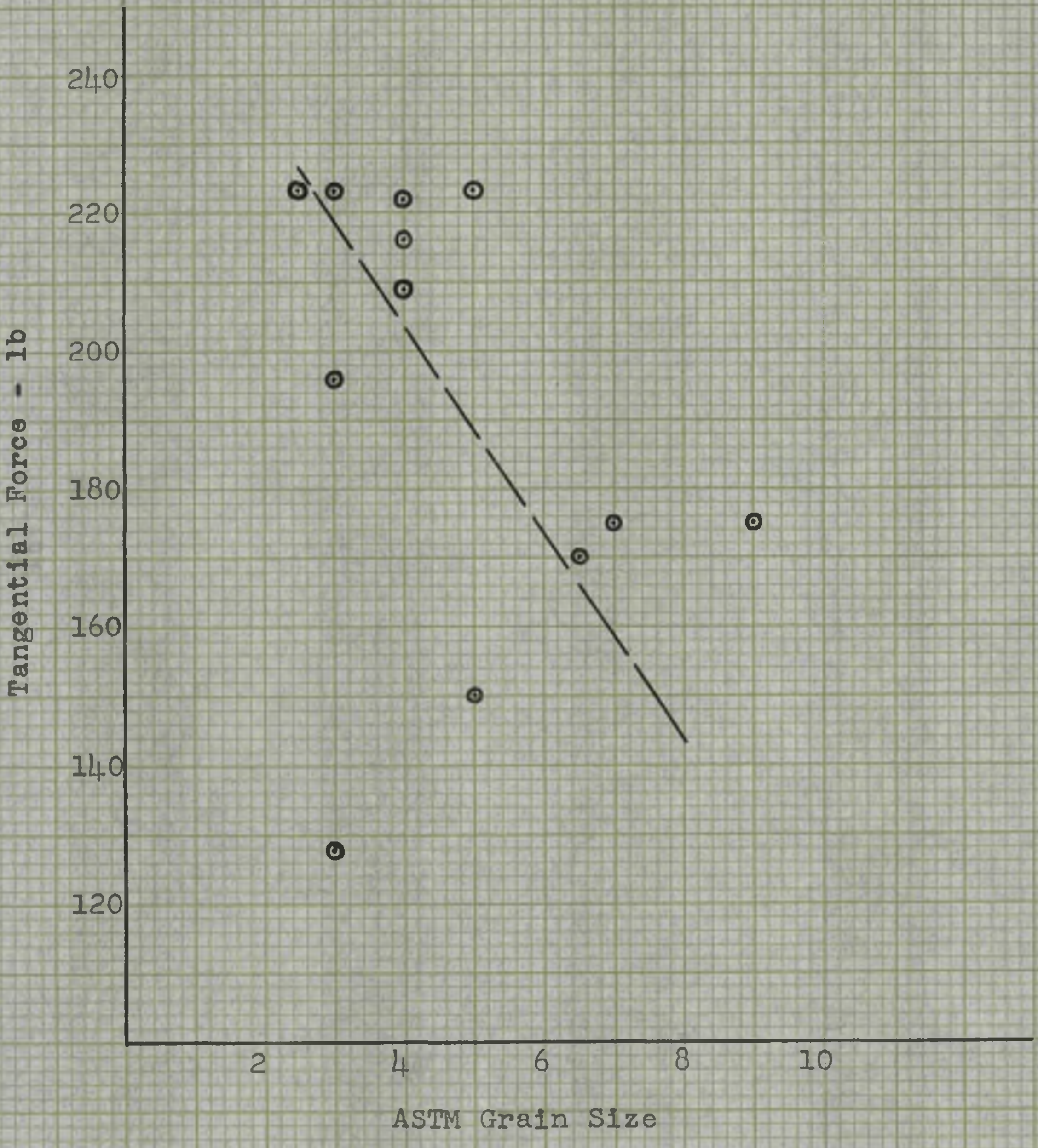


Figure 5.3 - Graph of Cutting Force vs. ASTM Grain Size

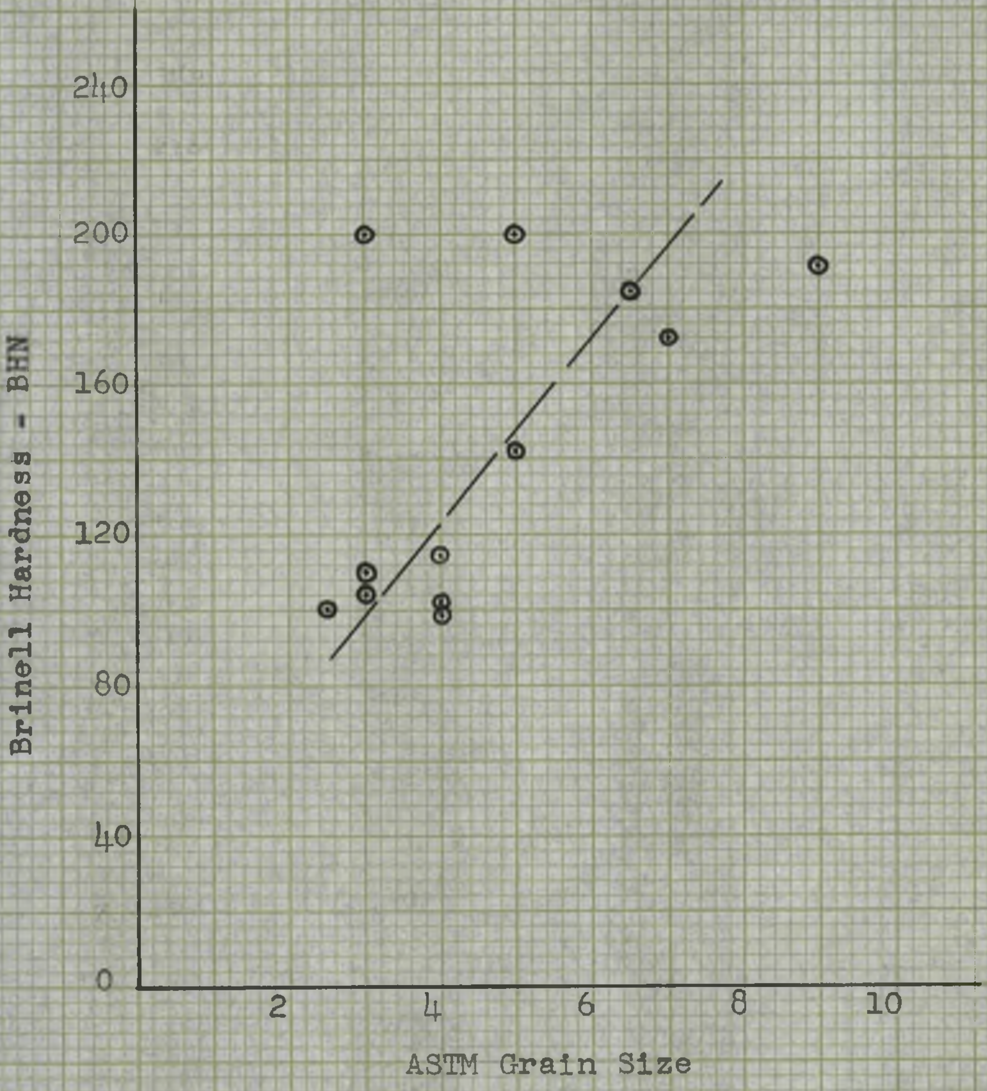


Figure 5.4 - Correlation, Grain Size vs. Hardness

quite logical that the harder certain constituents are the more tool wear would be apparent. Also, the finer distribution of the hard constituents in a small grained material would be detrimental to tool wear since more hard, abrasive particles come in contact with the tool. The fact that hardness increases with decreasing grain size, as mentioned by Lewis (11), seems to be indicated in Fig. 5.4. There seems to be a general trend in this direction but, as above, no specific relationship could be developed.

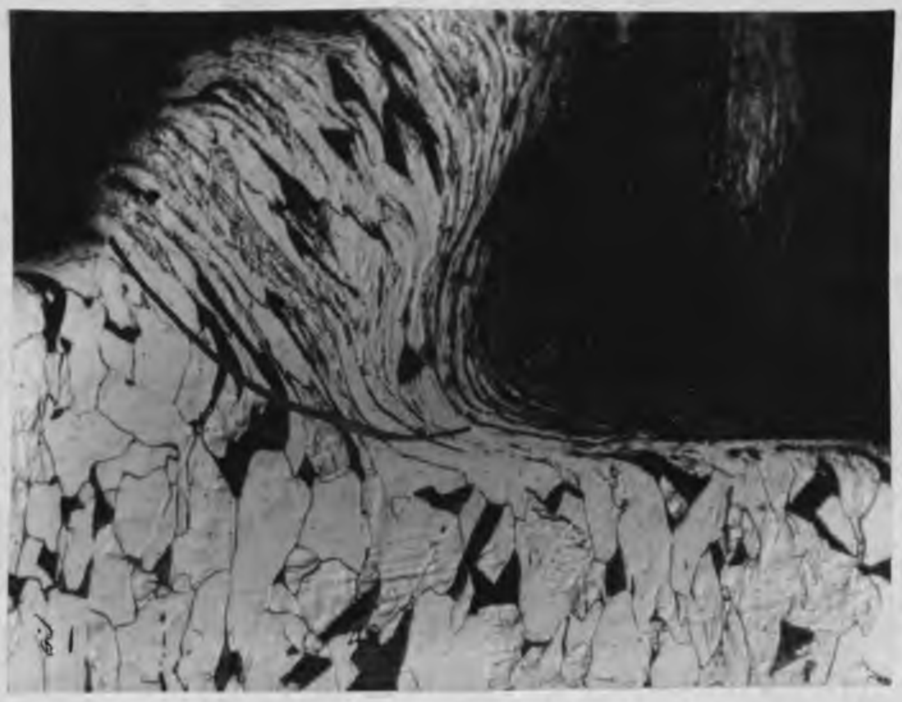


Figure 5.5 Photomicrograph of cutting region

Many investigators in their study of the shear zone consider this region of deformation a straight line. This, however, is not the case. Fig. 5.5 illustrates this point.

The curvature of the shear zone can be attributed to the grain size, orientation and distribution. A partly deformed grain seems to hold back the deforming process and thus keeps the shear zone from being a straight line. This can be seen very clearly in Fig. 5.5. For a small grain sized material the shear zone should be almost straight, whereas large grains tend to distort the deformation region. The shape and length of the shear zone is of great imortance in the study of the relationships of cutting speed and power consumption.

From the graph obtained from the Sanborn Recorder, the vibrational characteristics of the metal specimen could be observed. It was found that in general the large grained materials exhibited higher frequencies and higher amplitudes of vibrations than the small grained specimens. This can probably be explained by the fact that in the large grain structure the tool has to overcome the buildup of resistance of the individual grains, whereas in the small grain type the material acts very much like a homogeneous structure. This is in line with the theory of slip mentioned earlier in this report. In order to deform a large grain more force is required to overcome slip resistance after slight deformation and consequently the peak to root distance on the strain recorder graph could be expected to be higher. This is of importance in designing tools for machining so that the natural frequency of vibrations of tool and machine set-up is not near the frequency of cutting vibrations.

CHAPTER 6

CONCLUSIONS

It has been found that for a problem as involved and complex as the science of metalcutting a dimensional analysis is a very helpful guide. Not enough is known about the many parameters affecting metalcutting to formulate a complete mathematical theory, but the existing dimensional set-up serves as a stepping stone and channeling device to new discoveries, and advancement.

The results of this research indicate that for ductile materials the cutting force increases as the hardness increases. This improves the surface finish but the tool wear can be expected to increase.

The hardness of a material increases by decreasing the grain size. This is true in general but no definite relationship exists, so that a specific hardness cannot be linked with any grain size.

The force required for cutting goes down as the grains become smaller. This, too, is a general statement and cannot be used to obtain a definite cutting force for a specific grain size.

In accord with the dislocation theory, the materials containing more dislocations - those that were cold worked - exhibit less resistance to deformation and failure.

The vibrational frequencies are, in general, less for small grained materials. This is in accord with the theories of slip.

CHAPTER 7

RECOMMENDATIONS FOR FURTHER STUDY

The area of study involving the effect of the metallurgical properties of a material on the metalcutting conditions is far from exhausted. A large volume of experimental data is necessary to make comprehensive predictions, e.g. predictions for any material, of the material's influence on tool wear, surface finish and power consumption. During the course of work on this thesis certain areas of interest and importance to metalcutting were revealed and need further study.

The following is a list of specific projects that are recommended for further study and investigation:

1. The influence of the metallurgical properties of brittle materials on cutting characteristics.
2. Further investigations of the nature of dislocations in materials and their influence in connection with grain size.
3. The effect of the metallurgical properties on the vibrations induced in cutting.
4. The influence of grain size and hardness on tool wear and surface finish.

TABLE IV

Cutting Data

Run	Sample	Horiz. Force	Tang. Force	RPM	Feed ipr	Cutting Speed, FPM	Radius of B.E. $\frac{1}{1600}$ in.
16	1	71.5	170	141	.0041	64.5	2
17	5	72	209				7
18	6	76	150				2
19	7	71.5	175.5				3
20	7	71.5	175.5				-
21	8	75	196				4
22	9	76	216				7
23	11	107	222				$6\frac{1}{2}$
24	10	78	175.5				4
25	12	-	128				$\frac{1}{2}$
26	13	107	223				9
27	14	100	223				7
28	15	78	223				-
29	16	75	189				2

TABLE V

Metallurgical Data

Sample	Heattreatm.	Mat'l	Microhardness, VHN Fe	Pearlite	BHN	ASTM Grain size
1	Cold worked	C1018	162.4	184.8	185	6½
5	1700°F-2hr.	C1018	105.0	190.2	116	4
8	1900°F-4½hr	C1018	109.2	233.0	114	3
6	Cold Drawn	SHELBY	166.2	209.0	200	5
9	1900°F-2hr.	"	850	158.0	106	4
11	1700°F-2hr.	"	-	-	100	4
13	1900°F-4hr.	"	-	-	101	2½
7	as is	4130	110.5	171.7	185	9
10	1650°F-3hr.	"	-	-	172	7
16	1900°F-4hr.	"	-	-	172	-
12	as is	CAST I	-	-	200	-3
14	as is	C1040	-	-	141	5
15	1900°F-4hr.	C1040	-	0	112	3

TABLE VI

Chemical Composition of Tested Materials (Per Cent)

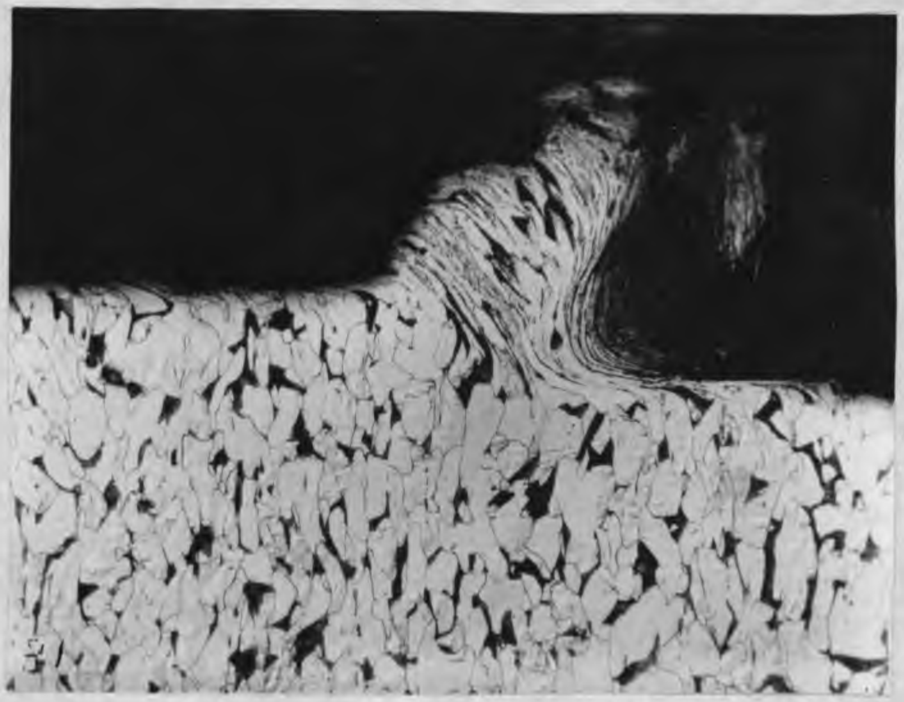
	Carbon	Manganese	Phosphorus
C1018	0.15-0.20	0.60-0.90	0.040 Max.
SHELBY	0.25 Max	.30-.60	0.04 Max.
4130	0.28-0.33	0.40--.60	0.04 Max.
CAST I	-	-	-
1040	-	-	-

Sulphur	Silicon	Chromium	Molybdenum
0.050 Max	-	-	-
.055 Max	-	-	-
.040 Max	0.20-0.35	0.80-1.10	0.15-0.25
-	-	-	-
-	-	-	-

Run 16 - C1018 - "AS RECEIVED" (100x)

Run 17 - C1018 - 1700°F - 2 hr. (100x)

Run 21 - C1018 - 1900 F°- 4½ hr. (100x)

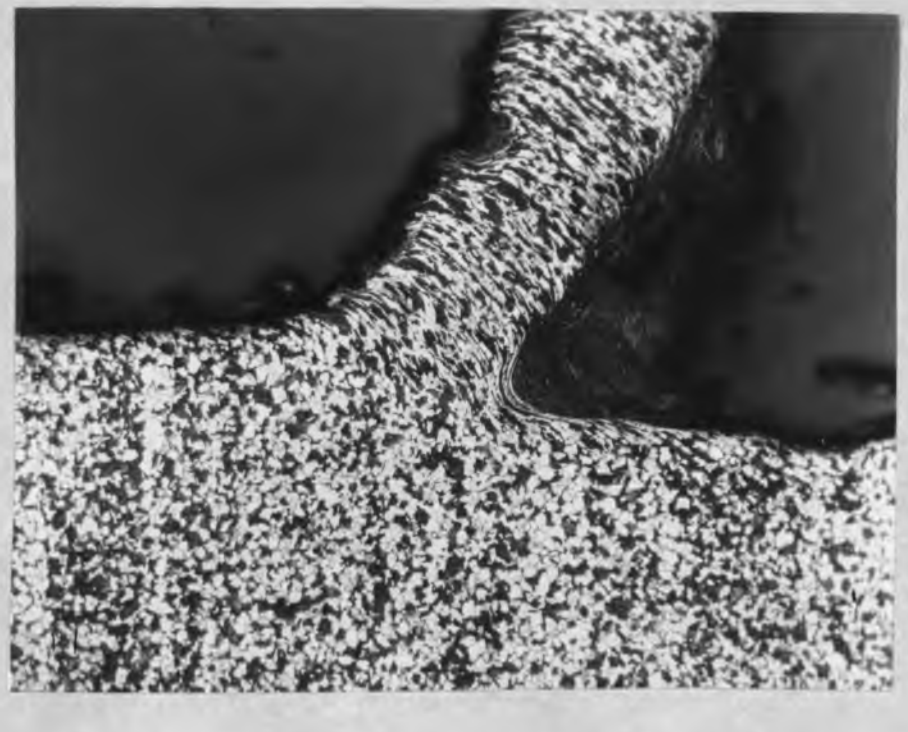


Run 18 - SHELBY - "As Received" (100x)

Run 22 - SHELBY - 1900°F - 2 hr. (100x)

Run 26 - SHELBY - 1900°F - 4 hr. (100x)

Run 23 - SHELBY - 1700°F - 2 hr. (100x)



Run 19 - 4130 - "AS RECEIVED" (100x)

Run 24 - 4130 - 1650°F - 3 hr. (100x)

Run 29 - 4130 - 1900°F - 4 hr. (100x)

Run 27 - Low Carbon Steel - "As Received"
(100x)

Run 28 - Low Carbon Steel - 1900°F - 4 hr.
(100x)

Run 25 - Cast Iron - "As Received" (100x)

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