THE RELATIVE SLIDING WEAR RESISTANCE OF SOME HARD ALLOYS

Thesis by

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SUMMARY

This thesis presents a discussion and the results of an investigation of the wear resistance of some hard alloys to sliding wear. The relative order of wear resistance of these alloys and combinations for a speed of 786 feet per minute and a load of 300 pounds per square inch is given.

The effect of the speed and load on the wear factor of gray cast iron running on an alloy cast iron is shown.

A discussion is presented of a metallographic investigation which was made of the surface conditions obtained on the specimens in the wear tests.

A method is proposed for the determination of the relative wear resistance of materials to sliding wear, in which the energy required to scratch the material with a diamond point is considered to be proportional to the wear resistance.

An attempt is made to correlate the results of the wear investigation with those of the scratch investigation.

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THE RELATIVE SLIDING WEAR RESISTANCE OF SOME HARD ALLOYS

GENERAL INTRODUCTION

This thesis presents a discussion and the results of an investigation of the relative sliding wear resistance of some hard alloys. At the present time there are several hard alloys on the market which are being used in cylinder liners for engines and pumps, as well as in many other applications. The wear resistance of these materials is one of their most important properties.

The relative wear resistance of materials can be determined in the laboratory on a suitable wear testing machine which simulates the conditions to which the material is subjected in actual practice. Tests for this investigation were made on a machine which gave the sliding wear resistance of the various alloys. These tests and results are described in Part I of this thesis. Such tests as these require considerable time for completion. A test requiring much less time would be very desirable.

The energy required to remove material ffom the surface of a specimen should be proportional to the sliding wear resistance. A scratch method in which the energy required to scratch is measured has been devised and is discussed in Part II of this thesis. Tests of this kind can be made in a few minutes.

A correlation of the results of the two types of tests is very desirable because it is known that the results of the sliding wear tests are commensurate with the results of actual field tests.

PART I. - WEAR INVESTIGATIONS

Introduction

The subject of wear is extremely complicated and at the present time is far from solution. Many investigations and experiments have been carried out, each producing valuable data and furthering the solution of this complex problem.

Of the available literature on wear, the investigations considered in the following paragraphs have seemed to be of the greatest interest in view of the present research.

The Bureau of Standards has made a large number of tests on the wear resistance of materials under different applications. (16,18,19,21,23,29)* They have made tests investigating the effect of various alloying elements and various amounts of these elements on wear resistance. At the present time they are attempting an investigation of the fundamental factors involved in the wear of metals.

Louis Jordan of the Bureau of Standards (18) states that the mechanism of wear is composed of three factors; namely, mechanical abrasion, erosion, and galling. Mechanical abrasion is the "mechanical distortion of the surface layers of the metal followed by the removal of the distorted surfaces by frictional forces between the wearing material and solids". Wear by erosion "involves

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*Numbers in parentheses refer to bibliography.

an alteration of the surface layers by chemical attack followed by the removal of the metal or the products of oxidation by frictional forces, which frictional forces are restricted to those between the wearing metal and flowing liquids, gases, or vapors". Wear by galling "involves the adhesion or cohesion of localized areas of two bearing surfaces of metals, followed by the tearing out of small fragments from one surface or the other".

Max Fink (28) has given as the three components of wear, the following; mechanical removal of particles, cold hardening process, and wear oxidation. The mechanical removal of particles accompanies wear usually in the sliding process, while cold hardening is encountered in rolling wear. Of course both of these types of wear may occur at once. Wear oxidation is as yet only a theory, but Fink and Hofmann (14) have performed many experiments which agree with the theory. Malmberg (26) has also lent some support to the oxidation theory. In 1934, Jordan and Rosenberg (5) completed tests at the Bureau of Standards on steels in various atmospheres; their results did not agree with those found by Fink and Hofmann. The tests were accomplished on an Amsler machine with rolling friction. Their test conditions duplicated as nearly as possible those of Fink and Hofmann. Their results were reported under the title of "The Influence of Oxide Films on the Wear of Steels". In this series of tests Messrs. Jordan and Rosenberg obtained characteristic types of surfaces. One was a rough film free surface which was accompanied by high rates of wear. The metal adjacent to the worn surface was severely cold-worked and cracks were found which were caused by the stresses accompanying the wearing process. The second type of surface was a filmed surface which was accompanied by low rates of wear. The material adjacent to this surface was only slightly distorted. These tests were made on steels of 0.88% Carbon and under. The analysis of the wearing dust obtained from the tests resulting in a filmed surface on the specimens showed the dust to be composed of Fe_2O_3 and Fe_3O_4 with no Fe or FeO present. The investigators concluded, therefore, that the film was an oxide film and that such a film protected the surface of the specimen, preventing metal to metal contact, thus reducing the rate of wear. Such films have been observed by many other investigators, including Dr. Max Fink (28,5) who reports that the film is usually about 0.006 mm. thick. These films are usually observed on specimens tested on the Amsler machine with rolling contact and slight slipping. If the pressures are quite high or the slipping speed is high, mechanical removal of particles takes place and the film does not form. Dr. Fink states that a film may form on the surfaces with sliding friction if the pressure is very low and the rate of slip is not too high.

The theory of wear oxidation as presented by Fink and Hofmann (14) in the paper "Zur Theorie der Reiboxydation" in 1933 is rather long. Briefly, however, they show that wear does not occur when materials are tested in pure inert atmospheres, if the pressures are not high enough to cause the mechanical removal of particles. Wear does occur when oxygen is present and all other conditions are the same by the formation of iron oxides on the wearing surfaces. The oxides are rubbed off after formation and new ones occur, which process causes a loss in weight of the specimens.

J. G. R. Woodvine (22) performed tests which were reported in 1931 under the title "The Influence of Nickel on the Wear of Case Hardened Steel". He found the 3% nickel and plain carbon steels to have about the same wear resistance with dry rolling friction or abrasion with emery. Case hardened steels having 1% or 5% nickel were inferior. With dry sliding friction the plain carbon case hardened steel was superior, with 5%, 3%, and 1% nickel steels in descending order. From his investigations Woodvine deduced that work hardening of itself is not an important factor when considering the wear resisting properties of very hard materials. At the same time, it was recognized that this is not a general rule to be applied to all steels in varying conditions.

C. J. G. Malmberg (26) made a series of investigations on an Amsler machine and found several interesting results. When two rotating surfaces are travelling in the same direction, cold working takes place and a black wearing dust appears which contains only 75% iron, the rest being oxides of iron. He feels that Fink's explanation of these oxides in the latter's theory of wear oxidation is good. Further, when two surfaces are travelling in opposite directions, giving sliding contact, no cold working occurs and a pure metallic dust is formed. He concludes that the wear resistance is greatly dependent upon the structure of the material. For example, two materials having the same analysis and heat treatment, but from different furnace melts, may have quite different wear resistance.

Recent tests have been made in connection with the wear of cylinders and pistons in motors. H. Ricardo (7) and the Institute of Automotive Engineers in England have data supporting the theory that wear in combustion engines is not due to mechanical abrasion, but is due to corrosion. The worst condition is when the motor is cold. The relation of corrosion to wear in this field is important and needs further investigation.

R. Knittel (11) has reported a very extensive investigation in Die Giesserei, 1933, in which tests were made on a high grade gray cast iron. These tests determined the effect of various alloying elements on the wear resistance. They were made by rotating a small test cylinder, the end of which was in contact with the test block. These tests were made in the dry condition. The wear was taken as the total loss in weight of both test pieces. Knittel found that the least wear occurred when the hardness of the two test pieces was the same. This fact was also mentioned by Malmberg in his paper, although the latter said that such is not always the case. Knittel further found that the surface condition was also important. This was found to be true in the present investigation.

Wallichs and Gregor (10) have also made investigations of the "Wear Resistance of Cylinder Cast Irons". They reported their work in Die Giesserei in 1933. They also found that the structure is very important and that the hardness of the material is not a true measure of its wear resistance.

The results of the investigations reviewed above may be summarized as follows:

1. Wear is a very complex problem and is far from solution.
2. Wear may take place in one of the following ways:
    a. The mechanical removal of particles from the wearing surfaces.
    b. The cold hardening process.
    c. Wear oxidation.
3. There is still considerable controversy about the wear oxidation theory of Dr. Fink.
4. Oxide films which form on the surface of specimens subjected to rolling contact affect the wear.
5. The structure of the material influences the wear resistance.
6. The condition of the wearing surface affects the wear.
7. The effect of corrosion on wear is an important factor and warrants further study.

8. There is no relation between the hardness of a material, as determined by the usual tests, and the wear resistance.

The investigations by Fink and Hofmann, Jordan and Rosenberg, and C. J. G. Malmberg are of importance in the present research because of their bearing on the fundamental factors concerning wear. The others have been of interest because of their similarity with the present research. Each has had a particular object in view and has made tests on specific materials. No data has been found which would allow direct comparison with the results of the present research. The literature is conflicting at times and in general affords no concrete comparisons of results.

Field tests to determine the wear resisting qualities of materials are, of course, the most reliable and give the true relations for the application. However, tests in the field are necessarily long and expensive and afford no data upon the variables and their relation to the wearing resistance. Laboratory tests have therefore been devised in which the various conditions of test can be controlled and duplicate as nearly as possible the actual field application. In this way the effect of the many variables which can be controlled are studied. It should be said that most of the laboratory tests which have been made were carried out in order to answer some definite problem in the field.

In this research, a comparison of various hard materials has been made in tests in which the materials have been subjected to pure sliding friction in a bath of petroleum distillate. Due to the fact that the relative wear resistance of hard alloy materials in cylinder liners, primarily in Diesel motors and gasoline engines, was desired, it was felt that a test in which wear was accomplished by pure sliding would be superior to any other. Also, these tests should be such that any combination of materials could be investigated. The machine was designed in such a way that this could be accomplished. Distillate was used in these tests because of its low lubricating properties and probable similarity to actual conditions when metal to metal contact occurs in actual operation. It served to cool and maintain the test parts at a moderate temperature and in addition served the important function of washing away any abraded material. The specimens were designed in such a way that a constant area was maintained throughout the test, thus giving a constant pressure. Also, the specimens were small, thereby increasing the accuracy with which the loss of weight could be determined.

Apparatus

The wear tests were carried out on a wear testing machine in the Testing Materials Laboratory at the California Institute of Technology. This machine was originally a bearing testing machine, but was redesigned under the direction of Dr. Donald S. Clark, in order to adapt it to the requirements of the wear tests.

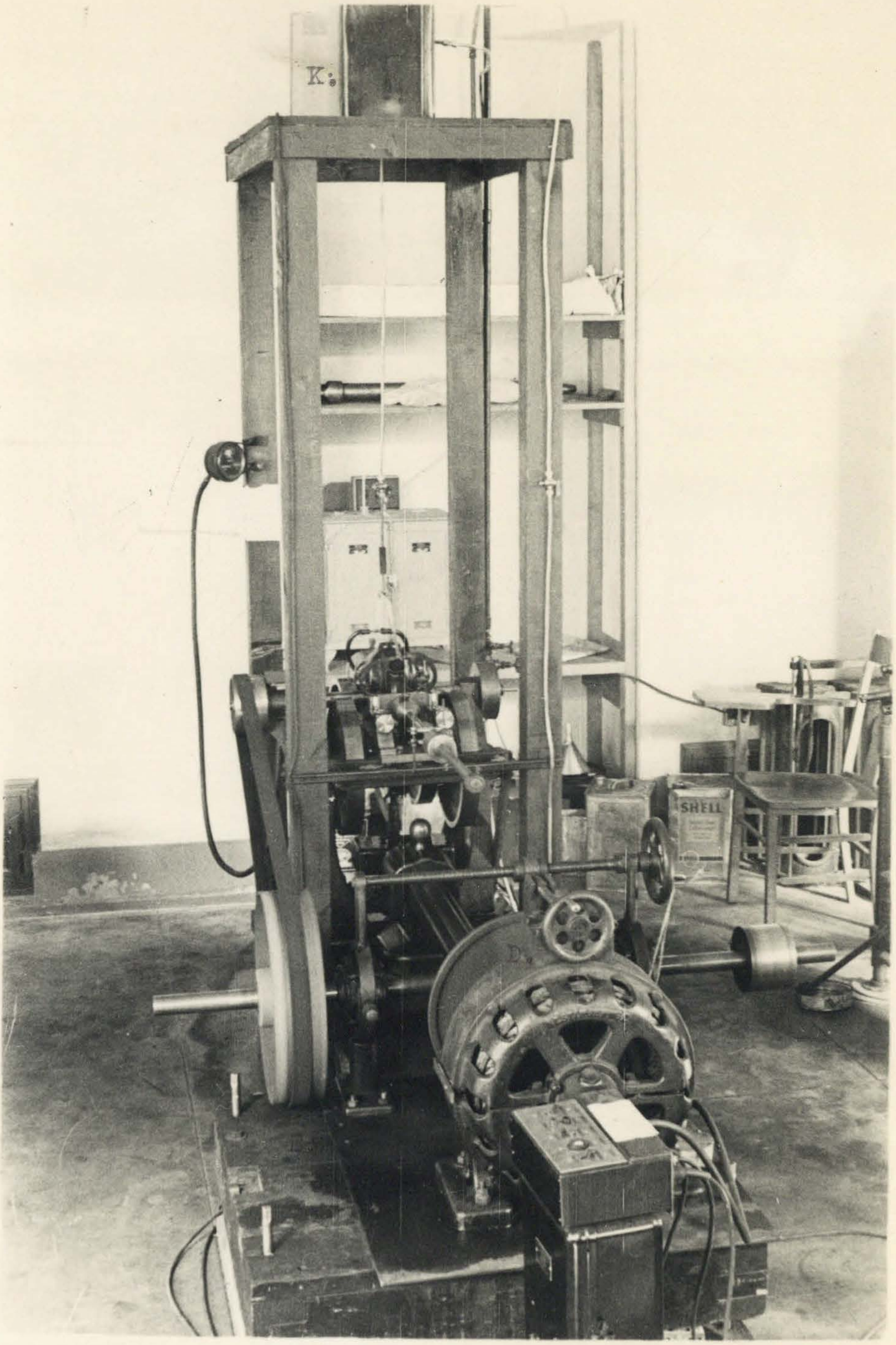
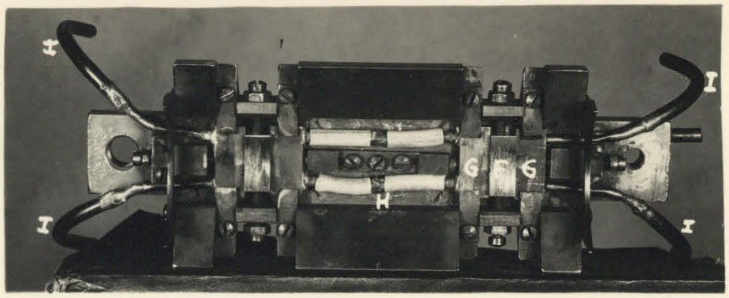


Figure 1.



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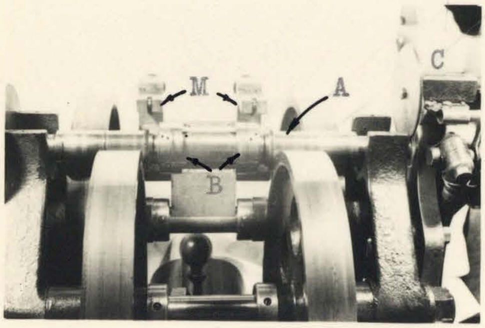
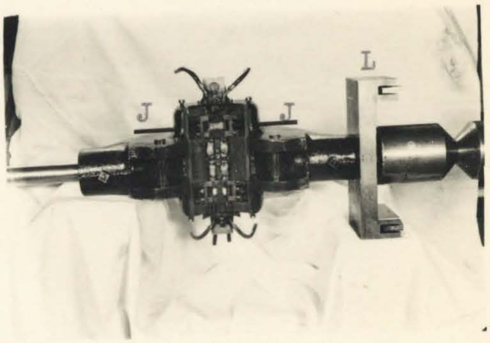


Figure 2.



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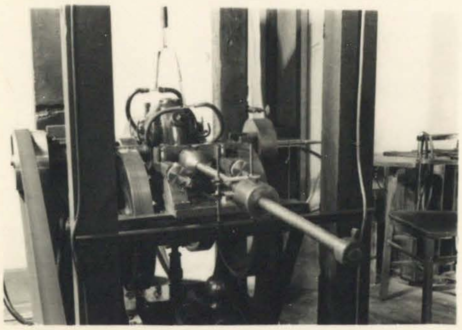


Figure 5.

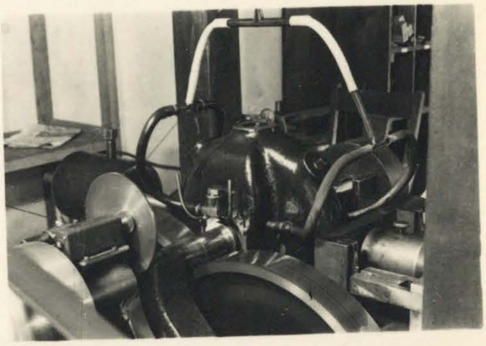
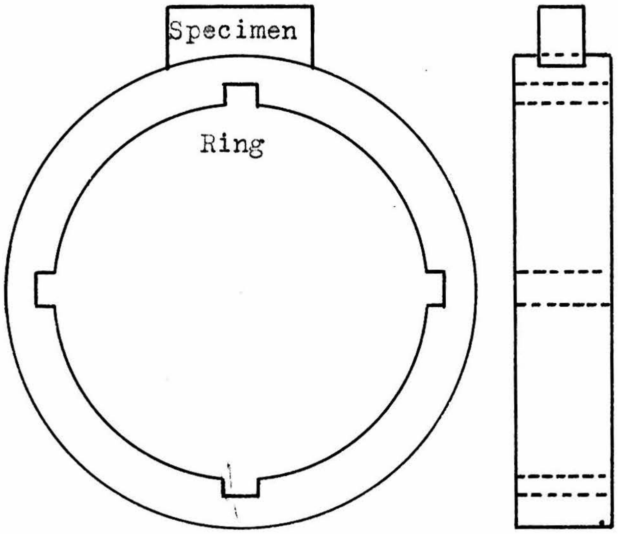


Figure 6.

A general view of the machine is shown in Figure 1. It consists of a rotating shaft, A, on which are placed the two rings, B, against which the specimens wear, as shown in Figure 2. The shaft is supported by four wheels running freely on fixed axes. The number of revolutions made by the shaft is recorded by a counter, C, geared to the shaft. The shaft is rotated by belt drive from a variable speed unit, D, mounted on the main driving motor stand, E, as shown in Figure 1. The outside diameter of the rings is 2.4375 inches and they are one-half inch wide. Each ring is keyed to the shaft and is held firmly in place by two locking rings. The specimens are small blocks having a cross sectional area one-fourth by three-fourths of an inch, or seven-sixteenths by seven-eights of an inch, depending upon the test being made. The larger specimens were used for low pressures and the smaller ones for high pressures. The surface of contact on the specimen is ground on the same radius as the rings against which it wears. The axis of curvature is parallel to the



Sketch of Specimen and Ring

short side of the specimen, as is shown in the accompanying sketch. The two specimens are mounted in a special head, shown in Figure 3, which holds them firmly in position on the rings. On each side of the specimen, F, is a copper holder, G, which is drilled for water cooling. The backing plate, H, is also water cooled when necessary. The tubes, I, extending from the head are the intake and the outlet pipes for water cooling. Figure 4 shows a general view of the head. The tubes, J, shown in position over the specimens are those used for bathing the specimens and rings with distillate. The distillate is supplied from the tank, K, overhead, as shown in Figure 1. The arrangement, L, shown to the right of Figure 4 is set against the bearings, M, shown in the background of Figure 2. By proper adjustment, the specimens are made to set evenly on the wearing rings and any movement in the direction of motion is prevented by the arrangement shown. The friction moment is not affected by this system, because the sectors which contact the bearings are ground on a radius whose center is at the center of rotation of the shaft. Figures 5 and 6 show the head in position with the beam balanced. In the lower right-hand corner of Figure 6 can be seen the arrangement of sectors and bearings which prevent movement of the head in the direction of motion. The proper load is applied to the head by means of a suitable lever mechanism. The head is maintained in balance in order to determine the friction moment during the test. The machine was equipped so that it could be run continuously if desired. Any radical change in the position of the head or the lowering of the surface level of distillate in the reservoir immediately stopped the power supply.

Procedure:

The specimens and rings were run in a bath of distillate which acted as a coolant and removed the worn material from the surfaces throughout the entire test. Clean distillate was run onto the wearing surfaces at the rate of about 0.1 gallons per minute when the surface speed was 393 feet per minute or less, and at a rate of about 0.2 gallons per minute when the surface speed was 786 feet per minute. It was then drained off for settling and recirculation. When the wear was high the distillate was filtered before recirculation.

The wear of the specimens was determined by the loss of weight experienced during the run. The specimens were washed in alcohol before each weighing to remove any foreign matter. All specimens were given a first period of wearing in. The specimens were weighed before and after each run. Where possible, the tests were continued until uniform results were obtained for the material under test. The wear on the rings was not measured, but the surface condition after the test periods was observed closely and reported.

The wear at any given load and speed is a function of the contact surface area and the length of the surface passed over.

Therefore, the results of these tests were determined by dividing the loss in weight experienced by the specimen by the projected area of contact and the length of travel. The projected area of contact is the area of the specimen cross section. Since all of the tests were made on the same type of rings having a constant radius of curvature, this area could be used instead of the actual circumferential area of contact. In case the finish of the surface of the specimen was not exact and the rate of wear was low, the area of contact was not over the whole surface and the running-in period did not remove sufficient material to cause complete contact. Where this condition occurred, the area of contact was estimated, and the unit pressure was computed on this basis. All pressures of this type are listed in the data with a "±" after the value. The length of travel was determined from the circumference of the ring and the total number of revolutions of the shaft. The unit value obtained in this way is expressed in grams per square inch per foot. To simplify the presentation of results, the term "wear factor" has been selected whichis equal to 10^8 times the loss in weight expressed in grams per square inch per foot. The higher the wear factor, the greater will be the rate of wear of the given material.

The coefficient of friction was determined by dividing the force tangent to the surface of contact by the normal force applied to the specimens. The tangential force was obtained from the friction moment, which in turn was obtained by balancing the head of the machine.

TABLE I.

Materials Tested

Material Designa-tion	Material		Carbon Total %	Carbon Graph. %	Si %	Mn %	P %	S %	B %	Ni %	Cr %	Mo %
A	Plain I.R. Metal		3.05		1.13	1.02	0.047	0.020	1.19			
B	4.5% Ni. I.R. Metal		2.75		1.00				0.80	4.50		
C	Grey Cast Iron		3.29	2.65	2.56	0.94	0.356	0.022				
E	Engine Block	Quench 1500°F. Draw 700-750°F.	3.33		1.60		0.05			1.75		0.50
F	Engine Block		3.38		2.16	0.65	0.05			1.40	0.45	0.40
G	Piston Rings		3.64		2.82		0.48					
WC	White Cast Iron		3.25		0.30	0.40	0.10	0.02				
CH	Case Hardened											
FA	Brown Flint Alloy											
N	Nitrided Nitralloy											
St	Haynes Stellite											

Materials:

Eleven different materials were used in these tests. They are listed with designations in Table I. The analysis is given where possible. Metals "A" and "B" are alloy white cast irons having hardnesses of about 700 and 850 diamond brinell, respectively, as determined by the Monotrone machine. These materials are products of the same company, and initial tests showed that "B" was superior to "A" so that only a few tests were made on the latter material. These alloys have a lower melting point than steel, so that they can be spun in steel cylinders giving a hard lining on the steel base. For this reason, they are very suitable for wear resistant liners in various applications. Metal "C" is a typical gray cast iron and was used extensively in the tests for determining the relations between load and wear at various speeds. The rate of wear is high, therefore the length of time required for a test run is short. Metals "E" and "F" are gray cast irons which are typical of those being used in engine blocks in Diesel applications. "E" is used after heat treatment and "F" is used in the as-cast condition. Metal "G" is a typical piston ring material. Metal "WC" is a plain white cast iron and has a diamond brinell hardness of about 475. The analysis of the remaining materials is not known. "CH" is a case hardened steel. "FA" is a special material known as Flint Alloy. "N" is a nitrided nitralloy. "St" is a stellite manufactured by the Haynes Company.

The various materials will be referred to by their designations in the discussion which follows.

Comparison of Wear Factors:

The results of about two hundred test runs are given in Table II. This table has been divided into nine sections to provide easy comparisons of materials. The combination tested is indicated by the first two columns, in which are listed the material of the specimen and the ring. The third and fourth columns list the load and speed, respectively. The wear factor of the specimen for the combination is given in column five. The coefficient of friction is given in the succeeding column. If the coefficient of friction was not determined, the space is left blank. In case it is designated by 0.00-, the coefficient was less than 0.01 and the apparatus is insufficiently accurate to determine its exact value. The surface condition of the ring and specimen after test is also indicated by abbreviations, which are explained at the end of the table.

The first section of Table II gives the results of tests in which the same material was used for rings and specimens. Section B shows the results of tests in which "B" metal specimens were run on "A" metal rings. In the following section, C, the results of tests in which several different materials were used for the specimens and "B" metal was used for the rings, are given. Sections D, E, G, H, and I compare "B" metal running on another metal with

TABLE II.

Specimen	Ring	Load #/in^2	Speed Ft/min.	Wear Factor	Coefficient of Friction	Condition Specimen	Condition Ring	Runs
Section A:								
A	A	300	393	1.4	0.00-	V.Sm.	V.Sm.	17,18,19,20
B	B	500	393	0.0°	0.00-	V.Sm.	V.Sm.	28,29,30
B	B	300	786	0.2	0.02	V.S.G.	Sm.	35,36
B	B	300	1180	1.6	0.05	G.	S.G.	48,49,50,53,54,55
WC	WC	400	393	0.2	0.00-	Sm.	Sm.	31,32,33
WC	WC	400	786	2.6	0.00-	R.	R.	34
WC	WC	300	1180	0.5	0.01	Sp.	S.R.	58,59,60
N	N	300	786	3.4	0.00-	V.Sm.	V S.G.	216,218,219
CH	CH	300	786	34.0	0.00-	S.R.& S.G.	S.R.& S.G.	159,160,161
FA	FA	300	786	15000.		S.R.	S.& S.G.	209,210
St	St	300	786	45.5	0.03	R.	R.	37,38
Section B:								
B	A	300	393	0.3	0.00-	V.Sm.	V.Sm.	21,22
B	A	600	393	017	0.00-	S.G.& S.R.	Sm.	23,24,25
Section C:								
CH	B	300	786	0.05*	0.00-	V°V.Sm.	V.S.R.	165
B	B	300	786	0.2	0.02	V.S.G.	Sm.	35,36
WC	B	400	786	0.1	0.00-	Sm.	Sm.	45,46,47
N	B	300	786	0.6***	0.00-	S.R.& G.	V.Sm.& S.R.	225,226
FA	B	300	786	0.6**		G.	R.	212,213,214,215
St	B	300	786	1.0	0.00	B.G.	R.	39,40,41
E	B	300	786	140.	0.05	S.R.& S.G.	S.G.	139,140,141,130
E	B	300	786	3500.	0.07	S.R.& S.G.	G.	127,129,131,132,141
F	B	300	786	1.5	0.02	S.Sp.	Sm.	135,136,137,138
G	B	155	786	164800.	0.11	S.R.	Sm.	112,113,114
C	B	33	393	14.2	0.16	R.	Sm.	82,83,84,85
C	B	33	786	40.5	0.45	R.	Sm.	86,87,88,89

TABLE II. Cont.

Specimen	Ring	Load #/in^2	Speed Ft/min.	Wear Factor	Coefficient of Friction	Condition Specimen	Condition Ring	Runs
C	B	70	393	2.2	0.11	Sm.	Sm.	98,99
C	B	70	786	560.	0.16	R.	Sm.	92,93,94
C	B	96	295	20.	0.03	V.V.S.R.	V.V.Sm.	191,192,193
C	B	96	393	0.0^{00}	0.07	Sm.	Sm.	100,101
C	B	96	393	86900.	0.11	R.	Sm.	77,78,79,80,81
C	B	96	786	7400.	0.13	S.R.	Sm.	90,91
C	B	130	786	122000.	0.35	B.R.	G.	95,96,97
C	B	150	393	86400.	0.14	S.R.	Sm.	102,103,104,105,106
C	B	200	295	62000.	0.11	V.V.S.R.	V.V.Sm.	184,185,186,187,188
C	B	200	393	220000.	0.12	S.R.	V.Sm.	202,203,204
C	B	300	197	700.	0.06	V.V.S.R.	Sm.&V.V.S.R.	174,175
C	B	300	295	123000.	0.11	S.R.	V.Sm.	179,180,181
C	B	300	393	390000.	0.12	S.R.	S.G.	199,200,201
C	B	450	295	288000.	0.11	R.	S.G.	182,183,197,198
C	B	600	197	80000.	0.14	S/R.	S.R.	65,66,176,177
Section D:								
B	St	300	786	1.7		V.V.S.G.	Sm.	42,43,44
St	St	300	786	45.5	0.03	R.	R.	37,38
Section E:								
B	WC	300	1180	0.7	0.01	B.G.	R.	61
WC	WC	300	1180	0.5	0.01	Sp.	S.R.	58,59,60
Section F:								
G	B	155	786	165000.	0.11	S.R.	Sm.	112,113,114
G	F	155	786	160000.	0.11	S.R.	S.G.	115 to 120 incl.
G	E	155	786	125000.	0.10	V.S.R.	Sm.	121 to 126 incl.

Specimen	Ring	Load $\#/in^2$	Speed Ft/min.	Wear Factor	Coefficient of Friction	Condition Specimen	Condition Ring	Runs
Section G:								
B	CH	300	786	1.1	0.03	Sm.	V.S.R.&V.V.S.G.	207,208
CH	CH	300	786	34.0	0.00-	S.R.&S.G.	S.R.&S.G.	159,160,161
Section H:								
B	FA	300	786	0.6		V.S.R.&V.S.G.	Sm.	214,215
FA	FA	300	786	15000.		S.R.	R.&S.G.	209,210
Section I:								
B	N	300	786	0.2½	0.00-	V.S.R.	S.R.&S.G.	221,222
N	N	300	786	3.4	0.00-	V.Sm.	V.S.G.	216,218,219

Abbreviations:-

Sm. = Smooth	V. = Very
G. = Galled	S. = Slightly
R. = Ridged	B. = Badly

Symbols:-

o = 4×10^6 feet of travel
oo = 13000 feet of travel
* = 5.7×10^6 feet of travel
** = 2.9×10^6 feet of travel
*** = 2.5×10^6 feet of travel
½ = 3×10^6 feet of travel

the metal running on itself. Section F shows the results of tests in which the material "G" was run on rings of three different materials.

Note that in section C, two values for the wear factor of "E" on "B" are given. In tests on this combination the exact value was difficult to determine. The loss in weight on several tests seems to fall into two classes; one, a low value, and the other, a higher value. The wear was computed for both and is listed in section C. It appears that for this combination the critical load is about three hundred pounds per square inch for a surface speed of 786 feet per minute. Therefore small variations in conditions greatly affect the wear factor.

Effect of Speed and Load on the Wear Factor:

In order to study the effect of load and speed on the wear factor, a series of tests was made wearing gray cast iron against "B" rings. The results of these tests are found in section C of Table II. These tests indicate an increase in wear factor with an increase in speed, as can be seen from the table. It is apparent that the effect of the speed on the wear is not as great as the load. The relation between the wear factor and the load at surface speeds of 786, 393, 295, and 197 feet per minute for gray cast iron running against "B" is shown in Figure 7. The data for these curves was taken from Table II, section C.

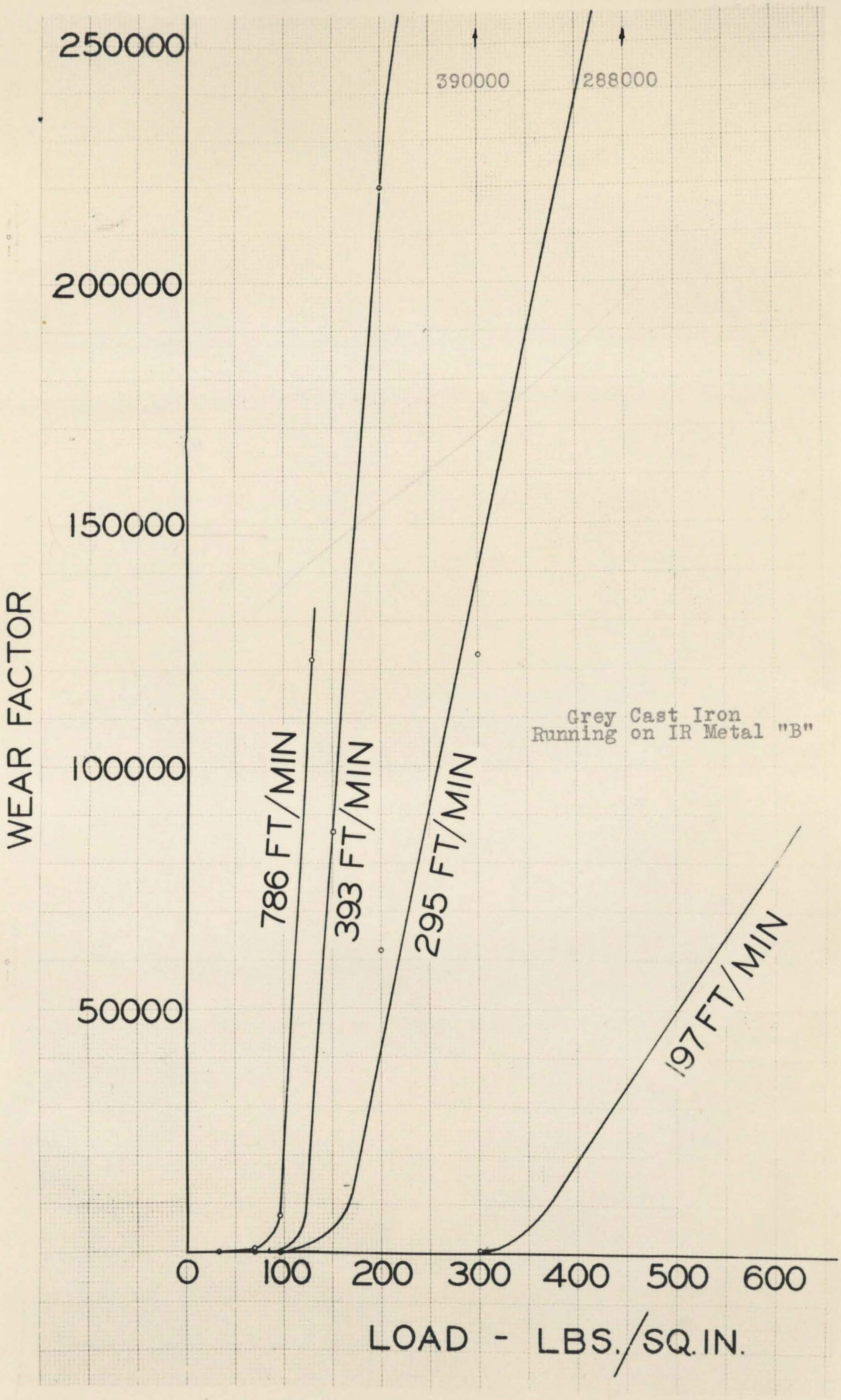

250000
200000
150000
100000
50000
WEAR FACTOR
390000
288000
786 FT/MIN
393 FT/MIN
295 FT/MIN
197 FT/MIN
Grey Cast Iron
Running on IR Metal "B"
0
100
200
300
400
500
600
LOAD - LBS./SQ.IN.

Figure 7.

This same relation has been observed by other investigators working with cast iron. When the pressure is low, the rate of wear is extremely low and as the load is increased a critical point will be reached at which time the rate of wear increases very markedly.

It was observed during these tests on gray cast iron that the value of the wear factor was greatly dependent upon the condition of the wearing surfaces before the test run. It was found that under certain conditions, if the wearing elements were polished with 400 grain alundum paper, the wear values were zero for the length of run tested. However, if the wearing surfaces were smoothed with 280 grain alundum paper, approximately the same length of run gave wear values which were uniform, as shown in the data.

The results of this investigation with gray cast iron cannot be applied directly to the results with other materials. However, these tests indicate that at loads below a critical, the speed is of minor importance and the wear factor will be small. Also they indicate that at loads above this critical, the speed is of great importance in the test results. The critical pressures for materials other than gray cast iron have not been determined. It can be seen that such a determination would be a long procedure. It was observed that for material "E" running on "B" the critical load at a surface speed of 786 feet per minute appeared to be about 300 pounds per square inch. The tests on other materials seem to indicate that the conditions of the test were below the critical pressure.

In section A of Table II the wear factors for "B" on "B" at speeds of 393, 786, and 1180 feet per minute are given. The pressures are the same for these runs with the exception of the first, where the wear factor is zero for the length of run given. It is seen that the wear factor increases with the speed, although it is low in all cases. In the same section are shown the results of tests on white cast iron at approximately the same pressure. In these tests the highest wear factor was obtained at a speed of 786 feet per minute, but this value is based on only one run, and, further, the specimens had been used on previous tests at lower speeds which may have affected the results. At any rate, the wear factor does increase with speed even for the low values obtained with the hard materials.

The Relative Wear Resistance of Combinations of Materials:

When considering the wear of two dissimilar metals against each other, the wear of each material must be taken into account. The tests as they were conducted do not allow a direct evaluation of the wear resistance of a combination, but give only a value for the wear resistance of each material rubbing against the other member of the combination. The wear factor for the combination of materials, which is the inverse of the wear resistance, has been computed by taking the average of the individual values of the two materials rubbing together. These computed values are shown in Table III. The first column of the table gives the rating of the various combinations

TABLE III.

RELATIVE WEAR RESISTANCE

At 300 lbs/in^2 and 786 Ft/min

Rating	Combination	Wear Factor	Ratio	Surface Conditions
1	B-B	0.20	100	Very slight galling
2	B-N	0.40	50	B shows slight ridging and N shows slight ridging and galling
3	B-CH	0.58	35	Both very slightly ridged
4	B-FA	0.60	33	B shows ridging and FA shows galling
5	B-F	0.8	25	B shows smooth surface and F shows slight galling
6	B-St	1.4	14	B shows ridging and St shows galling
7	WC-WC	2.6	8	Ridging
8	N-N	3.4	6	Very slight galling
9	CH-CH	34.	0.6	Slight ridging and galling
10	St-St	48.	0.4	Ridging
11	B-E	140. 3500.	0.14 0.006	B shows slight galling and E shows slight ridging and galling
12	FA-FA	15000.	0.001	Shows ridging and slight galling

in order of decreasing wear resistance, i.e., number one has the highest wear resistance. The third column gives the computed wear factor as discussed above. The fourth column gives the wear resistance of the particular combination in per cent of the wear resistance of "B-B". The values given in this table are only for a load of 300 pounds per square inch and a rubbing speed of 786 feet per minute.

Tests indicated that "B-WC" would be a combination superior to "B-B" although the data is insufficient to give an exact value. The difficulty in evaluating this combination was due to the exceedingly long time required to obtain any measureable loss in weight of "B" running against "WC".

Surface Conditions:

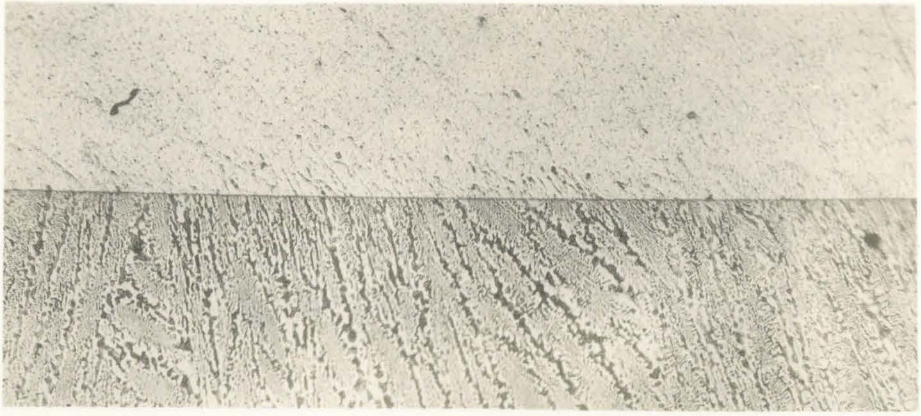
During these tests, three different types of surface conditions were observed. Specimens were either smooth, galled, or ridged after test. The smooth surfaces were mirror bright in appearance on the hard materials and were very even and uniform on the gray cast iron. The galled surfaces were those surfaces which showed that adhesion or cohesion of localized areas of the two mating materials had taken place. This causes a tearing out of small fragments from one surface or the other. This definition of galling has been given by Louis Jordan of the Bureau of Standards and is included in the introduction of Part I of this thesis. The ridged surfaces were grooved in the direction of wear.

A-1 5X

Figure 8.

A-1-A Unetched 150X

Figure 9.



A-1-B Etched 150X

Figure 10.

The surface conditions of the wearing materials have been reported in the tables according to the above designations.

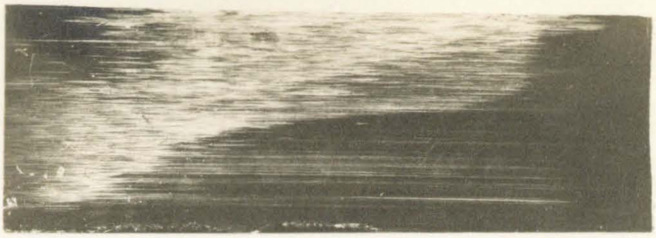
A metallographic investigation was made of each type of surface condition. Specimens having a surface condition corresponding to each of the three types mentioned above were examined. Macrographs were first taken of each specimen to be investigated in order to show the condition of the worn surface. A layer of copper was plated on the worn surfaces of the specimens. A longitudinal section at right angles to the worn surface was polished in the usual way for metallographic investigation. The copper layer which was bonded to the worn surface helped maintain a flat surface to the edge of the specimen. This gave a view of the worn edge along the entire length of the specimen.

Of the specimens which had smooth surfaces after test, A-1, B-14, C-25, CH-4, N-2, WC-3 were selected for metallographic investigation. With the exception of the gray cast iron specimen, C-25, all of these surfaces were mirror bright after test. Some showed evidence of slight ridging or slight galling, but the surface as a whole was smooth. The gray cast iron was very even and smooth, but was not mirror bright due to the presence of the graphite. Also, this surface was slightly ridged.

The macrograph of specimen A-1 is shown in Figure 8. Contact was not complete over the entire surface of the specimen so that the lighter area shows the condition of the surface before test. The dark area is the worn surface which was mirror bright. However, slight ridges may be seen. This specimen was run on ring A-7 at a pressure of 300 pounds per square inch and at a surface speed of 393 feet per minute. Figures 9 and 10 show a cross-sectional view of the worn edge at a magnification of 150 diameters. At the top of the picture is the copper plate and below is the structure of the specimen. Figure 9 shows the surface unetched and Figure 10 shows the structure after etching ten seconds in a solution of 1% nitric acid in methyl alcohol. The edge is smooth, clean cut, and shows no evidence of distortion. The structure of the specimen is characteristic of white cast iron. The white areas are cementite, Fe_3C, and the dark areas are grains of pearlite, which is the eutectoid of iron and iron carbide.

In all of the photomicrographs to follow the copper plate will be at the top of the picture. The structure below the worn edge will be that of the material of the specimen. Unless otherwise stated the etch for all specimens was a solution of 1% nitric acid in methyl alcohol.

Specimen B-14 was run on ring B-6 at an approximate load of 500 pounds per square inch and at a surface speed of 393 feet per minute. This specimen did not seat properly on the ring so that only about one-half of the surface was worn. Figure 11 is a macrograph of the surface. The darker area on the picture is the worn part of the surface. The lighter portion was not in contadt. The

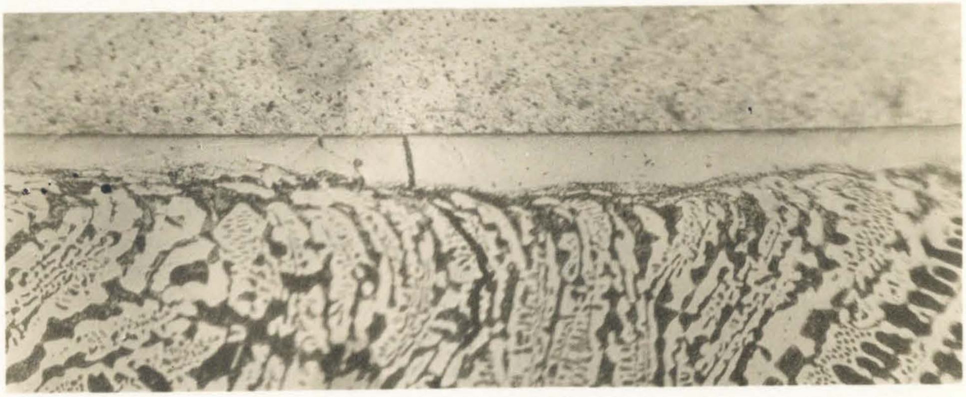


B-14 5X

Figure 11.

B-14-A 150X

Figure 12.



B-14-B 400X

Figure 13.

B-14-C 400X

Figure 14.

worn surface was mirror bright after test, although slight ridges are visible in the macrograph. Evidence of galling can be seen on the edge at the top of the picture. Figure 12 shows the worn edge at a magnification of 150 diameters in the unetched condition. This cross section was taken on the edge seen at the top of the picture in Figure 11. Two surface cracks can be seen. These are caused by the stresses developed at the surface during the process of wear. Figure 13 shows one section of the worn edge at a magnification of 400 diameters after etching. A layer of worked material can be seen in this view. The nature of this layer will be discussed in detail later, page 60 , after the descriptions of the various surfaces examined. Below the layer of worked material can be seen the structure of the alloyed cast iron. The dark grains are composed of iron and solid solution of iron carbide and iron boride, and the white grains are the solid solution of iron carbide and iron boride. Note that the grains of these constituents are deformed to a considerable extent. The direction of wear in this case was from right to left over the surface of the specimen. The grains are bent in this direction. Figure 14 shows another section of the worn edge on which no layer of worked metal has formed. The magnification is again 400 diameters. The layer as shown in Figure 13 appeared only in a few places. The rest of the surface was similar to that shown in Figure 14.

Specimen C-25 was run on ring B-27 at a load of 300 pounds per square inch and at a surface speed of 197 feet per minute. The

C-25 5X

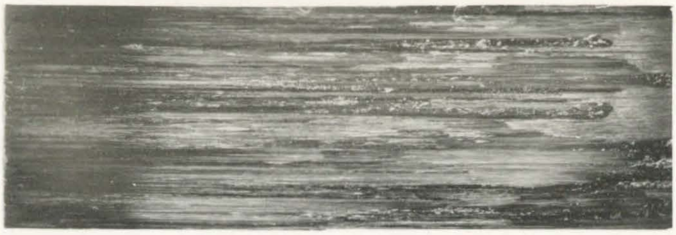
Figure 15.

C-25-A 150X

Figure 16.

C-25-B 150X

Figure 17.



CH-4 5X

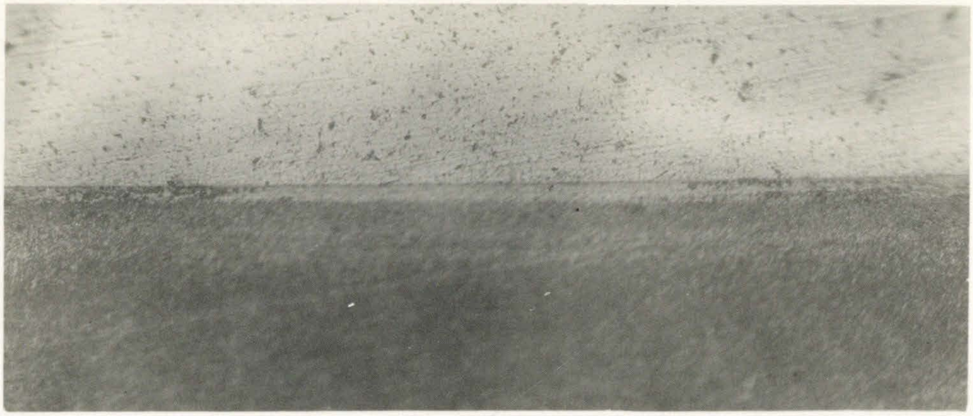
Figure 18.

CH-4-A 150X

Figure 19.

CH-4-B 400X

Figure 20.

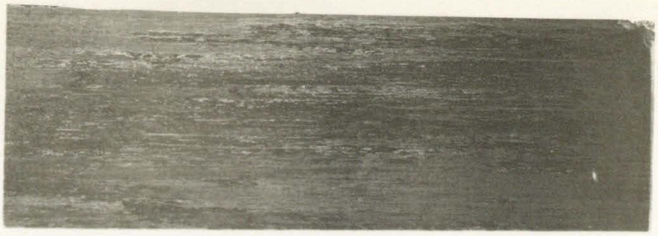


CH-4-C 400X

Figure 21.

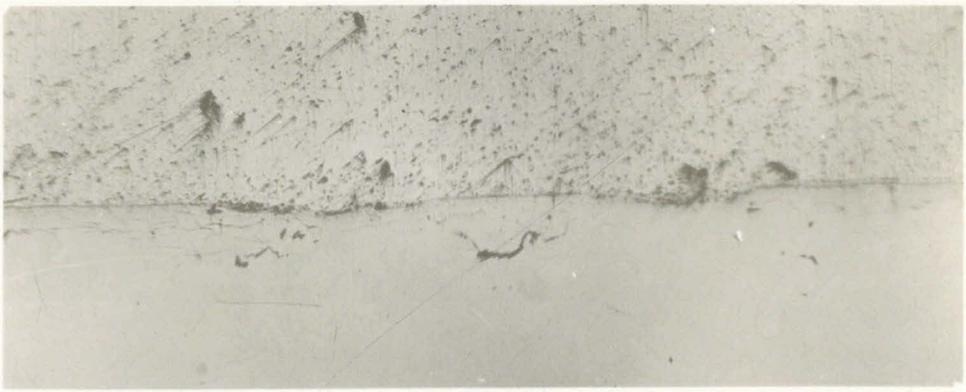
CH-4-D 1000X

Figure 22.



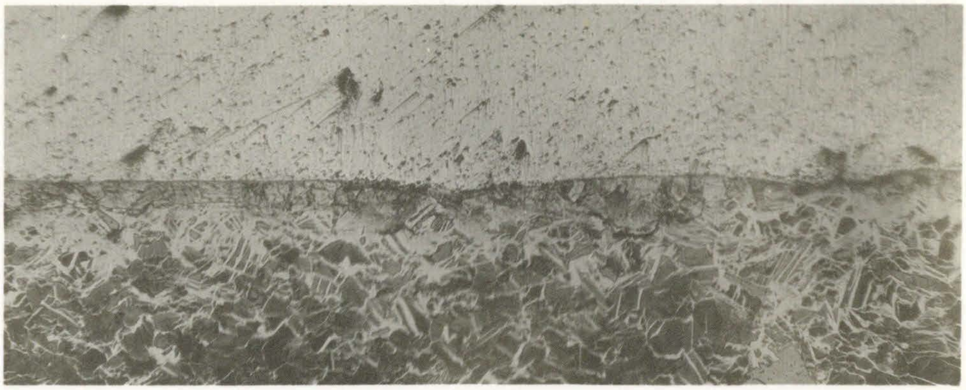
N-2 5X

Figure 23.



N-2-A 150X

Figure 24.



N-2-B 150X

Figure 25.

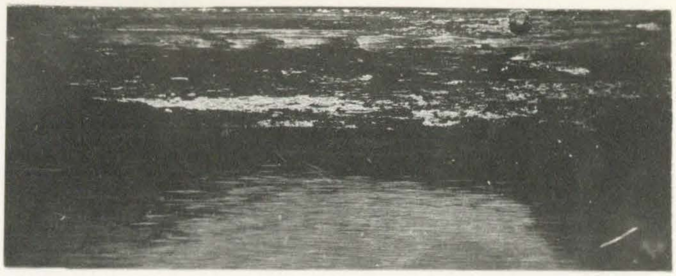
N-2-D 400X

Figure 26.

macrograph of the surface after test is shown in Figure 15. The surface was only slightly ridged and was quite smooth. Figures 16 and 17 show the worn edge and the structure of the gray cast iron unetched and etched, respectively. The edge is straight and smooth showing no evidence of distortion or a layer of worked metal.

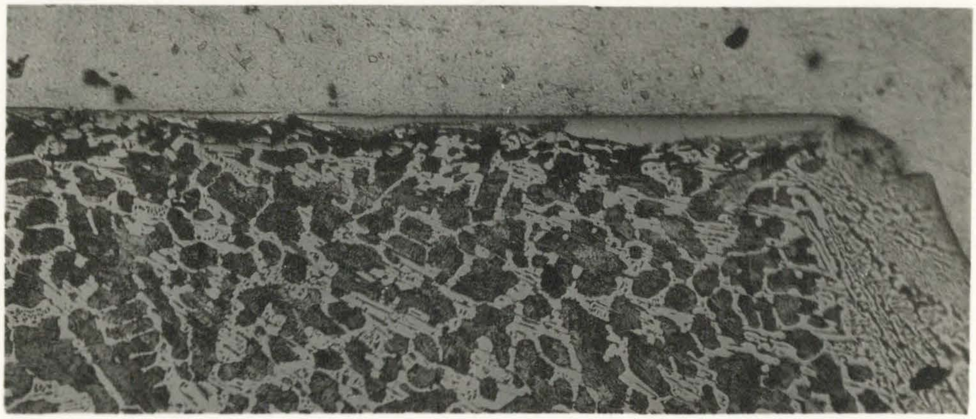
Figure 18 is a macrograph of the worn surface of specimen CH-4 which was run on ring B-26 at a load of 300 pounds per square inch and at a surface speed of 786 feet per minute. The surface after test was mirror bright except for a few dull places. A cross section of the worn edge, unetched, at a magnification of 150 diameters is shown in Figure 19. Further investigation showed that a worked layer had formed in some places. Figure 20 shows the thickest section of this layer at a magnification of 400 diameters after etching. The severity of the working is clearly shown. This is a very good example of the process by which wear takes place by cold hardening. The material is worked until cracks form which separate fragments from the rest of the material. The fragments are then easily worn away. Figures 21 and 22 show the surface where no worked layer has formed. The magnification is 400 and 1000 diameters, respectively, in each picture.

Figure 23 is a macrograph of specimen N-2 which was run on ring N-2 at a load of 300 pounds per square inch and at a speed of 786 feet per minute. The surface was mirror bright after test, although the macrograph shows it to be somewhat rough in places.



WC-3 5X

Figure 27.

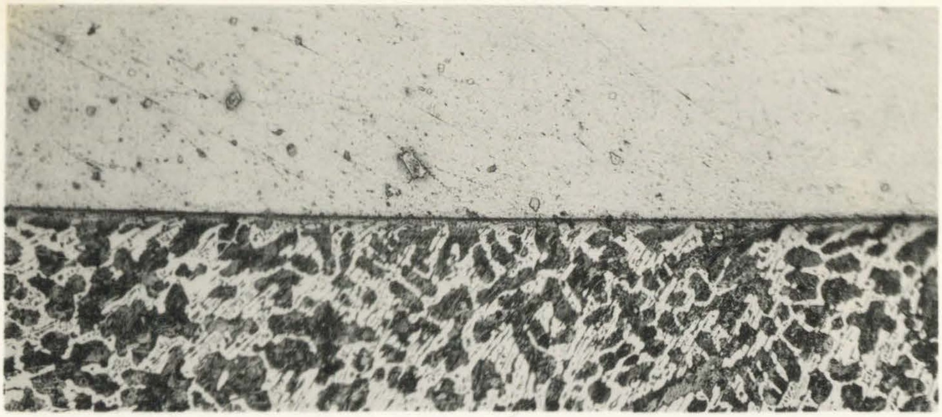


WC-3-A 150X

Figure 28.

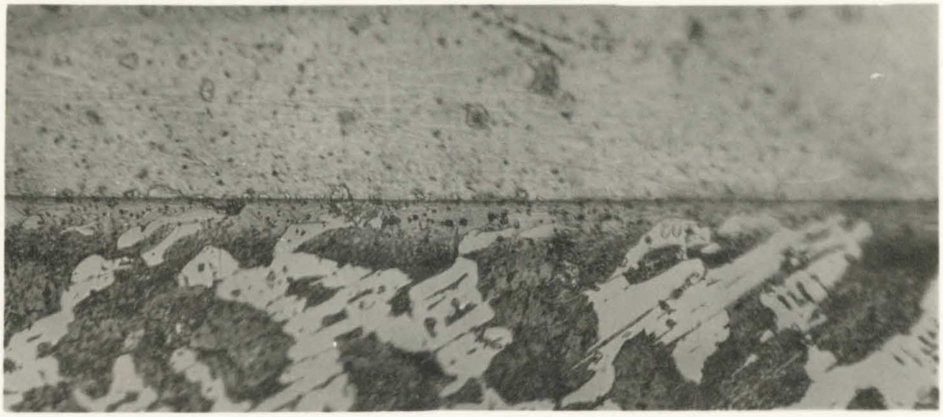
WC-3-B 150X

Figure 29.



WC-3-C 150X

Figure 30.



WC-3-D 400X

Figure 31.

Figure 24 is a view of the edge before etching, at a magnification of 150 diameters. Note the cracks which run parallel to the surface. The same area after etching is shown in Figure 25. The structure of the nitralloy is clearly shown. Figure 26 shows the same area at a magnification of 400 diameters.

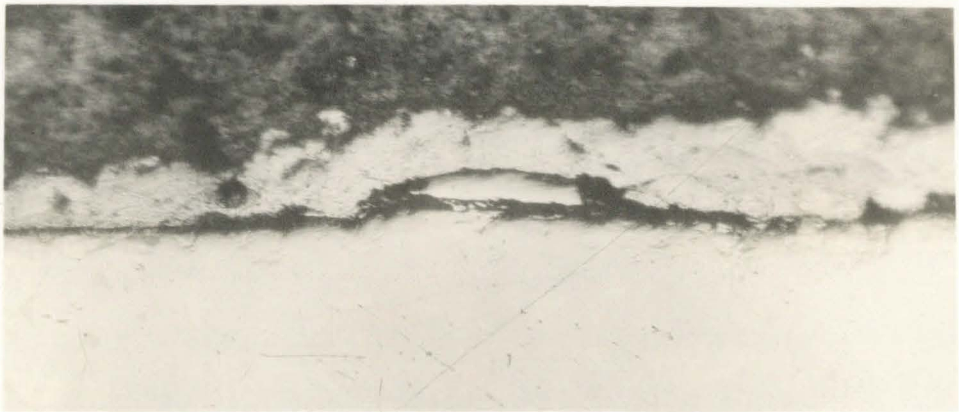
Specimen WC-3 was run on ring B-7 at a load of about 400 pounds per square inch and at a speed of 786 feet per minute. After test the surface was mirror bright, but slightly galled in places, as shown in the macrograph, Figure 27. Figures 28 and 29 show the edge and structure after etching, at a magnification of 150 diameters. These two views show the edge on each side of the blow-hole seen at the upper right-hand corner of the macrograph. The surface towards the end of the specimen on the section through the blowhole is smooth. The surface on the other side, towards the middle, is galled. Figure 28 shows the edge towards the middle which is a layer of worked metal corresponding to the galled surface. Figure 29, taken on the other side, shows no layer. This condition corresponds to the smooth surface. Further, the surface at the center of the specimen on a section through the blow-hole is smooth. The cross section of the edge at this point is shown at a magnification of 150 diameters in Figure 30. Figure 31 shows the same area at a magnification of 400 diameters.

From these observations it appears that a smooth mirror-bright surface is accompanied by a smooth, clean cut, edge with no layer of worked metal. If galling has occurred a layer is formed. The mechanism of the formation of this layer will be discussed later, page 60. Jordan and Rosenberg found in their work on oxide films, mentioned previously, that a rough film free surface was accompanied by evidence of severe working, while a smooth filmed surface was accompanied by a structure only slightly distorted with no evidence of severe working. The edge in the latter case appeared smooth even under the microscope.

The surfaces which were galled were quite severely worn in all cases. Several specimens were chosen for metallographic investigation and will be discussed in the following paragraphs.

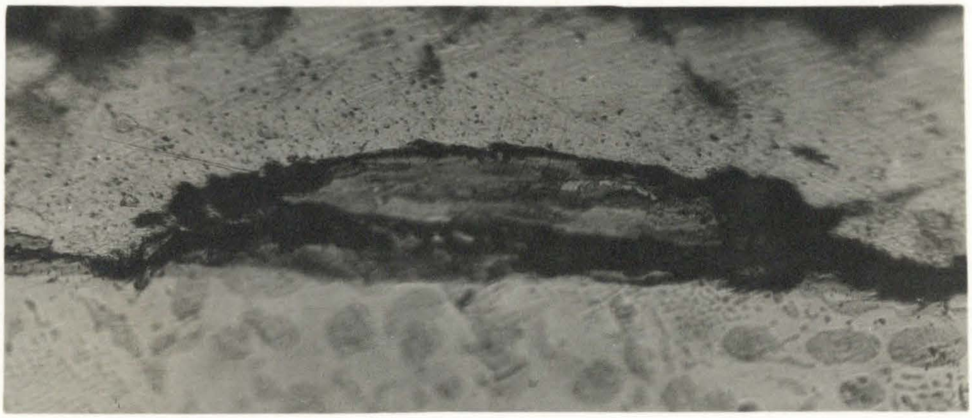
In Figure 32, is shown a cross section of ring B-17 at a magnification of 150 diameters. This ring was sectioned through a galled area where the material of the specimen, C-19, had adhered to the surface of the ring. At this particular section the bond between the two materials is very poor. In Figure 33 is shown the same area after etching, at a magnification of 400 diameters. The adhered material from the specimen has been severely worked and is not homogeneous in structure. The specimen and ring were run at a load of 130 pounds per square inch and at a speed of 786 feet per minute. After test there were several galled areas on the ring where the material of the specimen had adhered to the surface of the ring.

Figure 34 is a macrograph of specimen WC-5 which was run at a speed of 786 feet per minute. During the test on which this specimen was last run, the load increased to considerably more than 300 pounds per square inch, which caused severe galling to take place.



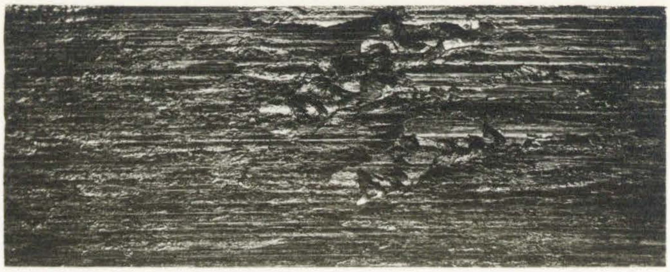
B-17 150X

Figure 32.



B-17 400X

Figure 33.

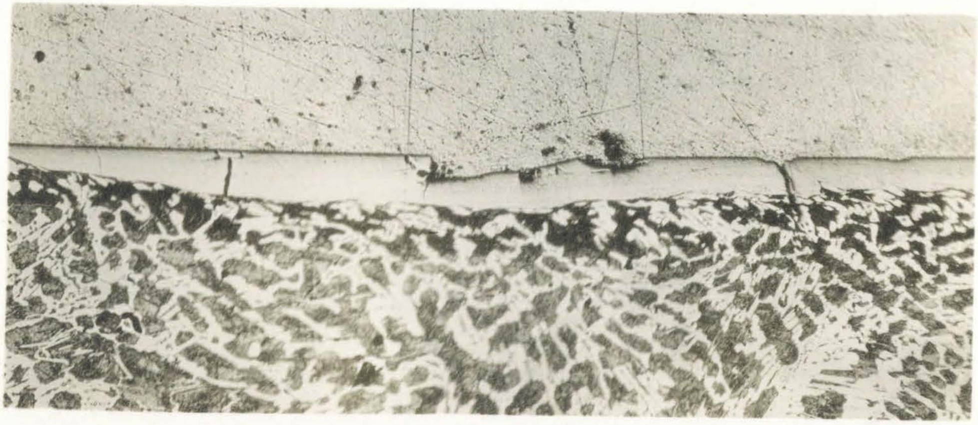


WC-5 5X

Figure 34.

WC-5-A 150X

Figure 35.



WC-5-E 150X

Figure 36.

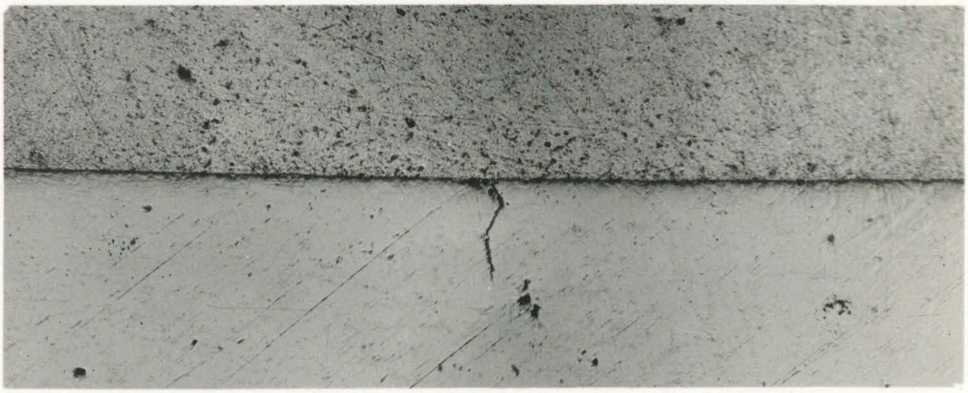
The galled areas are clearly seen in the macrograph. Although the results of this test are not recorded in the tables, due to the increased load, the specimen offers a good example of a galled surface. The worn edge is shown unetched at a magnification of 150 diameters in Figure 35. Surface cracks are clearly evident and one large fragment has been worn away. The same area after etching is shown in Figure 36. A layer of worked material appears on the surface, and the characteristic white cast iron structure composed of grains of cementite and pearlite is seen below.

Specimen B-19 also exhibits a galled surface, although it is smoother than that previously discussed. A macrograph of the surface of this specimen is shown in Figure 37. This specimen was run at a load of 300 pounds per square inch and at a speed of 1180 feet per minute on ring B-7. The edge is shown unetched in Figure 38, at a magnification of 150 diameters. Figure 39 shows the same area after etching, at a magnification of 400 diameters. Note that the cementite and pearlite grains have been deformed in the direction of wear. A layer of worked metal is in the preliminary stage of formation. Figure 40 shows the layer at a magnification of 1000 diameters. It is much thinner than that seen on specimen WC-5 and did not appear over the entire length of the specimen at this cross-section.

Specimen St-3 which was run on ring B-5 at a load of 300 pounds per square inch and at a speed of 786 feet per minute, also appears to have a galled surface, as shown in Figure 41. The edge is shown unetched in Figure 42 at a magnification of 150 diameters. The struc-

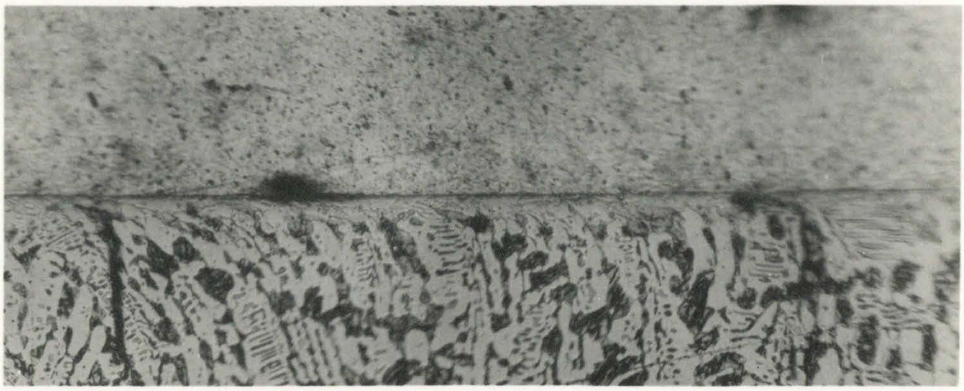
B-19 5X

Figure 37.



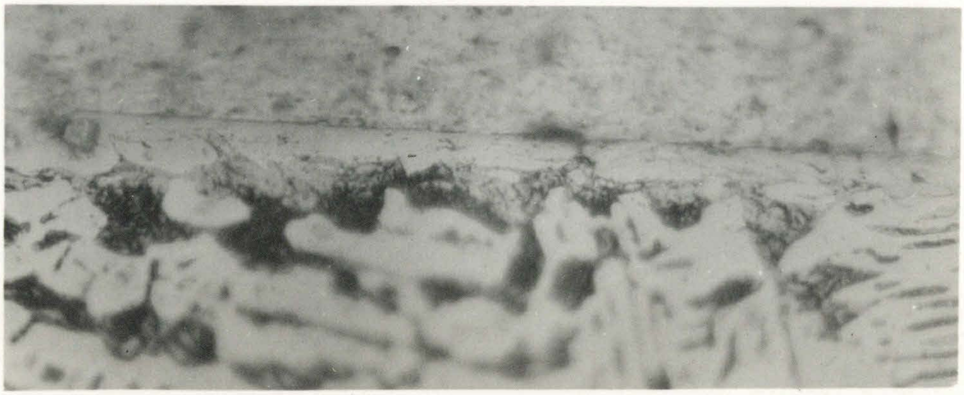
B-19-A 150X

Figure 38.



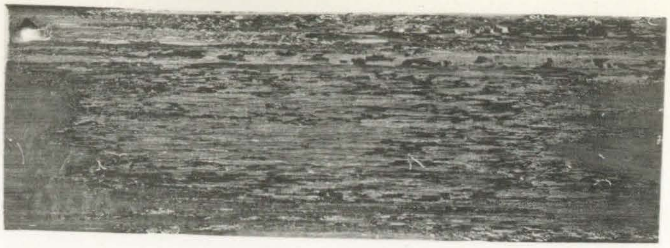
B-19-B 400X

Figure 39.



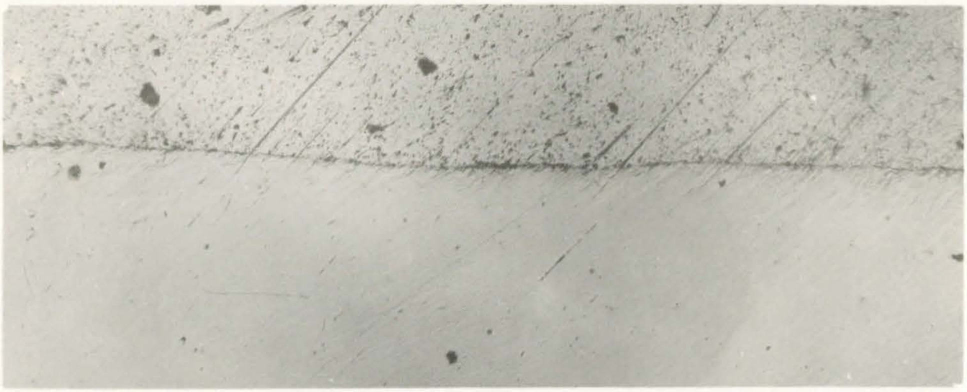
B-19-C 1000X

Figure 40.



St-3 5X

Figure 41.



St-3-A 150X

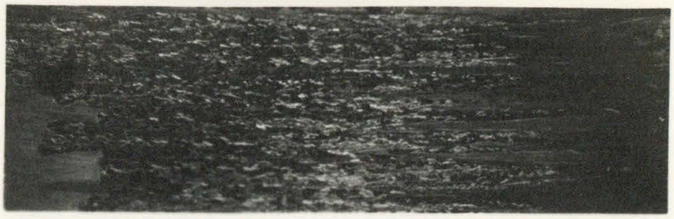
Figure 42.

St-3-B 150X

Figure 43.

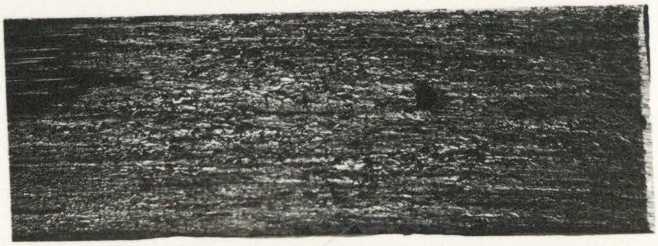
St-3-C 400X

Figure 44.



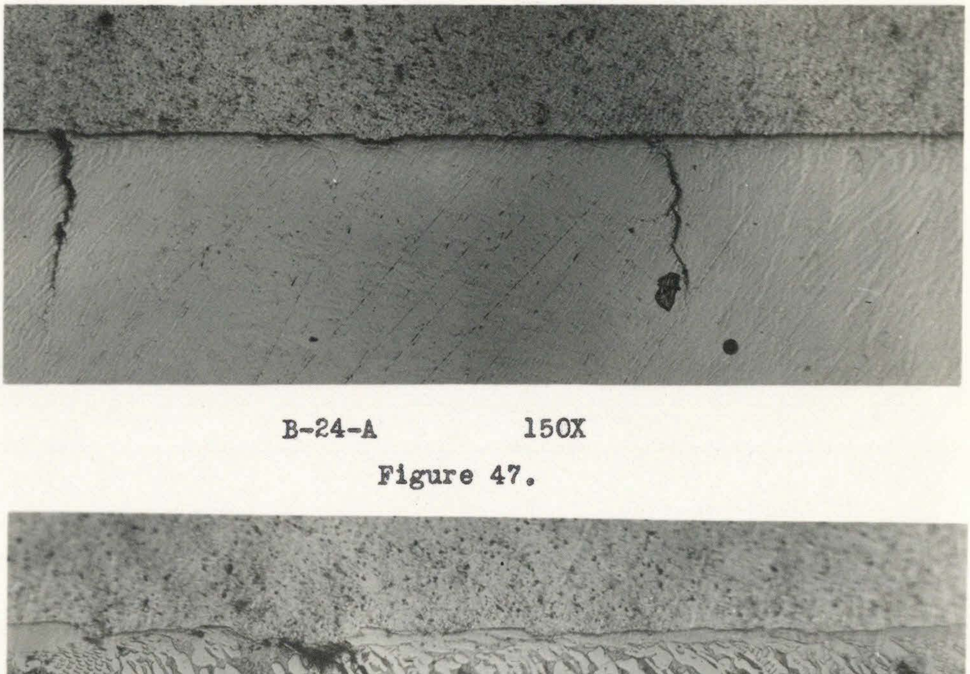
FA-2 5X

Figure 45.



B-24 5X

Figure 46.



B-24-A 150X

Figure 47.

B-24-B 400X

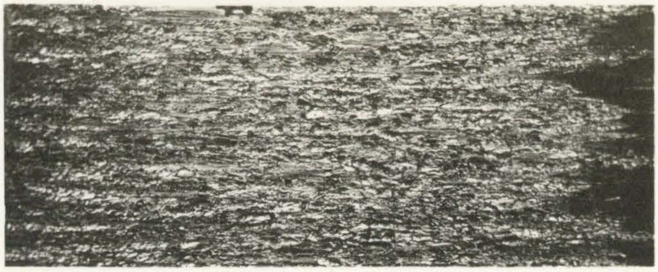
Figure 48.

ture after etching electrolytically in a 10% solution of NaOH and a 10% solution of HCl is shown in Figure 43. Figure 44 shows the edge at a magnification of 400 diameters. There is a slight indication of a worked layer and a higher magnification would have been desirable. This was impossible, however, due to the fact that the electrolytic etch is very severe and the edge was rounded off. Note that the edge is not straight, but has a wavy character.

Specimen FA-2 was galled during the test and the surface condition is shown in Figure 45. This material was badly pitted when an attempt was made to copper plate the specimen so that no photomicrographs were taken.

Specimen B-24 was run on ring WC-8 at a load of 300 pounds per square inch and at a speed of 1180 feet per minute. However, the speed increased to about 1500 feet per minute for a short period of time before the specimen was removed. Figure 46 shows the condition of the surface after test. The edge is shown in Figure 47 before etching, at a magnification of 150 diameters. Two very large surface cracks can be seen in this view. In Figure 48 is shown the edge and structure after etching at a magnification of 400 diameters. Here again the deformation of the cementite and pearlite grains in the direction of wear is clearly shown.

The condition of the surface of specimen WC-8 which was run on ring B-11 at a load of 300 pounds per square inch and at a speed of 1180 feet per minute is shown in Figure 49. The surface is very



WC-8 5X

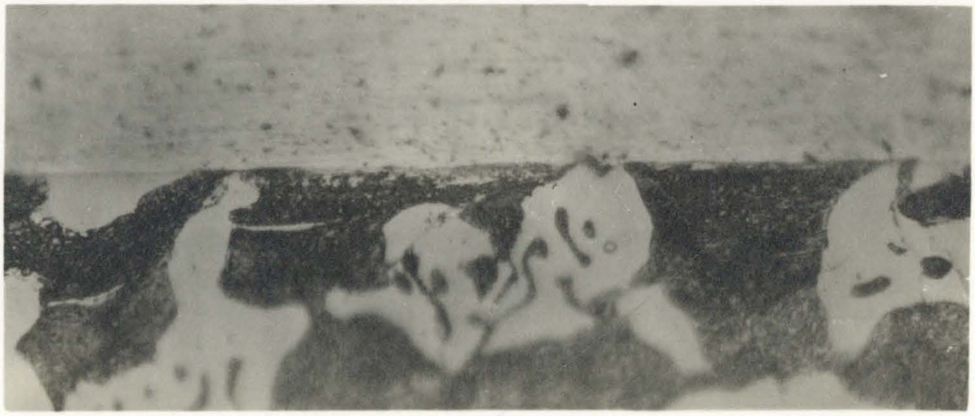
Figure 49.

WC-8-A 140X

Figure 50.

WC-8-C 140X

Figure 51.

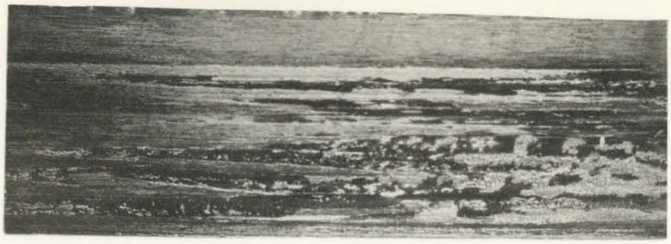


WC-8-D 1000X

Figure 52.

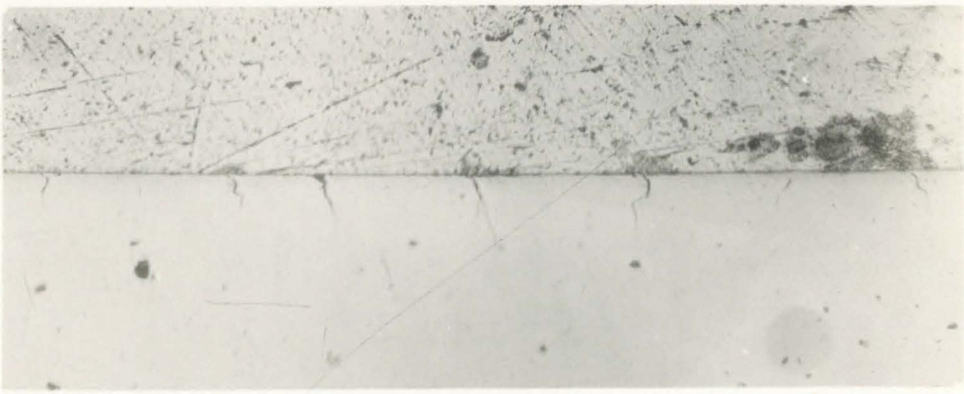
WC-8-E 1000X

Figure 53.



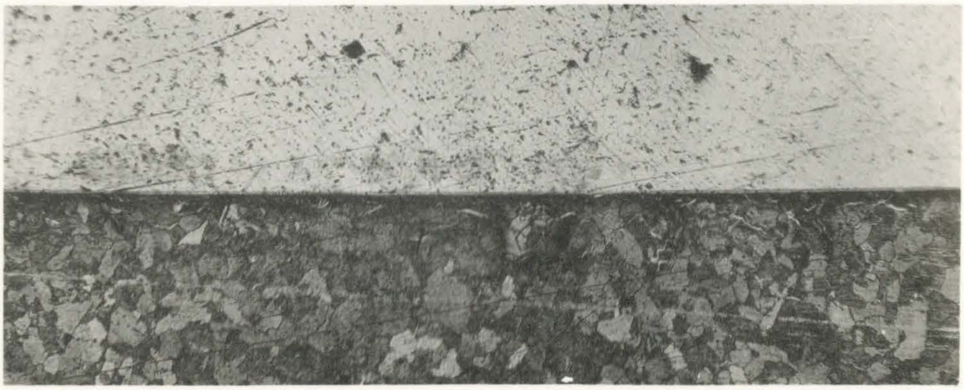
N-4 5X

Figure 54.



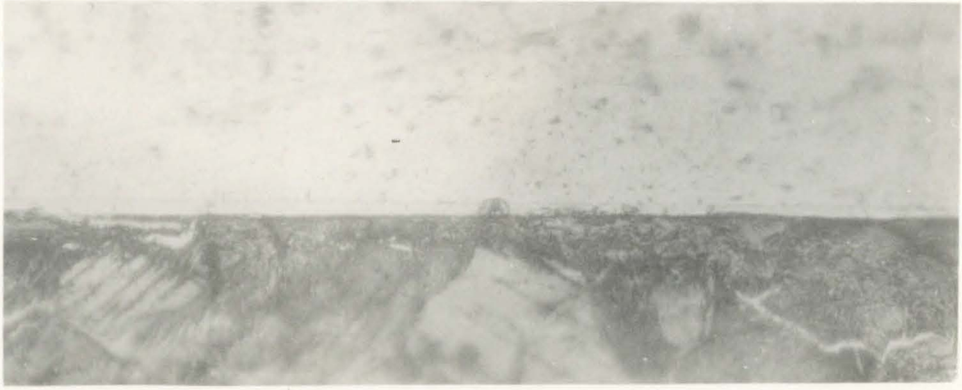
N-4-A 150X

Figure 55.



N-4-B 150X

Figure 56.



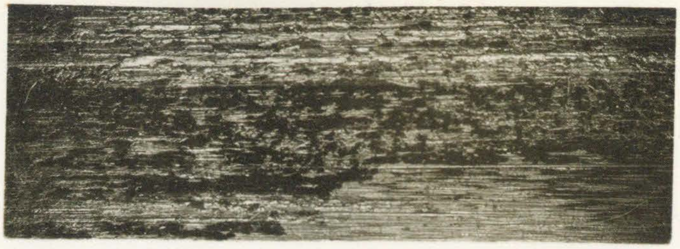
N-4-C 1000X

Figure 57.

rough and badly galled. Figure 50 shows the edge unetched, at a magnification of 140 diameters, and Figure 51 shows the same area after etching. The contour of the edge is very uneven and a layer of worked metal has formed. This layer did not appear on the entire surface, as is shown in Figure 52, where the grains have been cut evenly. In Figure 53 is shown another area where a layer is present and considerable working is evident. Surface cracks are clearly seen which run parallel to the edge. One large fragment has been broken away during the process of wear. The magnification of the last two pictures is 1000 diameters.

Specimen N-4 was run on ring B-25 at a load of 300 pounds per square inch and at a speed of 786 feet per minute. The galled condition of the surface is shown in Figure 54. The edge, unetched, is shown in Figure 55 at a magnification of 150 diameters. Note that there are several surface cracks which run approximately at right angles to the edge. Figure 56 shows the structure after etching, at a magnification of 150 diameters. The structure appears to be quite different than that of N-2, which was shown in Figures 24, 25, and 26. There are not as many hard nitride needles in the structure of N-4 as there are in N-2. Figure 57 shows the structure at a magnification of 1000 diameters and shows evidence of a layer of worked material. This layer extends over the entire length of the specimen at this section.

The surface of specimen F-2 was also galled, as is shown in Figure 58. The specimen was badly etched in the copper plating

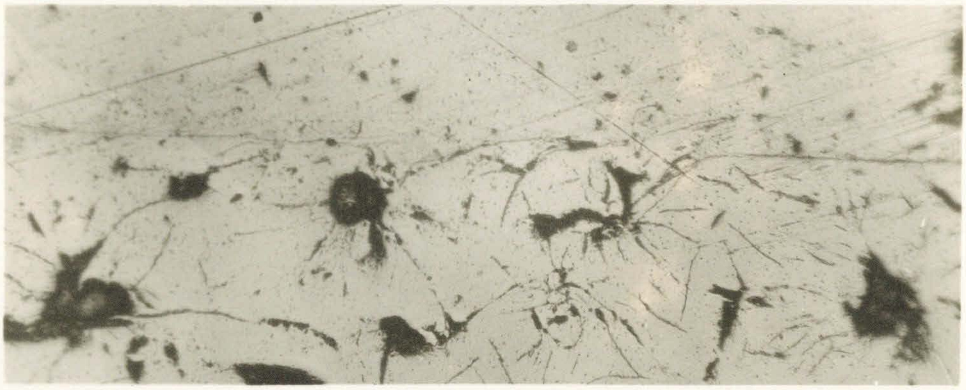


F-2 5X

Figure 58.

C-19 5X

Figure 59.

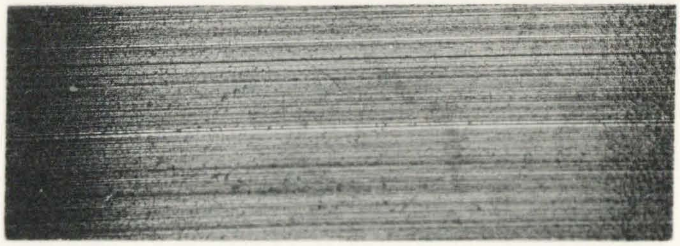


C-19-A 150X

Figure 60.

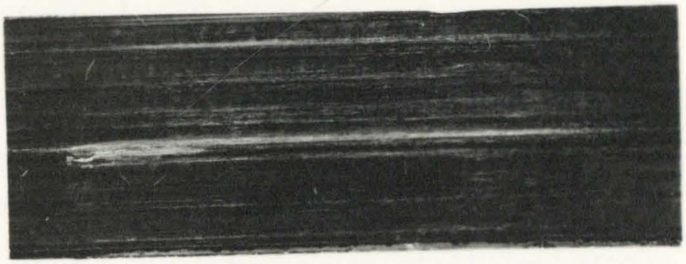
C-19-B 150X

Figure 61.



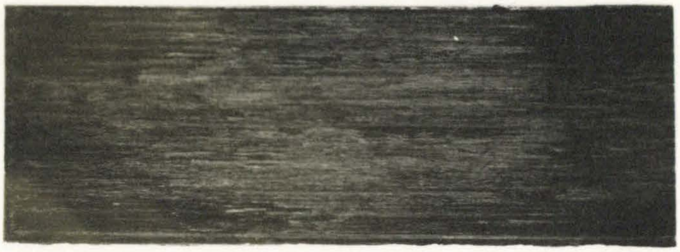
G-8 5X

Figure 62.



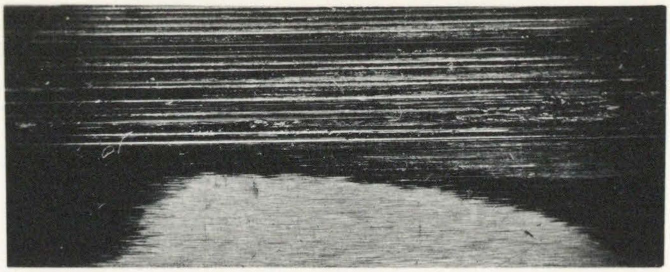
St-2 5X

Figure 63.



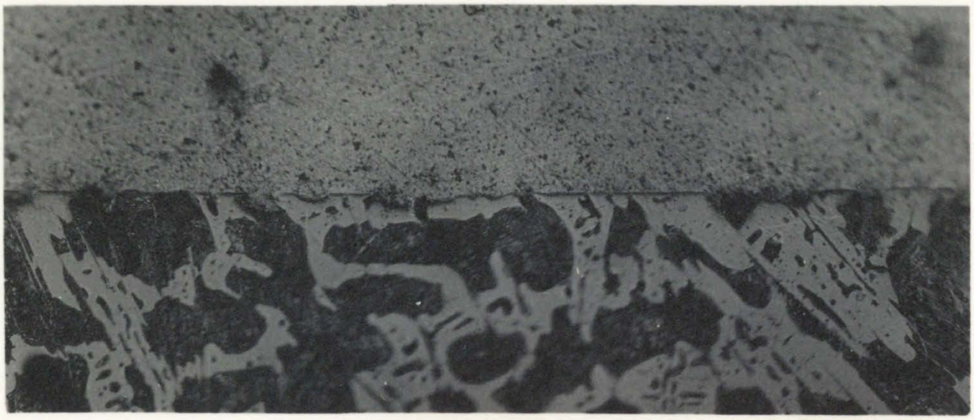
FA-1 5X

Figure 64.



WC-2 5X

Figure 65.



WC-2-A 400X

Figure 66.

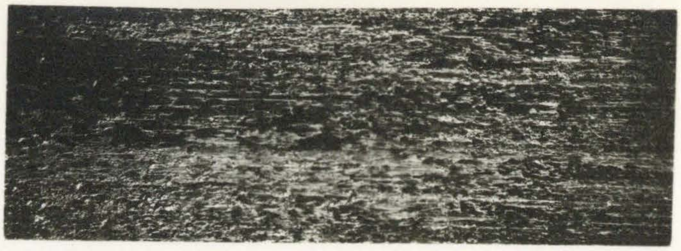
process, so it was not examined under the microscope.

Most of the grey cast iron specimens were ridged to some extent depending upon the conditions of the test. Specimen C-19 is a typical example. The surface after test is shown in Figure 59. The edge and structure are shown at a magnification of 150 diameters before and after etching in Figures 60 and 61, respectively. Note that one fragment has been lifted from the surface and that another has been worn away. The structure is typical of a grey cast iron and consists of ferrite, pearlite, and graphite.

The grey iron specimen G-8 which was run on ring B-20 at a load of 155 pounds per square inch and at a speed of 786 feet per minute was ridged after test, as shown in Figure 62. No photomicrographs were taken of this specimen because the copper plate was not bonded well to the cast iron. The grains appeared to be cut clean, and there was no evidence of a worked layer. The structure was very dirty and fine grained.

The stellite specimen St-2 and the "Flint Alloy" specimen FA-2 were also ridged after test, as is shown in Figures 63 and 64, respectively. It was not possible to plate these specimens with copper with the facilities available, so no microscopic investigation was made.

The white cast iron specimen WC-2 was run on ring WC-2 at a load of approximately 450 pounds per square inch and at a speed of 786 feet per minute. After test the surface was ridged, as is shown in Figure 65. After etching no worked layer was visible. The grains were cut cleanly, as shown in Figure 66 at a magnification of 400 diameters.

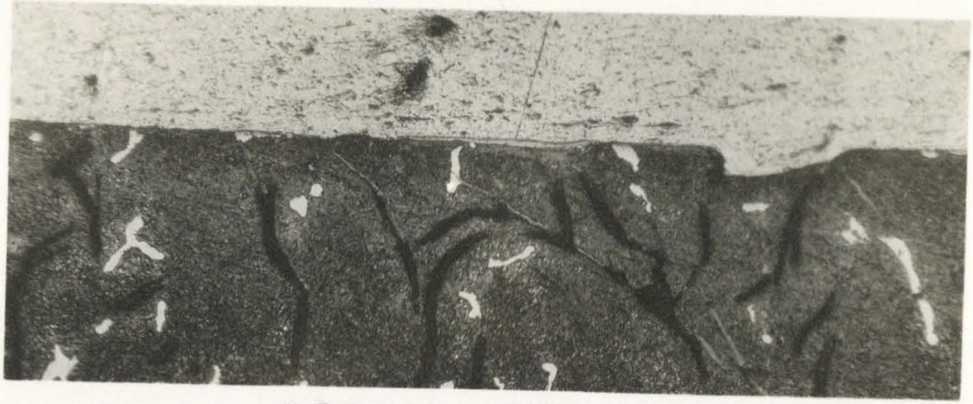


E-5 5X

Figure 67.

E-5-A 150X

Figure 68.

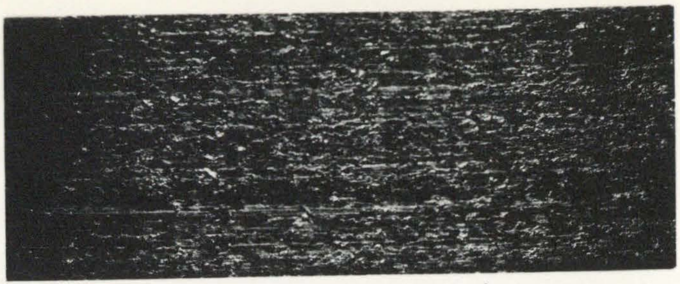


E-5-B 150X

Figure 69.

E-5-C 400X

Figure 70.

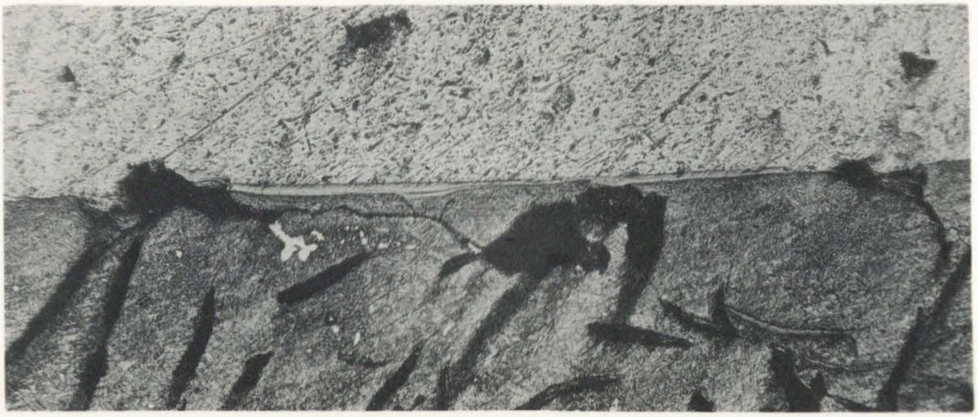


E-6 5X

Figure 71.

E-6-A 150X

Figure 72.

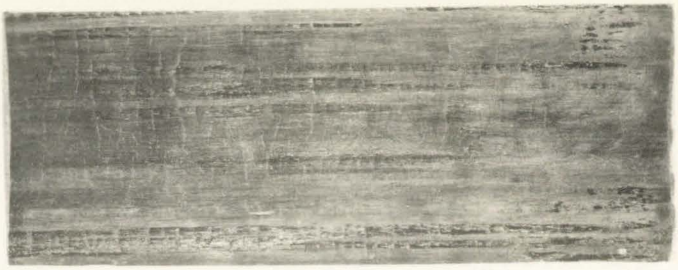


E-6-B 150X

Figure 73.

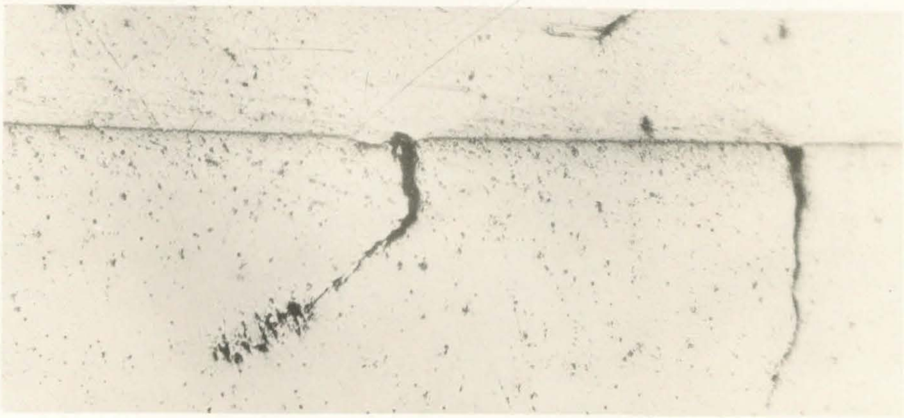
Specimens E-5 and E-6 were run simultaneously under the same conditions. They were run against rings B-21 and B-22, respectively, at a load of 300 pounds per square inch and at a speed of 786 feet per minute. After test the surfaces were ridged and galled, as shown in Figures 67 and 71. The edge is shown unetched in Figures 68 and 72 at a magnification of 150 diameters. The rough character of the surface is clearly seen. Figure 69 shows the edge and structure of specimen E-5 after etching at a magnification of 150 diameters. The typical grey iron structure is evident and a thin layer of worked metal can be seen. The same area at a magnification of 400 diameters is shown in Figure 70. The structure and edge of specimen E-6 after etching is shown in Figure 73 at a magnification of 150 diameters. This specimen also exhibits a layer of worked metal. The appearnnce of the surfaces and the structures of these two specimens is practically the same.

As mentioned earlier, page 22, the wear factor for this material running on "B" metal, as determined from the tests with these two specimens, was very erratic. E-5 had a low wear factor and E-6 had a higher factor. Since there appear to be no structural differences, this phenomenum can probably be explained by the fact that the critical load for this combination at a speed of 786 feet per minute is about 300 pounds per square inch. Therefore any slight variation in the conditions of the test will greatly affect the wear factor. The large variation in wear factor for small variations in load near the critical pressure has been shown for grey cast iron running on "B" in the curves of Figure 7.



A-4 5X

Figure 74.



A-4-A 150X

Figure 75.

A-4-B 150X

Figure 76.

As stated at the beginning of this thesis, all tests for comparative purposes were run in a bath of distillate. However, two runs were made with "A" specimens running dry on "A" rings. The wear factor was very high and the machine did not operate satisfactorily for this type of test. The surfaces of the specimens are interesting and are shown to be covered with cracks. The test was made at a load of 300 pounds per square inch and at a speed of 393 feet per minute. Figure 74 is a macrograph of the surface and shows numerous surface cracks which run perpendicular to the direction of wear. Figures 75 and 76 shows a cross section of the edge and surface at a magnification of 150 diameters before and after etching, respectively. The penetrating cracks are clearly visible and no worked layer can be seen.

Nature of the Worked Layer:

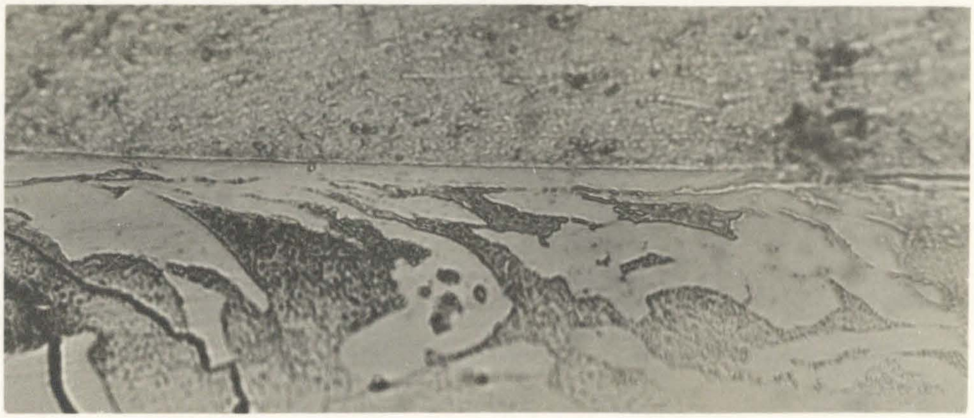
In the following paragraphs the nature of the layer of worked material which appears on several of the specimens discussed above will be considered in detail. It must be remembered that these materials are for the most part hard alloys whose chief constituents are iron and iron-carbide. The iron is ductile and the iron-carbide is brittle and hard. Each of these phases may have present in solution some alloying element or elements, but the general characteristics will be unchanged. Considering the specimen of unalloyed white cast iron, WC-5, shown in Figures 34, 35, and 36, a layer of worked material is seen on the edge. This layer is quite thick and shows evidence of considerable working. Since only iron and iron-carbide are present as constituents of the material, this layer must be composed of one or both of these unless it is a film of some foreign substance.

Other investigators have found oxide films on the surfaces of worn specimens which were tested in the Amsler machine with rolling wear. The tests of Jordan and Rosenberg (5) have been mentioned with regard to this phenomena. Max Fink (5) states that oxide films do not form when metal to metal contact occurs or when sliding wear takes place if the load is above about 5 pounds per square inch. When these conditions exist, the mechanical removal of particles takes place and no film can form. Further, these oxide films have been observed to be only about 0.006 millimeters thick, while in the present case the layer is about 0.050 millimeters thick. It seems rather improbable, therefore, that the layer is an oxide film.

Experience has shown that iron-carbide is very brittle and hard. Therefore, a layer of worked iron-carbide seems rather improbable, at first thought. However, experiments have been performed with brittle materials in which the brittle material has been made to flow in a plastic manner. For instance, marble was tested in compression when subjected to hydraulic pressure (52). It was shown that materials which fail in a brittle manner under an ordinary tension or compression test act as a soft ductile material when subjected to test under hydraulic pressure. It is also known that materials which fail in a

WC-5-F 400X

Figure 77.



WC-5-R 1000X

Figure 78.

WC-5-M 3000X

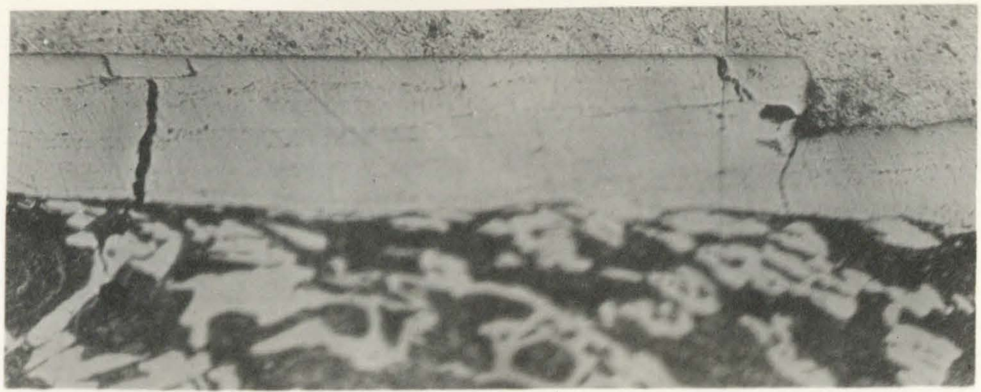
Figure 79.

brittle nature when subjected to rapidly applied loads will deform plastically when subjected to even moderate pressure over a long period of time.

Most of the wear tests under consideration required a long period of time. In many cases the travel was over one million feet. In addition to the normal load between the surfaces a shearing force existed which was the result of the action between two surfaces in contact. The continual action of the forces existing at the surfaces caused the grains of cementite and pearlite to deform. For example, in Figures 13, 39, and 48, it is clearly seen that the grains of iron-carbide and pearlite have been bent in the direction of wear. The more ductile constituent, pearlite, helped support the grains of cementite on all sides. In view of these observations, the fact that cementite is brittle in most cases does not mean that it cannot flow in a plastic manner such as occurs in the formation of the layer under consideration.

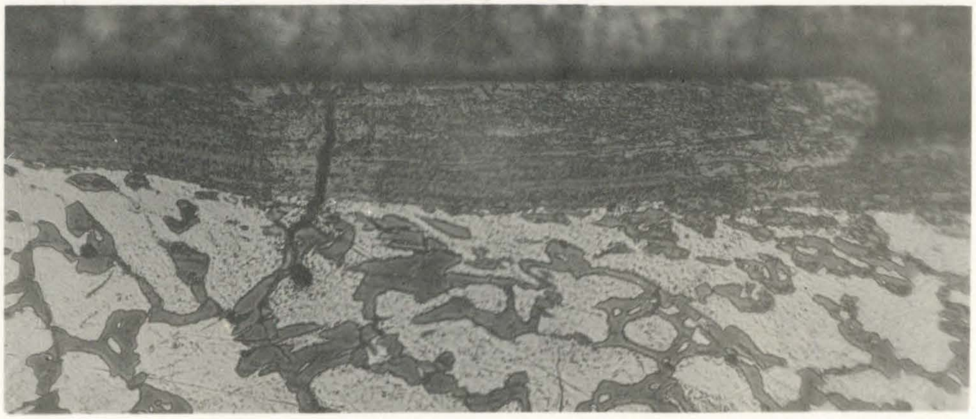
The third possibility as to the composition of the layer is that it might be composed of ferrite. In cast iron of this composition, all of the ferrite present has been precipitated simultaneously with a portion of the cementite present to form eutectoid pearlite. Therefore, no free ferrite should be present.

In Figures 39, 48, 77, 78, and 79, it appears that the more ductile pearlite grains have been squeezed out from between the cementite grains. Some of it is trapped in the layer which forms and some is



WC-5-G 400X

Figure 80.

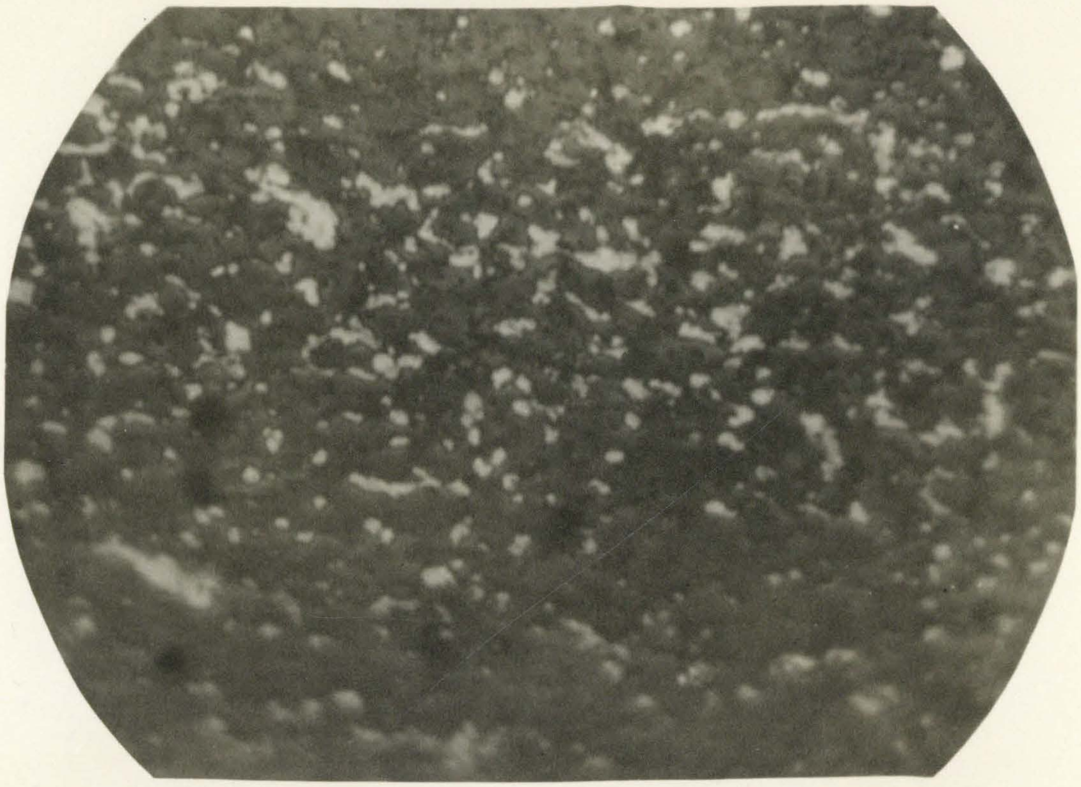


WC-5-H 400X

Figure 81.

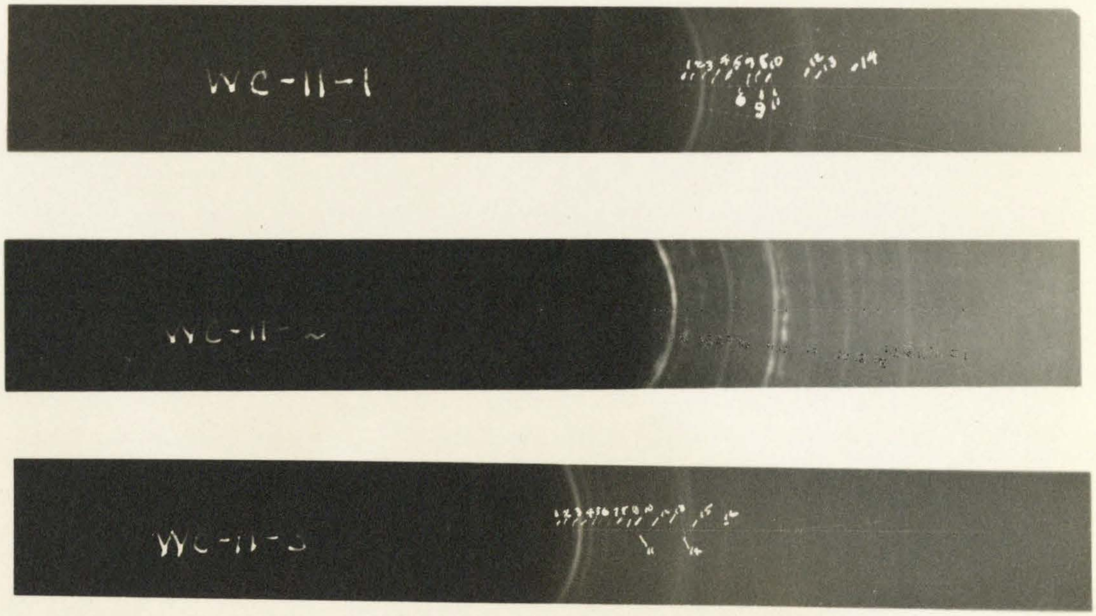
WC-5-I 400X

Figure 82.



WC-5-K 3000X

Figure 83.



WC-11 X-Ray Powder Pictures

Figure 84.

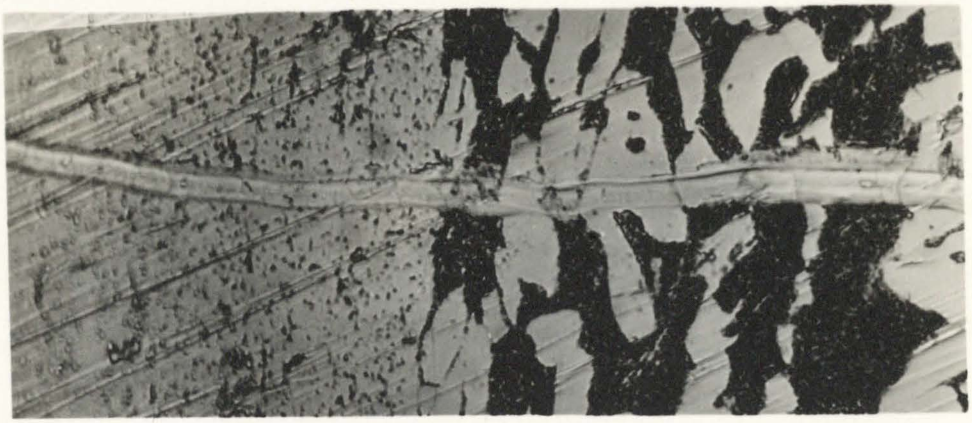
forced to the surface where it is swept away in the process of wear. Figure 80 shows a portion of the layer of worked material which is shown in Figure 36. At this magnification, 400 diameters, it is clearly seen that the layer is a banded structure showing evidence of considerable working. An etching solution of boiling alkaline sodium picrate attacks the carbides and does not affect ferrite. Carbide rich areas will be darkened and ferrite rich areas, such as pearlite, will appear light. Figure 81 shows the area of Figure 80 after etching in the above mentioned solution. The grains of cementite and the layer of worked material have been darkened while the pearlite has been only slightly attacked. Figure 82 shows another area at the same magnification and with the same etch. Figure 83 shows a portion of the layer at a magnification of 3000 diameters. The ground mass appears to be iron carbide in which are many small grains of pearlite. The grains of pearlite are equi-axed which suggests that recrystallization has taken place. This does not seem unreasonable because it is known that cold working will lower the temperature at which recrystallization will take place. The greater the deformation and severity of cold working the lower will be the recrystallization temperature.

Further proof as to the identity of this layer was felt necessary, so X-ray methods were applied. Since it was impossible to obtain a thin section or small fragment of the layer, it was necessary to reflect the X-ray beam from the surface. In this way the powder method could be used to determine the constituents present. The specimen used in this investigation was white cast iron, WC-11, which had run on ring WC-9 at a load of 300 pounds per square inch and at a speed of 1180 feet per minute. The specimen was mounted so that the X-ray beam of Mo-Kα radiation hit the layer at a glancing angle. The specimen was rotated through an angle of about 5° so that more random orientation of the reflecting planes would occur. The constituents which were most probably present in this layer were alpha iron, Fe-α, and iron carbide, Fe_3C. However, if the layer was an oxide film, FeO, Fe_2O_3, or Fe_3O_4 might be present. These various constituents were the possibilities which might show up in the powder picture. The "Strukturbericht" by P. P. Ewald and C. Herman gives the crystal structure of each of these materials so the positions of the reflections on the film for all reflecting planes could be determined. This was done and put in tabular form which is included in the appendix. The values of $Q = \frac{1}{d^2}$ are listed for all reflecting planes for each material up to values of $\theta = 45°$. From the powder picture the value of Q can be determined for each reflection by the relation $Q = 4 \sin^2\theta/\lambda^2$. By comparing the values of Q which were obtained from the picture with those calculated from the lattice constants, any reflection could be identified. Three pictures were taken. WC-11-1 and WC-11-3 show the reflections obtained when the beam was directed at the layer. WC-11-1 was exposed about 48 hours and WC-11-3 was exposed about 81 hours with Mo-Kα radiation. A metal tube would have been very desirable in order to shorten the time of exposure and increase the intensity of reflections, but none was available. WC-11-2 was exposed about 81 hours and the beam was directed at the back of the specimen on which there was no layer of worked material. The glancing angle and other conditions were as nearly the same as possible.

Due to the fact that some of the reflections appearing on the film were faint and others were broad, the accuracy of measurement was not very good. However, several reflections were without a doubt due to the iron carbide. On films WC-11-1 and WC-11-3 reflections were obtained from both films from the following planes of iron carbide; 003, 103, 122, 114, and 125. There was some doubt about other reflections, but these are sufficient to show that the layer contains iron carbide if these reflections are from the layer. The intensity of reflection from planes below the surface rapidly diminishes with the depth. For iron, planes at a distance of ten microns from the surface in the direction of the beam will reflect with only one-half the intensity of planes on the surface. Since Fe_3C has about the same density as iron, the absorption will be about the same. The thickness of the layer at the section on which the X-ray beam was directed was about ten microns. The beam, however, intersected the surface at an angle of not more than about 15°. Therefore the distance travelled by the beam in the layer was considerably more than ten microns, and the reflections which appear on the film are quite surely to be from the layer and not from the material below. Therefore, it is quite certain that the layer does contain Fe_3C. In addition, a

WC-11-A 400X

Figure 85.



WC-5-X 1000X

Figure 86.

reflection was obtained from the 110 plane of alpha iron, and other reflections from Fe_3C although some of the latter did not appear on both films. On the back of the specimen where no layer was present, reflections were obtained from the same planes of Fe_3C as were listed on WC-11-1 and WC-11-3. In addition to the reflection from the 110 plane, reflections from the 200, 211, and 220 planes of alpha iron were obtained. More alpha iron reflections were present at greater angles, but they were not indexed. By comparison of film WC-11-2 with WC-11-3 or 1, Figure 84, it can be seen that there are many more iron lines in the former than in either of the latter. This shows that the layer is richer in iron carbide than the parent material. Although the accuracy of the X-ray analysis is somewhat limited, it seems quite evident that the layer is composed of iron and iron carbide, and that the iron is present in less amount than on the back of the specimen. This checks the conclusions that have been drawn from the metallographic study.

After the X-ray analysis was completed the specimen was plated with copper and prepared for metallographic investigation. Figure 85 shows the structure and the layer at the section which was cut by the X-ray beam.

The relative hardness of the microconstituents and the layer of specimen WC-5 was determined by the scratch width method. The specimen was scratched with a diamond point subjected to a load of about 16 grams. The width of scratch was measured with a filar micrometer on the microscope. Figure 86 shows the scratch after test at a magnification of 1000 diameters. The width of the scratch in the layer was 4.2 microns, in the cementite 3.8 microns, and in the pearlite 8.5 microns. This shows the layer to be almost as hard as the cementite grains and much harder than the pearlite. For discussion of the relation between the width of scratch and the hardness, see page 75.

Summary:

In this investigation the relative merits of several materials to resist wear under particular conditions have been shown. IR metal "B" has been shown to possess wearing qualities superior to most of the common wear resisting materials. Some relations between wear and load at different speeds have been shown for gray cast iron running on "B".

A metallographic investigation has been made and the structures accompanying the various surface conditions have been discussed. Those surfaces which are smooth after test are apparently accompanied by a structure which is not distorted. The edge is clean cut and smooth even under the microscope. If galling has occurred, a layer of worked metal appears on the edge. This layer in the case of white cast iron is composed of iron carbide interspersed with small grains of pearlite. The layer shows evidences of severe working and distortion. It appears that during the process of wear, the softer pearlite grains have been squeezed from between the cementite grains. If they reach the surface they are rubbed off by the other wearing surface. If they do not reach the surface, they are trapped in the layer of worked carbide. The layer has been shown to be richer in carbide than the parent structure of the specimen. This layer of hard carbide is of about the same hardness as the carbide grains of the parent metal. In the literature which was reviewed no mention was made of a layer of worked carbide such as this investigation has revealed. Most of the work which has been done has been on gray cast irons and steels.

PART II. SCRATCH INVESTIGATION

Introduction:

In studying the conditions of the wearing surfaces of the materials used in the tests described in Part I, it was found that in many cases ridging occurred. Apparently the action is that of plowing a groove in the wearing surface. Even those specimens which were smooth and mirror bright showed evidence of ridging in the direction of wear. Such observations indicate that the action of a hard point on the surface which may duplicate this plowing effect might reproduce the conditions existing in actual operation.

Wear may be considered as the removal of material from the wearing surfaces. Such action implies the absorption of energy, i.e., any removal of material will require energy to do so. This energy is absorbed in friction, in the deformation, and in the removal of material from the specimen. It seems reasonable that some method which might be devised to determine the amount of energy absorbed in this process would lead to some correlation with the wear resistance. An attempt has been made to devise such a method. In essence, the method consists in using a diamond which makes a scratch in the material being tested.

It is apparent from a search of the literature that considerable work has been done on scratch methods in attempting to find a simple method of hardness testing. It has been known for some time that the relative wear resistance of materials is not a function of the penetration hardness. However, it seems reasonable that there might be some correlation between scratch hardness and wear resistance. No definite correlation has been made between these properties up to the present time.

Perhaps the oldest method for determining scratch hardness is that which resulted in Mohs scale of hardness. Here the various materials are arranged in such a way that a given substance is scratched by all of those minerals above it and not by those below it in the table. This method of hardness measurement has been taken over by the mineralogist, but has found very little, if any, application in engineering. The difficulty of distinguishing between a mark and a true scratch often leaves doubt as to the accuracy of this test. The load applied to the scratching member is a variable which should be controlled. Also, the intervals between the various minerals listed in the Mohs scale are quite different. Recently in a paper presented before the Electrochemical Society, Ridgway, Ballard, and Bailey (40) have included a modified Mohs scale in which some electrochemical products have been inserted to fill in the gap at the hard end of the scale between sapphire and diamond. Their tests were made with a definite load on the scratching point which was of a definite shape.

A sclerometer devised by Turner (41) and modified by Martens (42) employed a diamond point which was forced over the surface being tested. The width of scratch produced by a given load, or the load required to produce a scratch of a given width was taken as a measure of the hardness. A micro-sclerometer was devised by Jaggar (43) for determining the hardness of the micro-constituents of rocks and minerals. Boynton (44) used this same method to determine the hardness of the various constituents of iron and steel. Some of the most notable work on this method of hardness testing has been done by C. H. Bierbaum (45, 46, 47, 48). He developed an instrument which he calls the "Microcharacter". A diamond point is employed which is caused to move across the surface being tested under a given load at a definite speed. The Microcharacter is really a laboratory instrument and has not been accepted as a commercial means for hardness testing.

So far no mention has been made by any investigators of measuring the scratching force or energy, or of making direct correlation of their results with wear resistance.

The results of these investigations have shown that the best shape of the scratching point is that of the corner of a cube with the diagonal perpendicular to the surface being scratched. The intersection of two of the faces forms the leading edge of the cutting point.

An attempt was made by Dr. Donald S. Clark to find a relation between the width of scratch made by a diamond and the wear test results. The diamond used in these tests was slightly more blunt

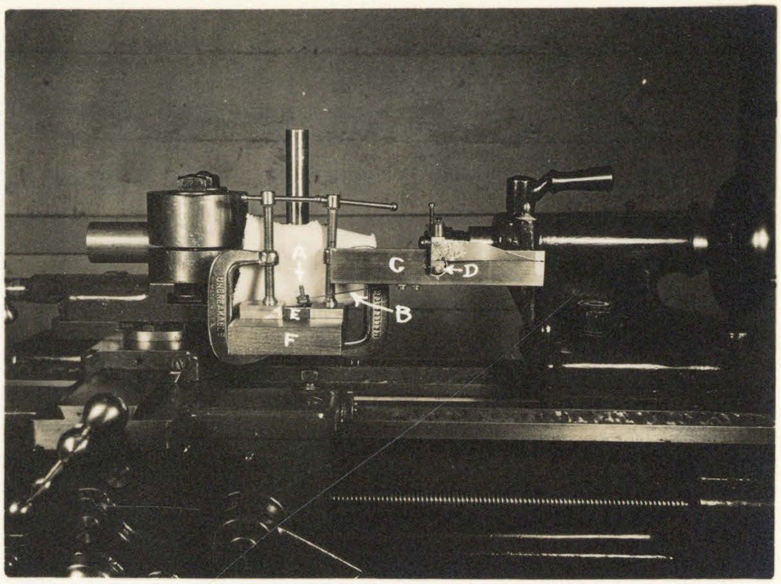


Figure 87.

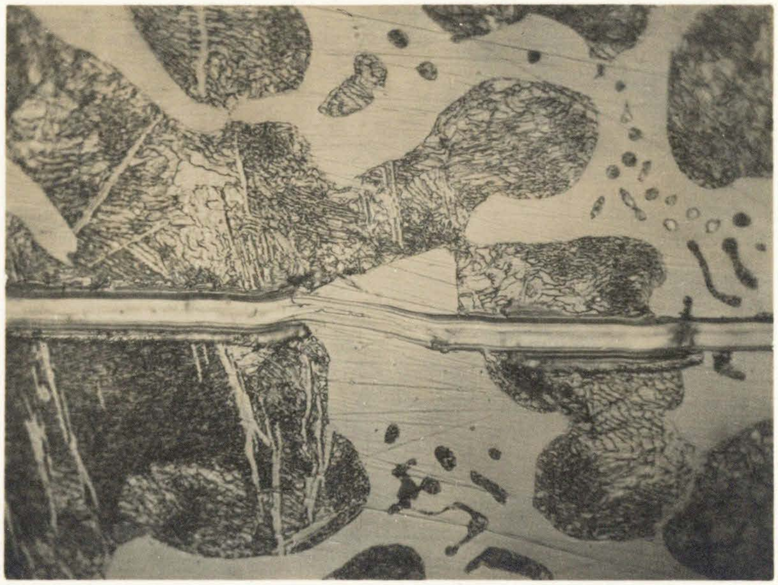


Figure 88.

than the corner of a cube. The three interfacial angles were found to be 101° 50', 98° 36', and 104° 45' instead of 90°.

A simple method of supporting the specimen to be tested and mounting the diamond was set up on a small lathe, as shown in Figure 87. The diamond was mounted in a threaded fitting, A, which in turn was placed on the end of a piece of spring brass, B. The spring was fastened to a beam, C, supported by a ball bearing, D, on the tail stock of the lathe. The specimen, E, was clamped in a special holder, F, on the carriage of the lathe which was moved away from the tail stock at a rate of 0.0023 inches per second. The beam was loaded with an appropriate weight so that the diamond pressed on the surface with a force of six grams. The beam was maintained in a level position by adjusting the height of the specimen. It should be noted that the axis of the diamond is not perpendicular to the surface being scratched.

The width of scratch was measured with a filar micrometer at a magnification of 1380 diameters. It was found that the width of scratch depended upon the constituent through which the diamond passed, as is shown in Figure 88. In the case of a specimen whose structure is composed of more than one micro-constituent, the scratch width was taken as the statistical average of the widths in each constituent. This value was obtained by determining the percentage of total area covered by each constituent. Some difficulty was encountered in determining the statistical average width of scratch in gray cast iron due to the presence of graphite flakes. The value taken for this material was the width in the matrix. The results of the determinations are shown in Table IV.

TABLE IV. STATISTICAL SCRATCH WIDTHS

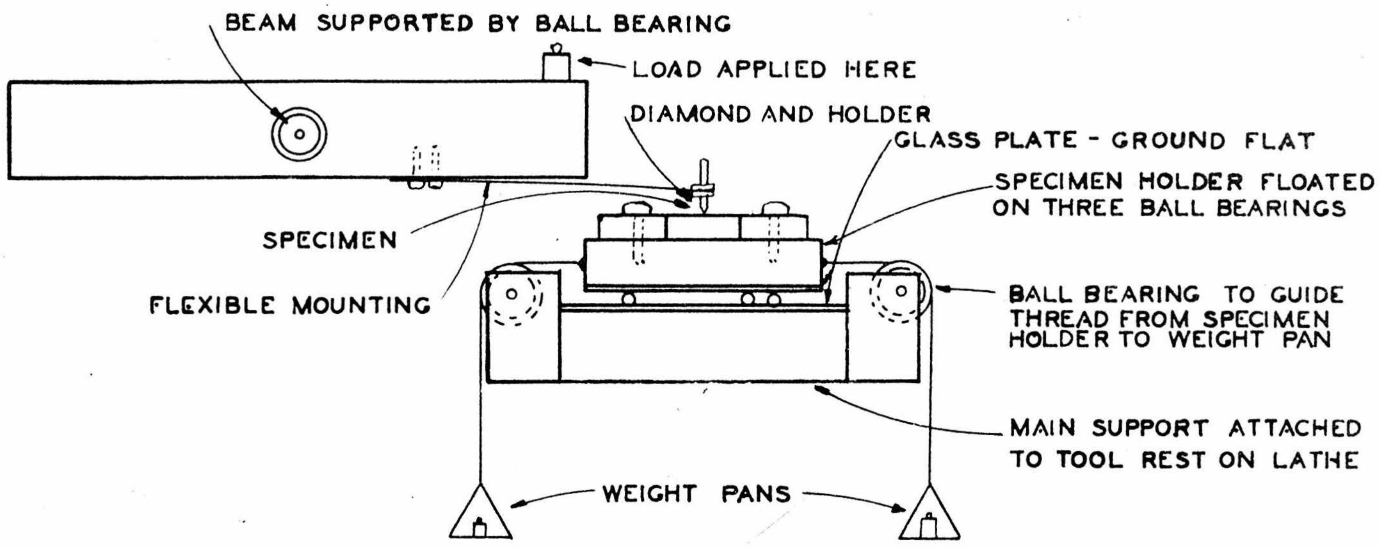
Material		Width of Scratch, Microns
Heat Treated Cast Iron	E-20	4.5
IR Metal	B-4	4.6
Case Hardened Steel	CH-	5.1
IR Metal	A-5	5.5
White Cast Iron	WC-13	5.8
Stellite	St-4	6.1
Ni,Cr,Mo Cast Iron	F-23	6.8
Plain Cast Iron	C-21	7.8

It would be expected that the softest material would have the greatest width of scratch, and that probably the most wear-resistant material would have the narrowest. The table above gives the results in order of increasing width of scratch or in order of decreasing wear resistance, as would be predicted by this method. From the results of the wear tests, the materials are arranged in the following order when running on themselves: B, WC, N, CH, and St. In the wear tests E was notably inferior when running against other materials, although no data was obtained for E running on itself. It is apparent that the scratch width results do not show any correlation with the wear results, in fact, E and WC are far from correlating positions in the list.

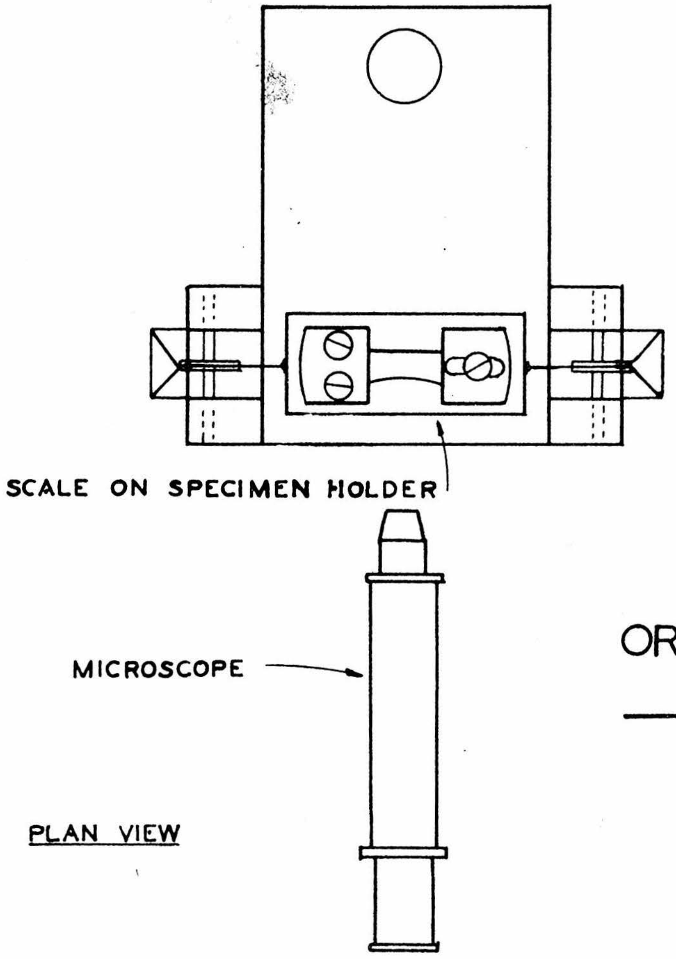
In view of the fact that no correlation could be obtained between the width of scratch and the wear results, it was decided to consider the energy required to scratch.

Theoretical Considerations:

In order to obtain values of energy, it is necessary to consider the nature of the energy involved in the scratching process. Energy or work is the product of a force times the distance through which it acts. In this case it is the force resisting the pull of the diamond times the distance through which the diamond moves. It is desirable to refer this energy to a unit volume of material since for greater loads on the diamond point deeper scratches will result and more material will be removed. If the diamond point is ground to the shape of a corner of a cube, and the intersection of two of the faces forms the leading edge with the diagonal perpendicular to the surface being tested, the depth of cut is proportional to the width. This has been checked experimentally by Bierbaum (47). The cross-sectional area removed will, therefore, be proportional to the square of the width, and the volume removed will be proportional to the square of the width times the length of travel. The work, or energy, per unit volume is then proportional to the force divided by the square of the scratch width, i.e., $E \quad f/w^2$. "E" is



ELEVATION VIEW



PLAN VIEW

ORIGINAL WEIGHING MECHANISM

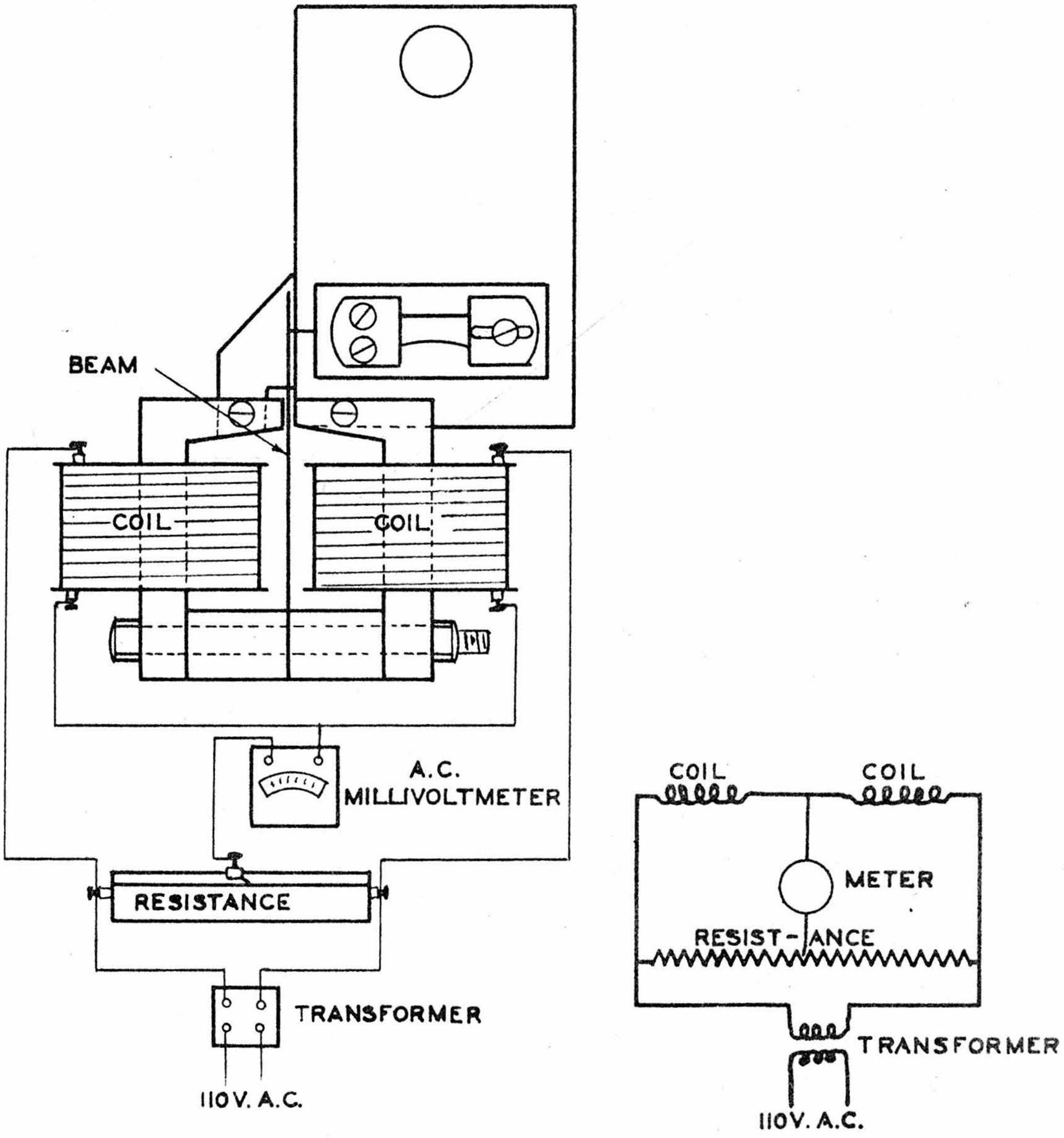
FIGURE 89.

the energy required to scratch per unit volume of material, "f" is the force required to scratch, and "w" is the width of scratch produced by the diamond point.

Apparatus:

Considerable experimentation was necessary before a suitable means of measuring the force required to scratch was obtained. The first attempt was made by supporting the specimen holder on balls. To each end of the holder was fastened a thread carrying a pan, as shown in Figure 89. A microscope was set up to observe a mark on the holder. The specimen was moved under the diamond in the same manner as was previously described in the discussion of Dr. Clark's work. The force resisting the motion of the diamond over the surface of the specimen was measured by placing the correct weight in the weighing pan so that the holder remained in approximately a fixed position. The difference in weights balanced the force required to scratch. The procedure was found to be very difficult and little difference could be detected between different materials. The system was not sensitive, probably due to friction, and was, therefore, discarded.

In order to determine the force more accurately, an induction bridge circuit was constructed. This is shown schematically in Figure 90. The construction of such an instrument is very critical. The proper number of turns on the coil, the proper shape of the pole pieces, and the proper voltage must be obtained. This instrument

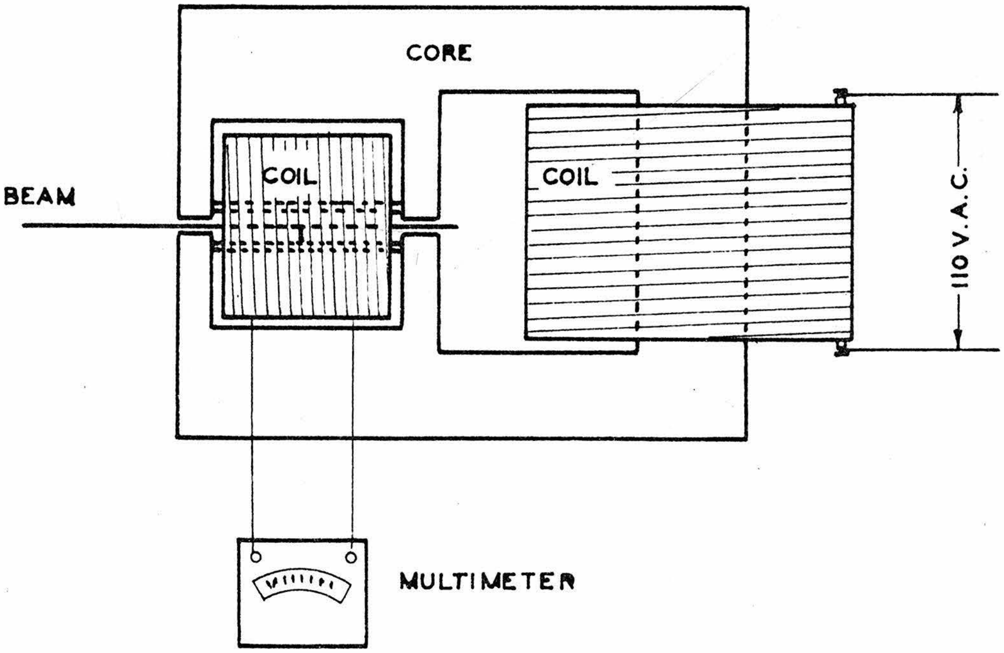


PLAN VIEW

ELECTRICAL CIRCUIT

INDUCTION BRIDGE

FIGURE 90.



MAGNETIC CIRCUIT

FIGURE 51.

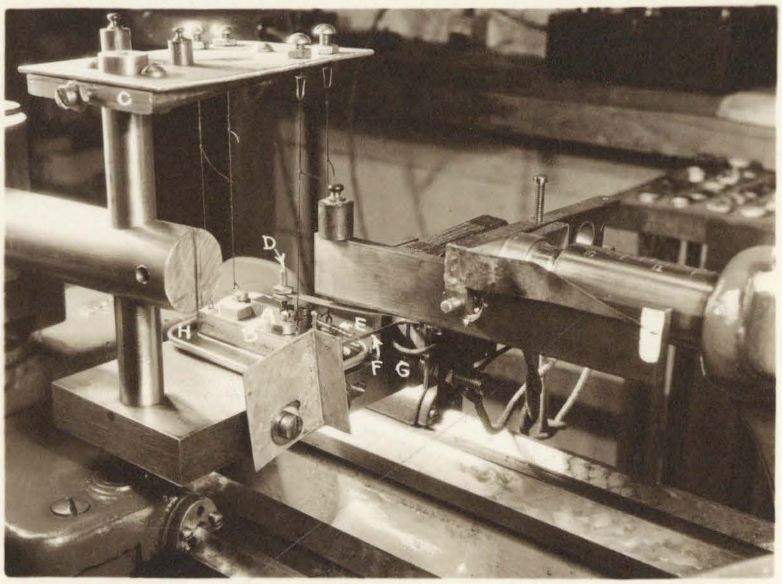


Figure 92.

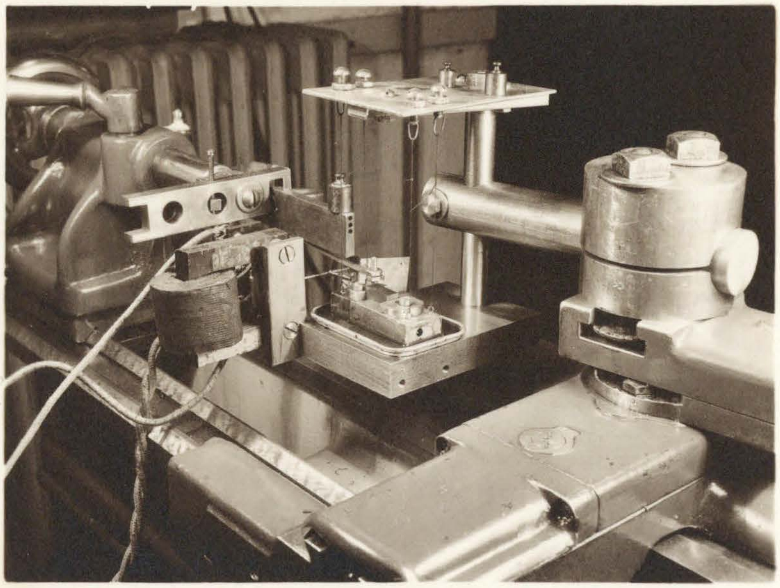


Figure 93.

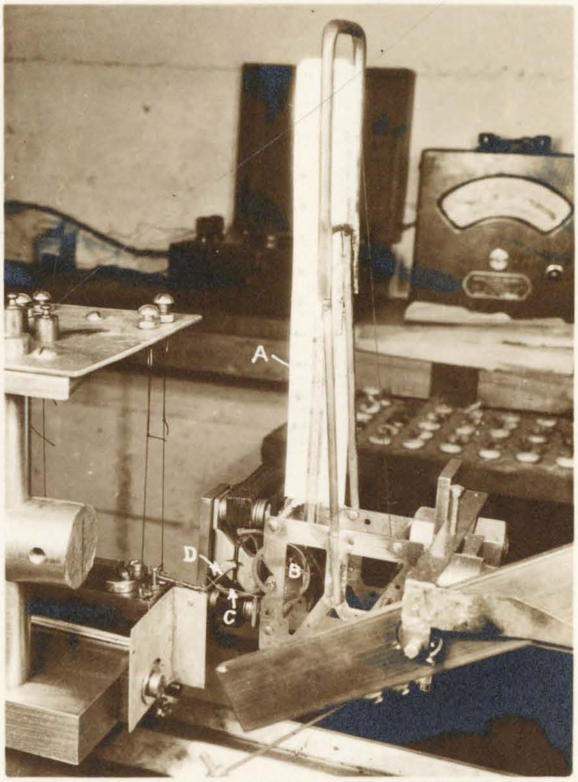


Figure 94.

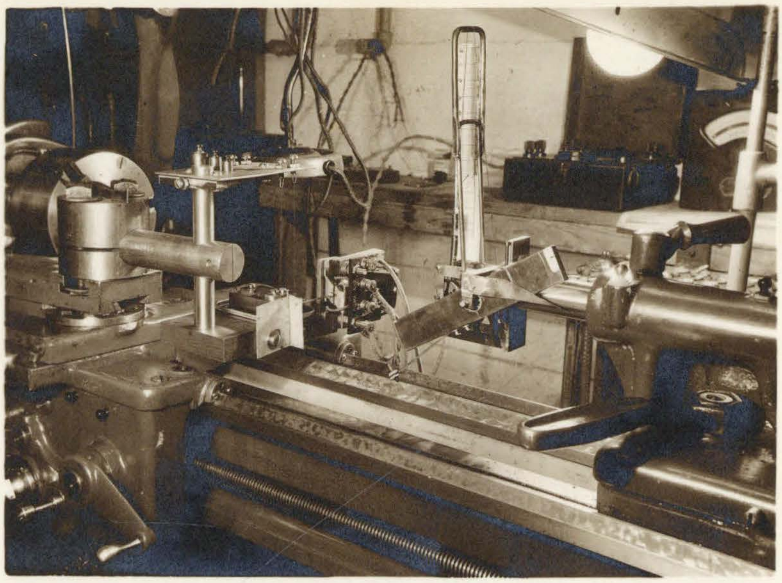


Figure 95.

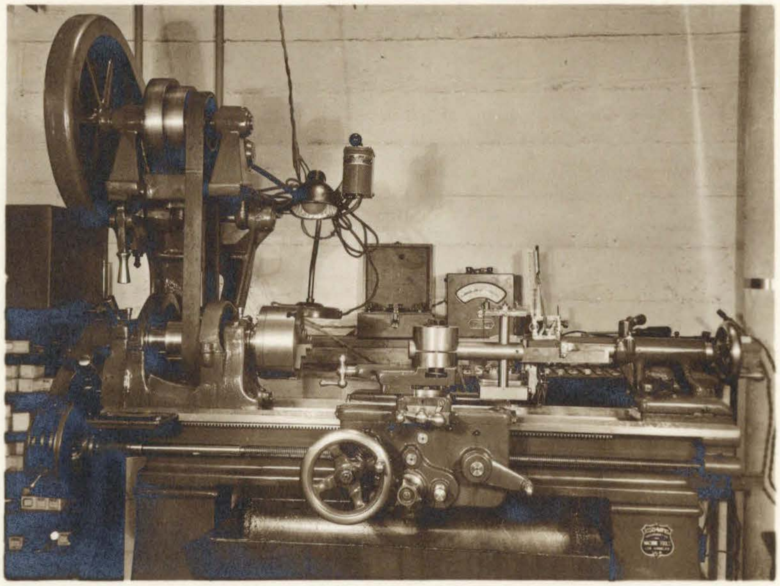


Figure 96.

was also not sensitive enough, probably due to its design and construction. It was replaced by a magnetic circuit, which is shown in Figure 91. This circuit is the same as that used in old magnetic loud speakers. The results with this instrument were satisfactory when the load on the diamond point was less than about 23 grams. The deflection limit of the instrument would not allow greater loads.

The arrangement is shown in Figures 92 and 93. The specimen, A, is clamped in the holder, B, which is hung from an overhead support, C, by threads. The diamond, D, is mounted as in the previous cases. The specimen was attached by means of the compression link, E, to the beam, F, fastened to the armature of the magnetic coil, G. Vibrations were held to a minimum by means of the oil in the pan, H, which was in contact with the holder, B. The deflection of the beam induced a current in the electrical circuit which was measured on the multimeter. The force measuring device, which is shown in Figure 94, was calibrated by means of a spring, A, which was connected through the balance wheel, B, and a tension member, C, to the beam, D. A close-up of the testing equipment may be seen in Figure 95 and a general view of the machine in Figure 96.

<u>Procedure</u>:

Each specimen was carefully polished as for metallographic examination and then etched with a suitable reagent to bring out the micro-structure. The specimen was then placed in the holder and moved into place under the diamond which was loaded with an appropriate weight. The carriage was moved under the diamond at a speed of 0.0023 inches per second. The speed was the same for all tests. When the scratch was completed the carriage was returned to the original position and shifted for a new scratch. A higher load was applied to the diamond and another scratch was made. The process was repeated for loads of 2.7, 6.0, 9.5, 12.9, 16.3, and 23.1 grams on the point of the diamond.

While each scratch was being made, the maximum, minimum, and average value of the force was observed on the multimeter which was read in micro-amperes. It was found that with loads below about 12 grams on the diamond point, large fluctuations occurred in the meter readings, and the scratch showed evidence of jumping. This produced a non-uniform scratch width and made the determination of the scratch width very difficult. Jumping did not occur when loads above 12 grams were used. Higher loads than reported would have been desirable, but were impossible with the deflection meter used.

The specimen was placed under the microscope and the width of scratch was measured with a filar micrometer. With the lower loads, considerable difference was observed in the width of scratch in the different constituents. Therefore, a statistical average was taken to obtain the average width of scratch. For higher loads this method of averaging was not necessary as greater uniformity was observed in the width of the scratch.

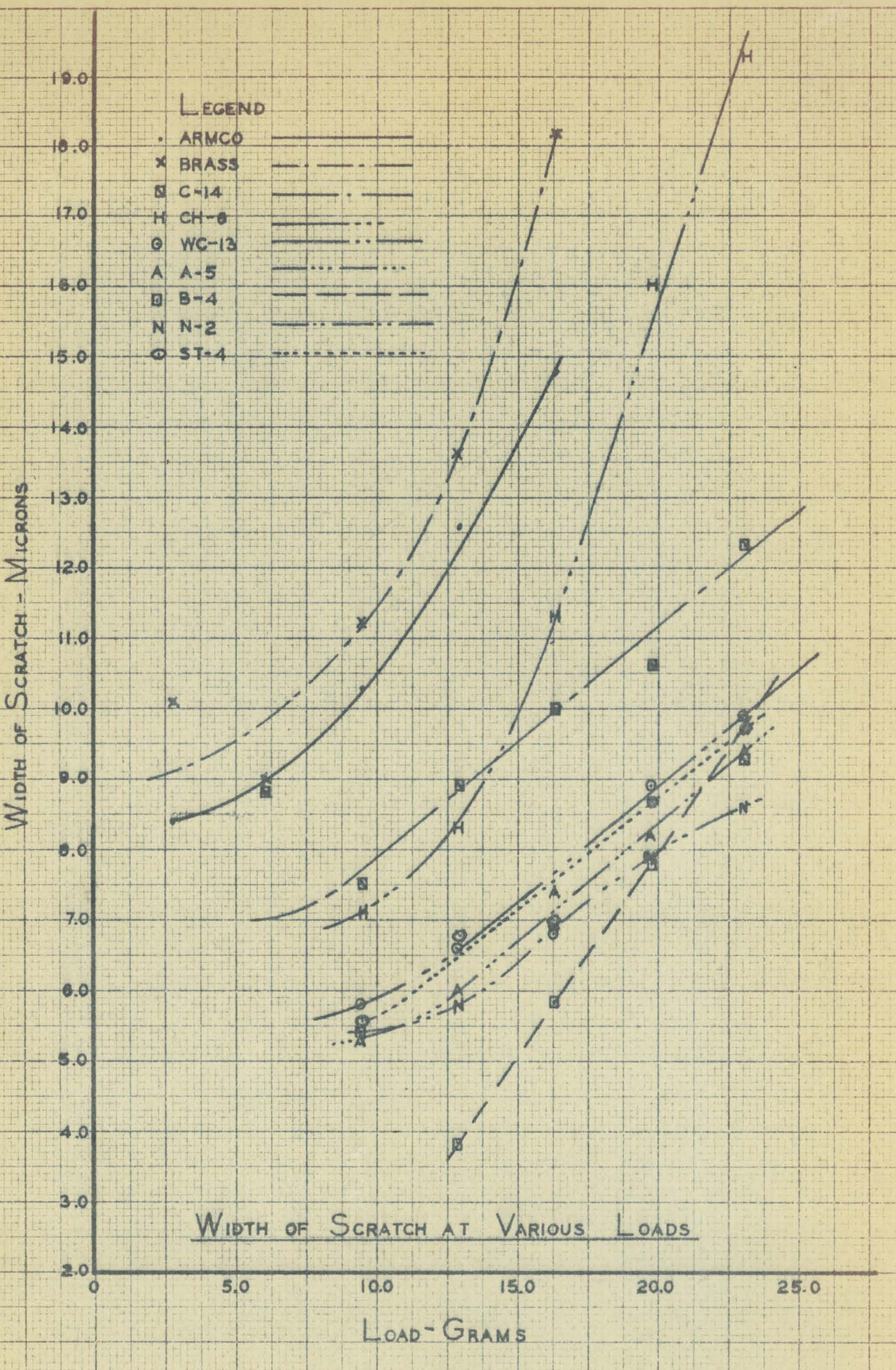
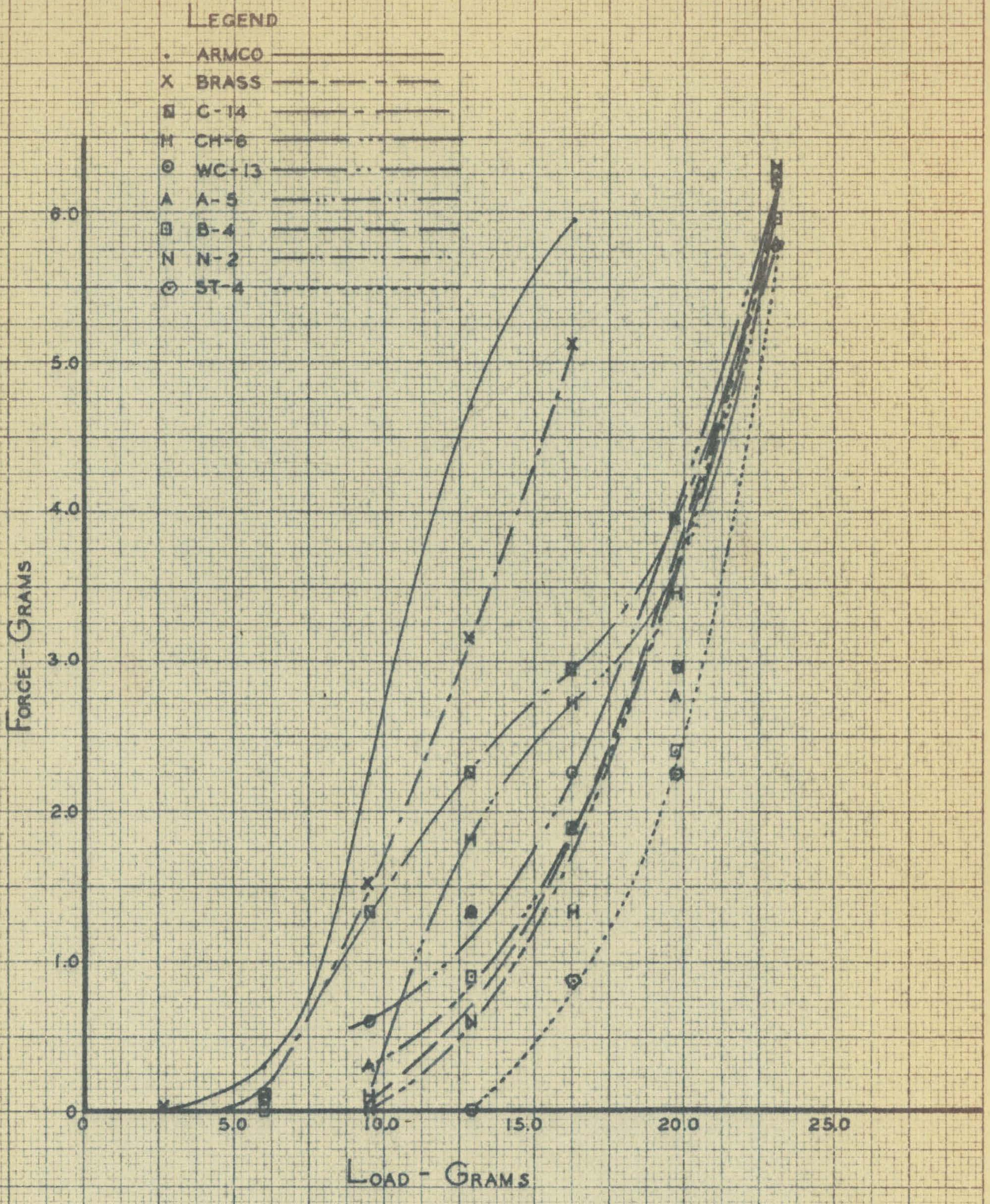


FIGURE 97.

5-31-35 R.B.F.



FORCE REQUIRED TO SCRATCH SPECIMENS
AT VARIOUS LOADS

FIGURE 98.

5-31-35 RGJ

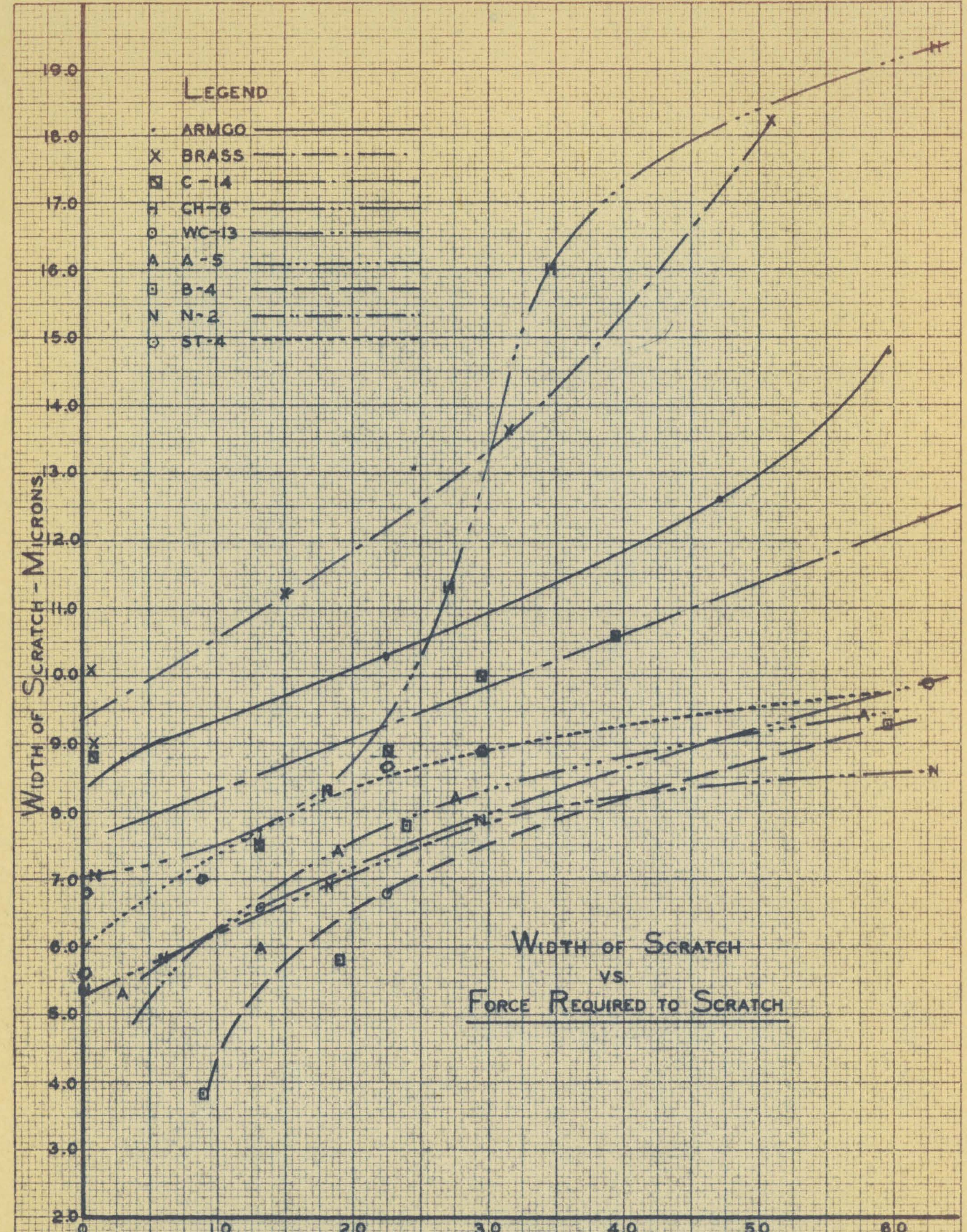


FIGURE 39.

6-4-35 R.B.F.

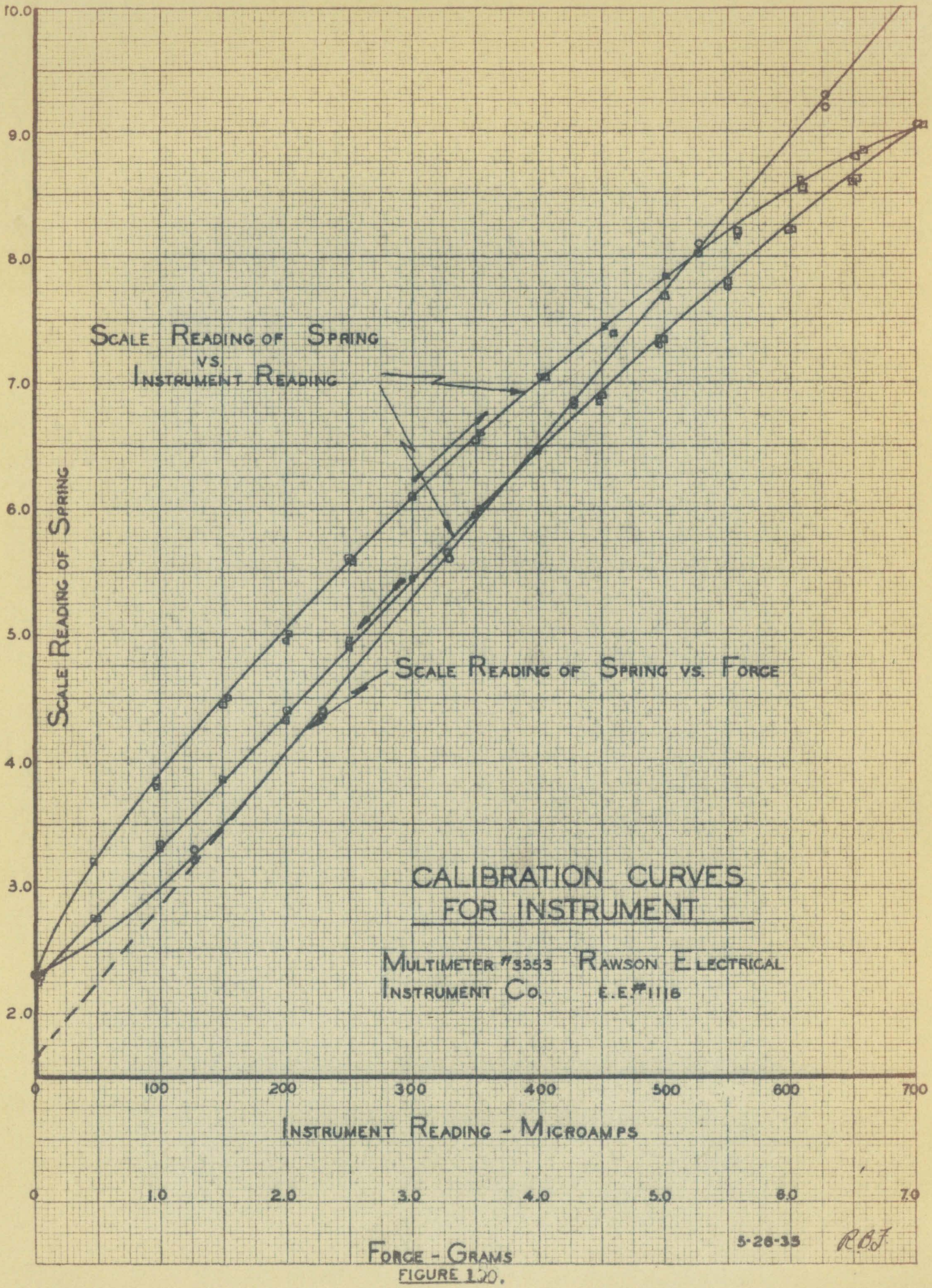

CALIBRATION CURVES
FOR INSTRUMENT
MULTIMETER #3353 RAWSON ELECTRICAL
INSTRUMENT CO. E.E.#1116
SCALE READING OF SPRING
VS.
INSTRUMENT READING
SCALE READING OF SPRING VS. FORCE
SCALE READING OF SPRING
INSTRUMENT READING - MICROAMPS
FORCE - GRAMS
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
100
200
300
400
500
600
700
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
5-28-35
R.B.J.

FIGURE 150.

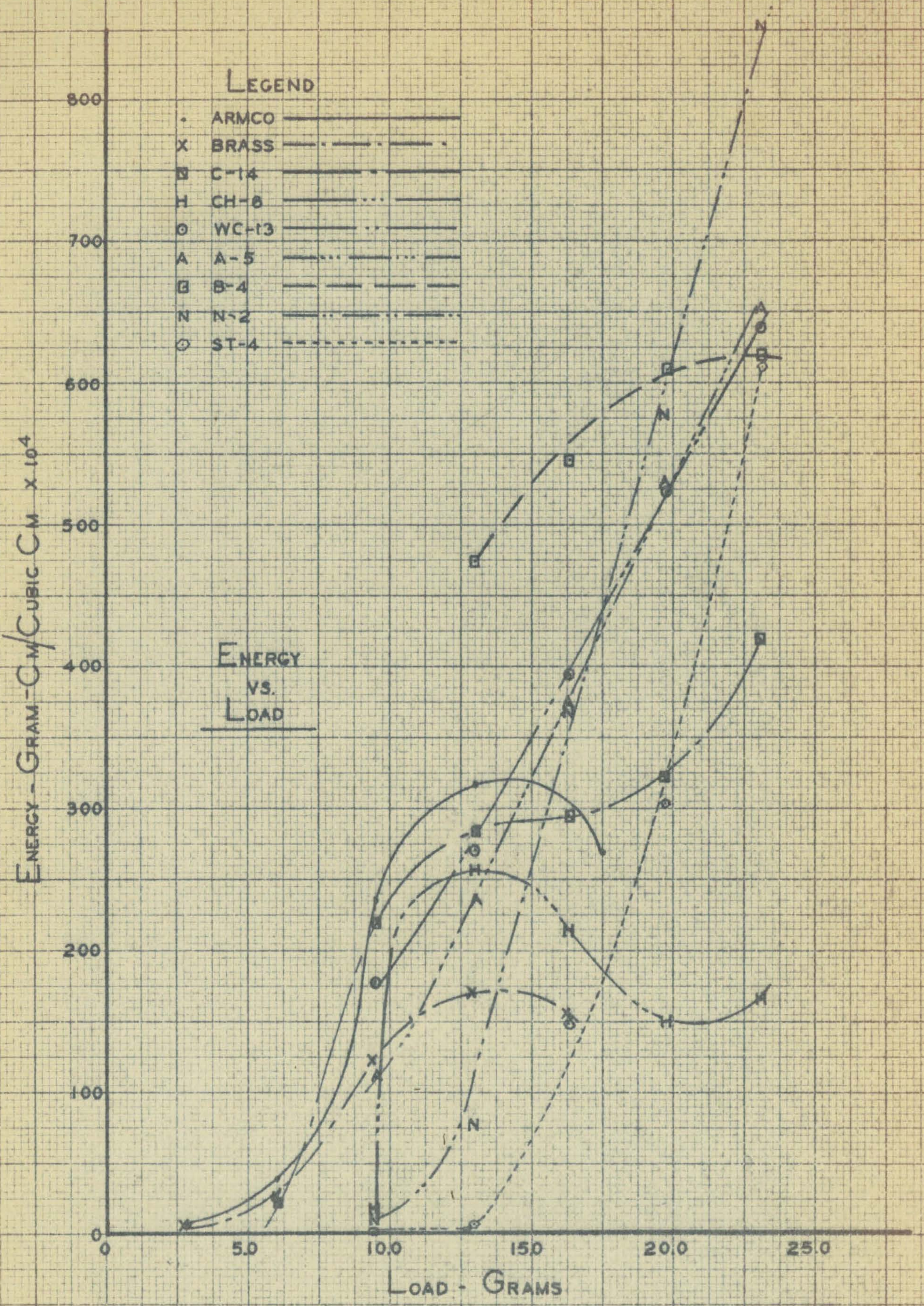


FIGURE 101.

6-4-35 R.B.F.

The force measuring mechanism was calibrated at intervals during the testing, and the calibration for the curve given in Figure 100 was made before run 53 and after run 56. The calibration was accomplished by means of a spring mounted as shown in Figure 94, which in turn was calibrated by weights.

After the tests were completed, the point of the diamond was observed under the microscope and was found to be rounded off, which indicated that wear had taken place on the diamond. For such a condition the depth of cut will not be proportional to the width, and the energy will not be proportional to that calculated from the relation given above. This will invalidate the results to some extent, although the general trend of conclusions may be unchanged. In work of this kind the diamond should be sharpened when necessary in order to obtain accurate results. No facilities were available for doing this in the laboratory.

Materials:

Ten different materials were used in these tests. Eight of them were also investigated in the wear tests which were discussed in Part I. In addition, a specimen of armco iron and a specimen of instrument brass were tested by the scratch method. These materials and their analyses, where known, have been listed in Table I af Part I. The analyses of the armco iron and the instrument brass are not known.

Results and Discussion:

The original and computed data for this investigation are reported in the appendix. The relations between the load, width of scratch, and force required to scratch are shown in Figures 97, 98, and 99. The relation between the energy and the load is shown in Figure 101.

In Figure 97, which shows the relation between the width of scratch and the load on the point of the diamond for the several materials tested, it is apparent that the softer materials are at the top and the harder materials are below. From top to bottom they are arranged in the following order: brass, armco iron, cast iron (C-19), case hardened steel (CH-6), white cast iron (WC-13), stellite (St-4), IR metal (A-5), nitrided nitralloy (N-2), and IR metal (B-4).

In Figure 98, which shows the relation between the force required to scratch and the load on the diamond, the softer materials are to the left and the harder are to the right. In order from left to right, they are arranged as follows: armco, brass, cast iron (C-19), case hardened steel (CH-6), white cast iron (WC-13), IR metal (A-5), IR metal (B-4), nitrided nitralloy (N-2), and stellite (St-4).

It is evident from these two sets of curves that the order is different, and that within each set the curves are not similar in form. At higher loads the results are more uniform, which indicates that if even higher loads were possible, more uniform results might be obtained. In their tests on the hard electrochemical products, Ridgeway, Ballard, and Bailey found that the values of width of scratch for loads less than 50 grams were very erratic. Their tests were made with loads ranging from 50 to 600 grams and a new point was used for each test. They used a diamond point which had interfacial angles of 120 degrees. In the present work higher loads were impossible because the beam in the magnetic bridge was not sufficiently rigid to withstand higher forces. Higher loads would also cause greater wear on the diamond point, which would necessitate frequent lapping. It is apparent that if higher loads were used, an order different from that stated might be obtained.

Bierbaum stated in one of his papers (48) that the width of scratch increased as the square of the load. Briggs and Williams (49) and Ridgeway and associates (40) found a linear relation between the load and the width of scratch. The former workers found that the width of scratch with a six gram load on different materials was from 1.7 to 2.1 times the width of scratch with a three gram load. Ridgeway and associates found a linear relation between the width of scratch and the load. However, their loads were much higher than those of Briggs and Williams. Referring to the curves in Figure 97, it is evident that at the higher loads the relation is approximately linear.

No comparison can be made with the results of other investigators in regard to the force load curves because no literature was found on this phase of the problem.

In Figure 99 curves are shown which give the relation between the force and the width of scratch. The softer materials are at the top and the harder below. The order from top to bottom is as follows: brass, armco, cast iron (C-19), stellite (St-4), IR metal (A-5), white cast iron (WC-13), nitrided nitralloy (N-2), and IR metal (B-4). The curve for case hardened steel (CH-6) is erratic and has not been included in the arrangement given above. It is seen that for the harder materials the force increases more rapidly than the width.

Figure 101 shows the relation between the energy per cubic centimeter required to scratch and the load on the diamond. The curves for armco, brass, cast iron, and case hardened steel are very erratic. The curves for nitrided nitralloy, white cast iron, IR metal "A", and stellite are approximately linear for the higher loads. As was stated previously, the energy per cubic centimeter required to scratch is proportional to the quantity obtained by dividing the force by the square of the width of the scratch. This assumes that the depth of scratch increases in proportion to the width, which will be true if the diamond is sharp and correctly ground to the shape of a corner of a cube. In case the diamond has become dull, the depth of scratch will not increase in proportion to its width. This means that for the same width of scratch, the area removed with a rounded point will be less than that removed with a sharp point. Not only will the area of material removed be different than assumed, but further error may be introduced in the energy calculations due to the difference in force required to scratch. Let us assume, for example, that the diamond has a rounded point and that we shall use the relation that the energy is proportional to the force divided by the width of scratch squared. If the material is one which shows only slight differences in width with changes in load on the diamond, small differences will be found in the energy calculations. However, if the material shows large differences in width of scratch for various loads, the differences of the squares of these widths will introduce large differences in the energy calculations. It is also apparent that the force determinations will depend upon the shape of the diamond point, and, as the point becomes more blunt; i.e., rounded off, during the testing, the force values will change. Such effects will introduce further inaccuracies in the determination.

It will be noted by studying the curves in Figures 97, 98, and 101, that those curves which are erratic in the first two figures result in the erratic curves in Figure 101.

It must be emphasized that the accuracy of the data obtained in these scratch tests is poor, partly due to the limited facilities at hand. No means were available for relapping the diamond and keeping it sharp. Higher loads could not be used because of the limitations of the force measuring device. However, the results indicate that with higher loads and perfect diamond points a relation might be obtained between the wear resistance and the energy required to scratch the material.

CONCLUSIONS

The research has shown the relative order of sliding wear resistance of some hard alloys and combinations, as is shown in Table III on page 26 . It has shown some relations between the load and the wear factor for gray cast iron running on IR metal "B" at various speeds. These relations are shown in Figure 7 on page 23 . A metallographic investigation has shown that for sliding wear under the conditions of these tests, a smooth surface is accompanied by a smooth, clean-cut edge, with practically no working of the material at the surface. When the conditions are such that galling occurs, a layer of worked material is formed, which in the case of white cast iron is composed of iron carbide and ferrite. This layer is richer in carbide than the parent structure and is almost as hard as the cementite grains, as determined by the scratch method. By the formation of this layer, the hardness of the surface as a whole is increased, although it may be rough. This may or may not be advantageous in a particular application. Any short time test will not be able to fully predict the effect of such a layer on the actual wearing life of a particular application.

The nature of the surface condition is important in its effect on the wear. This fact has been realized by other investigators and has been emphasized by the present research. An extremely smooth surface condition before test will give a very low wear factor. For the same conditions of test, the wear factor will be high if the surface is rough.

The scratch investigation has been primarily of a preliminary nature. The facilities were extremely limited and the results are of questionable value. The value of the investigation is in the presentation of a new method for testing a material in order to obtain a measure of its wear resistance. This method is limited in its application because it measures a quality which the material possesses at the time of test. The test determines an intrinsic property of the material under consideration. From such a test, nothing can be said as to how the material will act when worn against another material. Any beneficial effects due to cold working during the process of wear will not be shown in the scratch method. At the present time, the facilities which are necessary in order to satisfactorily perform the tests are too expensive and delicate to warrant extensive use.

In Table IV is shown the order of the various materials investigated arranged according to the method of test. The first column shows the order of decreasing wear resistance, for materials wearing on themselves, as determined by the wear tests. The second column shows the order arranged for increasing width of scratch, as determined by D. S. Clark. The next four columns show the orders obtained from the curves shown in Figures 97, 98, 99, and 101. These curves are discussed on page 96. The last column shows the order when the materials are arranged according to decreasing Diamond Brinell hardness, as determined on the Monotrone machine.

TABLE IV.

Wear Tests	Width (Clark)	Width vs. Load	Force vs. Load	Width vs. Force	Energy	Hardness Monotrone
B	E	B	St	B	B	N
WC	B	N	N	N	N	B
N	CH	A	B	WC	WC	CH
CH	A	St	A	A	A	A
St	WC	WC	WC	St	St	St
	St	CH	CH	C		WC
	F	C	C	Armco		C
	C	Armco	Brass	Brass		Armco
		Brass	Armco			Brass

The order as determined by the wear test results and the energy method is about the same. The exact position of "N" in the energy column is somewhat doubtful, due to the fact that the energy curve for this material crosses the others. The position of "CH" could not be determined because the energy curve was very erratic. The wear value at this speed and load; namely, 786 feet per minute and 300 pounds per square inch, was not determined for "A". Although a definite correlation has not been obtained between the results of the two methods, the order of the wear resistance as determined by the two methods is quite close.

APPENDIX

Original Remarks on Wear Tests

Run No. 1. The first eleven runs were preliminary runs.

No. 12. "B" specimens were run on "B" rings. The specimens were worn considerably. They had galled and were burnt on the edges. Small chips fell from the edges during the test. The unit pressure was too high. Run #13 was the same so was combined in the data as run #12.

No. 14. The same specimens were used as in run #12 so that nothing could be said as to the affect of the pressure on galling, however no further galling is apparent. The friction moment was very steady.

No. 15. The same specimens were used as in runs #12 and #14. The friction moment was quite steady but not as perfect as in run #14.

No. 16. Grey cast iron specimens were used. Wear was exceedingly high. Wearing rings were rubbing on the copper specimen holders at the end of the run.

No. 17 "A" specimens were used on "A" rings. A very long wearing in period was necessary. There was no galling. The surfaces were mirror bright and the friction moment was very steady.

No. 18 Same conditions exactly as in #17. The specimens were bright and shiny after wear.

No. 19. Same as #17 and #18.

No. 20. Same as #19. These runs were made for a check on the wear values.

No. 21. "B" specimens were run on "A" rings. Very little wear took place causing a long wearing in period. The friction moment was so low that it could not be measured on the machine. There was no appearance of galling.

No. 22. Same set up as in run #21. At the end of this run there was a very slight indication of galling on B-12. This specimen did not wear evenly so that the pressure was greater than 300 lbs./in^2. B-11 was smooth and shiny.

No.23. Same as #22 except that the load was increased to 600 lbs/in2. There is still no evidence of galling on B-11, although the metal seems to have been pulled along over the surface. B-12 did not wear over the whole surface, and there was one area which had galled.

Run No. 24. The set up was the same as for run #23. B-11 showed no indication of galling. It was very bright and shiny. B-12 had worn on only a little more than one half the surface. There were two areas which were galled.

No. 2 5. Same set up as for #24. B-11 had galled slightly. The surface was ridged and not as smooth as after previous runs. B-12 had continued to gall during this run. The galled area was larger.

No.26. Ring A-1 which was used in previous runs was used in this test for one wearing surface. It was only slightly worn and the surface was smooth. Ring A-4 was a new ring. Specimens A-3 and A-4 were new specimens. The friction at the first of the run was lowest and most even. After the run progressed for a short time the friction moment became very uneven and the loading beam vibrated excessively. The runs were unsatisfactory for this reason.

Both specimens galled quite badly, although the appearance of the surface is different than when the specimens gall in distillate. There are a great many cracks on the surface which are at right angles to the direction of wear. The specimens have been very hot at the edges as evidenced by the blue color. The cracks on the surface are probably due to heat.

In regard to the low coefficient of friction at the beginning of the run; it is probable that this is the true coefficient between the metal surfaces. As soon as the dust gets between the surfaces, the friction moment becomes uneven and the friction is higher.

The friction dust is a black powder in which there are many small shining particles.

No. 27. The rings and specimens appeared much the same as after run #26. Ring A-1 cracked during the test. Also during this run the load increased considerably for a time. This was caused by the fact that the loading beam vibrated very much and the operator was not aware of the incresed load for several minutes. This would cause the wear to be greater by some unknown amout for this run.

It can be concluded from these tests that dry conditions on this metal with this machine are very unsatisfactory.

No. 28. In this run after about 130000 feet of travel, the friction moment was so low that the value of the coefficient could not be determined. The specimens wore on only about one half of the surface, therefore the unit pressure was estimated at 700 lbs/in^2. There was no indication of galling and the surfaces were mirror bright. The wear was greater on the inside surfaces of the specimens and the edges were blue from heat. On these edges chunks had fallen out as in the case of those tested at 1000 lbs/in^2. Most of the wear, or weight loss, in this run was due to these particles which fell off.

Run No. 29 The specimens appeared about the same as after run #28. There was no evidence of galling. Wear had taken place over about one half the surface. The surface was bright and mirror like.

No. 30 The run was a contiuation of #29. The conditions of test were the same. The rings and specimens had smooth shiny surfaces at the beginning of these two runs. After the test the surfaces were not worn all over and the unit pressure was estimated at 500 lbs/in^2. There was no appearance of galling. The surfaces were smooth and mirror bright,

No. 31 After test the surfaces were not worn all over. The unit pressures were estimated at 400 lbs/in^2 for WC-1 and 600 lbs/in^2 for WC-2. There was no indication of galling. The surfaces were worn bright and shiny. The rings had not worn much, for the grinding marks were still visible.

No. 32. The specimens were not worn in yet. The unit pressure was estimated at 500 lbs/in^2. There was no evidence of galling. The surfaces were very well polished where worn. The rings were polished on a narrow strip where the specimens were wearing. The friction moment at the end of this run is comparable with that of B on B at the end of runs #29 and #30.

No.33. The conditions for this run were the same as for #32. The specimens did not wear over the entire surface. The unit pressure was estimated to be 400 lbs/in^2. There was a slight indication of galling on the specimens. The rings appeared to be about the same as after run #32. The rate of flow of distillate for runs #31, #32, #33 was about 0.11 gallons per minute.

No. 34. After run #33 it was decided to increase the speed to 1200 RPM, 786 ft/min. In order to see if the speed would affect the results of wear and coefficient of friction, run #34 was run under the same conditions as #33 with the exception that the speed was increased as indicated. The rate of flow of distillate was increased to about 0.25 GPM.

As can be seen from the data, the wear was considerably greater than in the previous runs. Also the coefficient of friction was slightly higher.

After this run the specimens were ridged in the direction of wear. The rings were also ridged. There was no indication of galling or overheating.

No. 35. Run #35 was made in order to study the affect of this speed on B metal. Rings 5 and 6 were used as the

Run No. 35. cont. wearing surfaces. These rings had been worn somewhat smooth in runs #28, #29, and #30. The grinding marks were still visible on most of the surfaces. Specimens B-15 and B-16 were new specimens. They had been ground smoothly and had worn all over the surfaces. There was no appearandce of galling and no particles had fallen from the edges. The surfaces were not ridged deeply as in the case of the white iron samples, but were smooth and shiny.

No. 36. Run #36 was run under the same conditions as run #35. After the run the specimens had worn over the entire surface. They were smooth with no ridges, but were not polished as at the lower speed. There was a slight amount of galling on B-15. The rings were smooth. The rate of flow of distillate was about 0.18 GPM on runs #35 and #36.

No. 37 The wearing surfaces on this run were new rings and new specimens. After the run the specimens were worn over the entire surfaces. They were slightly ridged. There was no appearance of galling. The rate of flow of distillate was about 0.2 GPM.

No. 38. Run #38 was run under the same conditions as run #37. The surfaces were run all over. St-2 was ridged rather deeply. St-1 was slightly ridged and quite smooth. There was no appearance of galling. The surfaces of the rings were the same as the corresponding specimens.

No. 39 The specimens were worn considerably. The surfaces were galled rather badly. The rings were ridged, although not deeply.

No. 40. The specimens and rings looked about the same as after run #39.

No. 41. The specimens still looked about the same as after the 39th run. The galled surfaces did not seem to be so severely scored during this run as in the previous runs.

NO.42. Runs 42, 43, and 44 were made with B specimens on stellite rings. The flow of the distillate was about 0.2 GPM. Specimen B-17 was worn all over. The surface was galled. Specimen B-18 had not worn over the whole surface so the unit pressure was estimated at 375 lbs/in^2. The surface was smoother than that of B-17 and was mirror bright in most places. The rings were only slightly worn, and the grinding marks were still visible on most of the wearing surface. There is no apparent reason for the large difference in the wear on the two specimens.

No. 43 The surfaces of the specimens were becoming mirror bright. B-17 was still scored, although it did not appear to be as bad as after run #42. Almost the entire surface of B-18 was mirror bright and highly polished. However, there was some evidence of galling. The rings looked about the same as after the previous run.

Run No. 44 The specimens were galled, but some smooth places were mirror bright. B-17 was galled more than B-18. The rings were not worn severely.

No. 45. The specimens were new when installed. They were badly ground and had low spots on the surfaces. The unit pressures were estimated to be; on WC-3, 500 lbs/in^2; and on WC-4, 550 lbs/in^2. WC-3 was galled slightly in some places on this run. The remainder of its surface was mirror bright. WC-4 was mirror bright where worn. The rings were only slightly worn. The rate of flow of distillate on runs #45, #46, and #47 was about 0.2 GPM.

No. 46. The specimens appeared to be about the same as after run #45. WC-3 had galled some. WC-4 was not galled. The unit pressures were estimated to be; on WC-3, 375 lbs/in^2; on WC-4, 425 lbs/in^2. The rings showed practically no wear.

No. 47. The specimens seemed to be about the same as after runs #45 and #46. The unit pressures were the same as after #46. The surfaces were bright and well polished. The rings were only slightly worn.

No. 48. Specimens B-19 and B-20 were new specimens, but rings B-7 and B-8 had been used on the three preceeding runs. They seemed to be very smooth.

After the run B-19 had worn over the entire surface and was badly galled. The ring on which it wore had a narrow path on it which was galled. Specimen B-20 had hardly begun to wear-in. The ring on which it run was brightly polished.

At this point it would be well to note that the wear on the ring listed above in the data has been greater in the last ten or more runs. This might indicate that the unit pressure on this ring was greater than on the other. If such is the case, the wear would be greater and the specimen would be more likely to gall because of the higher pressure. An attempt was made to remedy this condition before run #49. The knife edges were reversed on the loading mechanism. However, it can be seen from the results of the runs up to #55, at least, that the condition is still present. A ball and cup loading device would probably remedy this difficulty.

No. 49. Specimen B-19 looked about the same. It was galled over the entire surface. B-20 was galled on one half of the surface, which was the area in contact with the ring.

No. 50. The specimens looked about the same as after the preceeding run. The rings were quite smooth. The flow of distillate in the last three runs was about 0.3 GPM.

Run No. 51 New specimens and rings were used on this run. They wore over the entire surface. They were ridged deeply in the direction of wear and were severely galled. The surfaces of the rings looked about the same as that of the specimens.

No. 52. The data for this run was not given in the data because the load increased during the test and the wear values were very high.

No. 53. Because of the non-uniformity of results obtained in runs #48, #49, and #50, B specimens were run again on B rings in runs #53, #54, and #55. New rings and new specimens were used. One can see from the data that the results are little if any better than those of the previous runs.

After the run both specimens had worn on the whole surface. B-21 was badly galled while B-22 was not worn much. (This again indicates that the load was not evenly distributed between the two specimens.) Ring B-9 was worn more than ring B-10. The former was galled on a very small area. They were not ridged.

No. 54. B-21 did not appear to be galled as much as after the previous run. Ring B-9 was ridged slightly after this run.

No. 55. Specimen B-21 appeared to be about the same. B-22 was galled somewhat after this run. Ring B-9 had worn considerably more than B-10.

No. 56. New specimens and rings were used. After the run specimen WC-7 was worn only on a very small area. The unit pressure was estimated to be 1200 lbs/in^2, if the load was evenly distributed between the two specimens. WC-8 was badly galled. The edges were burned indicating that the surface had been hot. Ring B-12 was worn considerable, but B-11 was not. The results indicate that very probably the load was not evenly distributed.

No. 57. This run was made under the same conditions as the previous run, except that specimen WC-7 was run on ring B-12 instead on B-11.

After this run the specimens were badly galled. WC-7 was worn on about four fifths of the surface. The unit pressure was estimated to be about 375 lbs/in^2. WC-8 was worn over the entire surface. The rings were worn deeply and were galled.

In spite of the fact that the specimens were reversed on their respective rings, the wear on WC-8 was still considerably more than on WC-7.

No. 58. This run was made with new rings and specimens. After the run both specimens were worn over the entire surfaces and were galled. WC-9 seemed to be more badly galled than WC-10. Ring WC-5 was worn slightly more than WC-6. Both rings and specimens were slightly ridged.

Run No. 59. This run was the same as #58. After the run the specimens looked about the same as after the preceeding run.

No. 60 This run was the same as #58. The specimens did not seem to be galled as badly as after the preceeding runs. The rings were about the same. The wear was more consistent.

No.61. New rings and new specimens were used. After the run the specimens were worn all over and galled, although not severely. The rings were also galled and worn considerably.

No. 62. This run was thrown out because the thrust bearing on the friction wheel failed. The speed increased to about 1500 feet per minute. The results could not be used.

No. 63 This run was made as a check run to see if the wear would be consistent with different sets of specimens. The conditions were the same as for runs #58 and #59.

The specimens were worn severely after the run and were galled. The rings were worn considerably. Although WC-12 apparently lost no weight, it appeared to be worn almost as much as WC-11. This fact might be explained either by a mistake in the initial weight of the specimen in question, or by the fact that the specimen had picked-up some of the ring material.

No. 64. The run was the same as #63 except that the time of running was doubled. After this run WC-9 was worn much more than ring WC-10.

No. 65. Runs #65 to 108 inclusive were made with cast iron specimens wearing on B rings. These tests were made in order to study the affect of speed and pressure on the wear.

Run #65 was run at a pressure of 600 lbs/in^2 and at 197 feet per minute. After the run the specimens were slightly galled and slightly ridged. The rings were well polished.

No. 66. The specimens and rings looked about the same as after the preceeding run.

No. 67. New specimens were put on the same rings and the load was reduced to 300 lbs/in^2. After test the specimens were slightly ridged and slightly galled. The rings were highly polished.

No. 68. These runs were under the same conditions as #67.
69. The specimens and rings appeared to be about the same as
70. after the preceeding run. The wear gradually became smaller, and was zero for the length of run taken. Further runs were not considered because these tests are for comparative purposes and this speed is quite slow.

Run No. 71. The specimens after the run looked much the same as after preceeding runs.

No. 72. This run was the same as the preceeding one. The specimens looked the same as before. The wear was very uneven during these runs so the iron links from the fulcrum to the head were replaced by flexible wires. This would give point contact instead of line contact for applying the load. This gave a better distribution of the load.

No. 73. New specimens were used on the same rings. The surfaces
74. were the same as after preceeding runs, and the wear was
75. more evenly distributed.
76.

No. 77. New specimens were used on the same rings. The pressure was 96 lbs/in^2 and the speed was 393 ft/min. The specimens appeared about the same. They were slightly ridged and turned over at the edges.

No. 78. These runs were all made under the same conditions
79. as #77. The surfaces looked about the same after each
80. run.
81. Note that in runs #77 to #81, the wear values gradually increased. This may be explained by the fact that the surfaces were quite smooth when finish ground, but as wear took place the surface condition was altered, which increased the rate of wear.

No. 82. New specimens were used on the same rings. The
83. pressure was reduced to 33 lbs/in^2. After the run the
84. specimens were smoother than when they ran at the higher
85. pressures. The ridges were not as deep and the wear was much less.

No. 86. The same specimens and rings were used at the same
87. pressure, but the speed was increased to 786 ft/min.
88. After this run the specimens seemed to be galled a little
89. more, but otherwise appeared to be about the same. The wear dropped off with each succeeding run.

No. 90. The same set-up was used except the pressure was in-
91. creased to 96 lbs/in^2. After the run the specimens were considerably rougher than after previous runs. They were galled and the edges were turned over. They were ridged in the direction of wear.

No. 92. The same specimens and rings were used and the pressure
93. was reduced to 70 lbs/in^2. The surfaces were smoother after
94. this run. They were the same after each of the runs.

Run No. 95 The same specimens and rings were used in this run, but the load was increased to 130 lbs/in^2. The specimens were deeply ridged and the edges were turned.

No. 96. The specimens looked about the same after this run, but the rings were beginning to get rough.

No. 97. The specimens looked about the same after this run, but the rings were galled. The wear increased during this run over that of #95.

No. 98. New rings and specimens were installed. The load was lowered to 70 lbs/in^2 and the speed reduced to 393 ft/min. After this run the specimens were very smooth.

No. 99. This run was made under the same conditions as #98. The specimens were quite smooth, although not as smooth as when finish-ground.

Note that the wear in these two runs, #98 and #99, is much less than in runs ##77 to #85 inclusive. During the earlier runs, specimens were used which had been previously run at 300 lbs/in^2 and at a speed pf 393 ft/min. The surfaces before test were therefore not as smooth as those in runs #98 and #99. The surface of the specimens has undoubtedly considerable affect upon the wear.

No. 100. The same specimens and rings were used, but the pressure was increased to 96 lbs/in^2. In this run the wear is a great deal less than in runs #77 to #81 inclusive. The surface conditions probably account for the differences in the wear values. The latter values are probably the true values for smooth surfaces under sliding wear with distillate present.

No. 101. This run was the same as #100. The wear was nothing for the length of run tested.

No. 102. The same specimens and rings were used, but the load was increased to 150 lbs/in^2. The specimens were smooth and looked about the same as after 101 and 100.

No. 103 The conditions of the test were exactly the same as for #102 as far as they could be controlled. However, The wear suddenly increased a great deal. The surface condition evidently broke down during this run. The surfaces were quite smooth and the edges were turned.

No. 104 The conditions of test were the same as for 103. The surfaces of the specimens were ridged and the edges were turned.

No. 105.
106 These two runs were the same as #104. The specimens looked the same as after 104.

Run No. 107.
108. The same specimens and rings were used, but the load was increased to 200 lbs/in^2. The surfaces of the specimens looked about the same as after the runs with 150 lbs/in^2.

Run No. 109 Runs 109 to 126 inclusive were made with ring material "G", on rings of metal "B", rings of unheat-treated block material "F", and rings of heat-treated block material "E".

Run #109 was made with new G specimens on rings B-15 and B-16 which had been used on the grey iron runs. The rings were smooth. The pressure was 300 lbs/in^2 and the speed was 1180 ft/min.

After the run the specimens were ridged deeply and the rings were badly galled.

No. 110. New rings and new specimens were used. The pressure was 155 lbs/in^2 and the speed was 1180 ft/min. After the test the specimens were deeply ridged and the edges were turned.

The wear was less during this run than in the succeeding run. This might be accounted for by the fact that if the runs were continued at this speed, the wear would undoubtedly reach a much higher value as the rings roughed. The rings had started to gall during this run.

No. 111. The same rings were used on this run as on #110. However, before the run they were smoothed with alundum paper. New specimens were used and the speed was reduced to 786 ft/min. After the run the specimens were much smoother than after #110, but they were still turned on the edges.

Since the wear was considerably greater after this run than it was after #110, when new rings were used, it was decided to install new rings which were smoother than B-13 and B-14.

No. 112. New specimens were run against new rings. After the run the specimens were slightly ridged. The rings showed evidence of galling, but felt smooth. The wear for this run was higher than that for 110. It may be that the wear for #110 is abnormally low.

No.113.
114. These runs were the same as #112. The specimens looked the same. The rings showed only slight evidence of galling. The wear on the three runs is quite consistent.

No. 115. New G specimens were run on F rings. After the run the specimens were slightly ridged and the edges were turned.

The rings were quite similar to the B rings after wearing against the G material. A few spots developed on the surfaces of the rings. These spots do not make the sufface feel rough to the fingers, but the spots are visibly rough in the bottom. The writer feels that these spots are caused by a gouging action of hard cementite or phosphide particles which are worn from the specimens. The G material is rather high in phosphorous content and probably has some phosphide eutectic, which is very hard.

Run No. 116. The specimens seemed to be ridged a little more after this test. The rings were galled some more also. The wear is higher, but is still uneven.

No. 117. The specimens and rings looked about the same after this run. The wear was still uneven so that new specimens and rings were installed for the next run.

No. 118. The same condition of test were used as for the three preceeding runs. The specimens looked about the same after test. The wear was much more even.

No. 119. These two runs were the same as 118. After the test
120\. the specimens were the same as after #118. The rings
had more spots but they were smaller. These spots were
places where the ring material had been pulled out.

No. 121. New G specimens were used on new E rings. After
122\. the tests the specimens were only slightly ridged and the
edges were slightly turned. The rings were quite porous,
especially E-2. This might account for the higher wear
factor on specimen G-14. The rings did not seem to gall.

No. 123. After this run the specimens were really quite smooth. They were only slightly ridged. The rings showed only a slight indication of galling, but seemed to be quite porous.

The wear was not consistent on the two specimens, so new specimens and rings were installed before run 124.

No. 124. The specimens were again only slightly ridged. The rings showed only slight evidence of galling. They appeared to be superior to either B or E. The wear was fairly even between the two specimens.

No. 125. After these runs the specimens had practically no
126\. ridging on them. They were very smooth, although not
as smooth as when finish-ground.

The wear of the piston ring material G was about the same on B, F, and E. It was slightly less on the latter material. The surfaces of the E rings, however, were much superior after wearing against the G specimens than either B or F. The B and F rings galled rather badly and the E rings stood up rather well. At lower pressures probably neither B nor F would gall at this speed.

Run No. 127. Runs 127 to 134 were Made with E specimens on B rings. The load was 300 lbs/in^2 and the speed was 786 ft/min.After the run the specimens were badly galled and the edges were turned. The surfaces felt smooth in spite of the galling. The rings were slightly galled. The temperature of the distillate rose slightly during the run.

No. 128. This run was the same as #127. The specimens and rings looked the same. Note that the wear is less.

No. 129. This run was the same as #127 and #128. The rings were spotted after this run and the wear has increased.

No. 130. This run was also the same. The specimens and rings looked about the same. The distillate heated up on each of these runs, slightly.

The wear has again dropped. Due to the inconsistency in the results, new specimens were used in the following runs.

No. 131. New specimens were used on the same rings. They
132. looked about the same as after run #130. The rings spotted
133. up a little more.
134. Note that in these runs the wear is not at all consistent. It is sometimes low and sometimes high. The high values are rather consistent among themselves, but the low values are more scattered. It appears that the conditions are at a critical value.

No. 135 Runs 135 to 138 were made with F specimens on B rings. The load was 300 lbs/in^2 and the speed was 786 ft/min. New specimens were run on B-13 and B-14. The latter had been used but were smooth. After test the specimens were galled and seemed to be porous. The rings were smooth and did not spot up as when E ran on them.

No. 136. The specimens galled but were mirror bright in some places. There was a slight rise in temperature during this run. Notice that the wear is quite low.

No. 137. The rings and specimens were very smooth after this run. The surfaces of the specimens did not appear to be as porous as before. Perhaps the wearing process smoothed over the holes instead of removing material. There was no loss in weight for the length of run taken.

No. 138. This run was the same as the three previous runs, but the length of travel was increased. F-1 was smooth after test and had lost no weight. F-2 was rougher and had galled slightly. There were a few ridges in the latter. Ring B-13 was very smooth. B-14 had about four spots in it where galling had started.

No. 139. Runs 139, 140, and 141 were made to supplement 127 to 134. New E specimens were run on B-13 and B-14 after the latter had been smoothed with alundum paper. After the run the specimens were galled although quite smooth. The rings were also smooth.

Run No. 140. After this run the specimens looked the same but the rings had started to gall. Ring B-13 had only a few spots, but B-14 had many.

No. 141. Ring B-14 had galled still more during this run, which undoubtedly increased the wear on E-8. E-8 had galled considerably, and the dges were turned. E-7 looked about the same. It was fairly smooth although it was galled slightly. Note that the wear in these last three runs is low except for E-8 in the last two. The high value obtained in the last run checks with high value obtained in #131 and #132. The surface condition undoubtedly plays an important part in the wear.

General Remarks on Runs #142 to #226, inclusive.

Further tests were made with cast iron specimens wearing on B rings, under different speeds and pressures. New specimens were installed on new rings at the beginning of run 142. Runs 142 to 154 inclusive show decisively that the surface condition, of the rings especially, is of great importance. In this series of runs the wear value continued to decrease with the length of travel on the rings, even with increasing loads. These runs show little beside this, for the wear values are clearly higher than they should be. This type of test was continued in the runs 166 to 204, inclusive. It is to be noted that the friction coefficient is very uniform in all of these runs except those made at very low pressures.

Runs 155 to 165, and 205 to 208, inclusive, were made investigating the wear of case hardened steel against itself, on B metal, and the wear of B metal on the case hardened steel.

Runs 209 to 215 give the results of tests on Flint Alloy and B metal.

Runs 216 to 226 inclusive give the results of tests on Nitrided nitalloy and B metal.

No. 142. New specimens were run on new B rings. The speed was 197 ft/min. and the load was 400 lbs/in^2. Runs 142 to 146 were made under the same conditions. After this run the rings looked like new. Specimen C-15 was worn all over and the edges were turned. Specimen C-13 was worn only slightly. The surfaces were smooth, almost like finish-ground.

No. 143. The rings were the same. Specimen C-15 was smooth, but turned at the edges. There were no ridges. C-13 seemed not to have been worn. A dark fill seemed to cover the surface.

No. 144.
145.
146. The rings were the same. They were getting smoother. The specimens were worn all over and the edges were turned. They were smooth with no ridges. The film on C-13 had disappeared during these runs.

Run No. 147. The same specimens and rings were used. The pressure
148. was increased to 500 lbs/in^2. The specimens and rings
149. were smooth with no ridges.

No. 150 The specimens were really quite smooth although not as smooth as finish-ground. The rings were gradually becoming smoother and highly polished.

No. 151. The rings were the same as after the last run. The
152. specimens were very, very slightly ridged.
153.
154.

No. 155. New specimens and rings were used on this run. CH specimens were tested against CH rings. The load was 300 lbs./in^2 and the speed was 786 ft/min. After the run the surfaces of the specimens and rings both looked alike. They were mirror bright in some places and dull in others. This caused the surfaces to look ridged although they felt smooth.

No. 156. The conditions of the following runs, 156 through 161,
157. were the same as for run #155. After these runs the specimens
158. were slightly ridged and slightly galled. They were mirror bright.

No. 159. The surfaces after these runs looked the same as after
160. #158.
161.

No. 162 The following four runs were made with CH specimens on B rings. New specimens were installed on new rings at the beginning of this run. The speed and pressure was the same as those immediately preceeding. After the run the specimens were very slightly ridged. The rings appeared about the same as the specimens.

No. 163. After these runs the specimens were very slightly
164. ridged and mirror bright.

No. 165. This run was made under the same conditions as those immediately above. The total distance of travel for this run was almost 6000000 feet, over 1100 miles. The value of the wear for this run was considered to be correct for these conditions. The specimens were mirror bright over most of the surface, although there were a few dull places. The rings were also mirror bright although ridged slightly in the direction of wear.

No. 166. The following runs through 175 were made with cast iron specimens on B rings. The speed was 197 ft/min and the load was 300 lbs/in^2. After this run the specimens were very slightly ridged. The rings were smoother than finish-ground. They looked about the same as new rings, but felt smoother.

Run No. 167. 168. 169. After these runs the specimens and rings looked the same as after run #166.

No. 170. The specimens and rings looked about the same. The latter were getting smoother with each succeeding run.

No. 171. The specimens and rings looked the same after this run, except that specimen C-26 had a darker surface. This darker surface was thought to be an oxide film.

No. 172. After this run the specimens looked about the same. Note the small wear on C-26 on which the darker surface appears.

No. 173. New specimens were installed on the same rings and the conditions were held the same for runs 166 to 177. After the run both specimens were very, very slightly ridged. They were both dark on the surface as in the case of C-26 in runs 171 and 172. The rings were smooth, but ridged very, very slightly in the direction of wear.

No. 174. 175. The specimens and rings looked about the same after this run. C-28 was ridged slightly more on one side than on the rest of the surface.

No. 176. The same specimens and rings were used, but the load was increased to 600 lbs/in^2. The speed was 197 ft/min. After the run the specimens and rings were very slightly ridged. This ridging was greater than that for 300 lbs/in^2. The dark film had disappeared from the surface.

No.177. Ring B-28 broke during this run. The wear value on C-28 was of no value. The wear on C-27 might even be too large, although this value is included in the data. After the ring broke, the machine was stopped immediately.

No. 178. New specimens were run on rings B-27 and B-24. The rings were smoothed with #280 and #400 alundum paper. The speed was increased to 295 ft/min and the load was lowered to 300 lbs/in^2. The following runs through 181 were made under these conditions. After the run the specimens were slightly ridged and the edges were turned. The rings were very smooth and almost mirror bright.

No. 179. 180. 181. The specimens and rings looked the same as after run # 178.

Run No. 182. The same specimens and rings were used. The load
183. was increased to 450 lbs/in^2. After the run the specimens
were slightly ridged and turned at the edges. The rings
were very smooth.

No. 184. New specimens were used on the same rings. #400
185. alundum paper was used on the rings. This made them less
186. smooth, but made them more uniform. The laod was 200 lbs/
in^2. Runs #184 through #188 were made under these conditions.
After runs #184, 185, and 186 the specimens were very,
very slightly ridged and the edges were turned. The rings
wefe very smooth.

No. 187. The specimens looked the same. The rings were very,
188. very smooth and dimly mirror bright.

No. 189. New specimens were used on the same rings. The load
was reduced to 96 lbs./in^2. These conditions were maintained in the following runs through #193. After run #189
the specimens were very, very slightly ridged, and their
surfaces were darked by what appeared to be a film.

No. 190. The specimens and rings after these runs looked about
191. the same as after #189. After runs #192 and #193 the rings
192. were somewhat smoother.
193.

No. 194. New specimens were run on the same rings. The latter
195. were smoothed before the run with #280 alundum paper. The
speed was still 295 ft/min. and the load was 450 lbs/in^2.
These conditions were maintained through run #198. After
run #194 the rings were very smooth ,although not as smooth
as before the run. They were also somewhat galled. The
specimenswere slightly ridged and the edges were turned.
The ridges were worse than those at the lower pressures.
After run #195 the specimens and rings looked the same.

No. 196. New specimens were used on the same rings under the
197. same conditions. The rings were smoothed before the run
198. with #280 paper. After the runs the specimens were ridged
and the edges were turned. The rings were very slightly
galled.

Note. The rings were smoothed after run #195 on #400 alundum paper. They were very smooth and mirror bright after this procedure. Specimens were run under the conditions for this group of runs for 8000 revolutions, 5000 feet, with no loss in weight. The surfaces of the specimens appeared as though they had not been touched by the rings. Perhaps the smooth condition of the rings prevented metal to metal contact by maintaining a film of distillate between the surfaces. The rings were then smoothed with #280 paper and the wear of the specimens was high, as is shown in the data for runs #196 and #197. This again emphasizes the importance of the surface conditions on the wear.

Run No. 199. New specimens were run on the same rings at 393 ft/min
200. and at 300 lbs/in^2. After the runs the specimens were slight-
201. ly ridged and the edges were slightly turned. The rings
were galled **slightly.**

No. 202. New specimens were used on the same rings. The latter
203. were smoothed on #280 paper. The load was 200 lbs/in^2.
204. After these runs the specimens were slightly ridged and the
edges were slightly turned. The rings were very smooth.

No. 205. These runs were made at 393 ft/min. and at a load of
206. 300 lbs/in^2.New specimens were run on case hardened rings,
207. which were smoothed with #280 paper before the run. During
208. run #205 the friction moment was quite unsteady for parts
of the run. After the runs the specimens were smooth and
mirror bright. The rings were very slightly ridged. They
were very, very slightly galled but mirror bright.

No. 209. Runs #209 through #216 were run at a speed of 786 ft/min and at a load of 300 lbs/in^2. Runs 209 and 210 were made with Flint Alloy specimens wearing on one Flint Alloy ring and one B ring. The rings were new and they were smoothed before the run with #280 alundum paper. The specimens were also new. After run #209 both rings were ridged. Specimen FA-2 which wore on rin B-29 was badly galled. This ring was ridged worse than FA-1. Specimen FA-1 was slightly ridged. As can be seen from the data, FA-2 increased in weight during the run. Probably some of the B metal ring adhered to the specimen during the test. The system was quite warm after the run.

No. 210. This run was made under the same conditions as #209. Before this run ring FA-1 was smoothed with #280 paper. B-29 was replaced by B-26, which was also smoothed. Specimen FA-2 was also smoothed slightly with #280 paper.

After this run ring FA-1 was ridged and slightly galled. The specimens looked about the same as after run #209. During this run specimen FA-1 on ring FA-1 became warm. FA-2 on ring B-26 did not. Ring B-26 was very slightly ridged.

No. 211. Specimen FA-1 was replaced by B-18. FA-2 remained on B-26. The rings were smoothed with #280 paper before the run. Specimen B-18 had been run on stellite and was extremely smooth and mirror bright. After the run ring FA-1 looked about the same as when it was installed. The B ring was ridged. The B specimen was very slightly ridged and mirror bright. The FA specimen was slightly galled.

No. 212. The rings looked the same after this run. The B speci-
213. men was very slightly ridged, very very slightly galled, and
214. mirror bright. The FA specimen was galled.

Run No. 215. The FA ring looked about the same after this run. The B ring was gradually worn down during these runs and was ridged in the direction of wear. The B specimenwas smooth and looked about the same. The surface of specimen FA-2 was not good; it was galled and ridged.

No. 216. New nitrided specimens and rings were used. The rings were smoothed with #280 paper. The speed was 786 ft/min and the load was 300 lbs/in^2. Runs #216 to #226 were made under the same conditions. After this run the surfaces of the rings and specimens each looked the same. There was a dull central portion with brighter portions on the edge. The whole surface was a mirror.

No. 217. The surfaces looked about the same except the shiny areas were larger.

No. 218. The surfaces were streaked with dull and shiny areas. They were very smooth. There were small flaked places on the rings. The latter condition may be galling or due to the nitrided surface.

No. 219. The specimens and rings looked the same. The surface conditions were quite satisfactory.

No. 220. New B specimens were run on the same rings. After the run the specimens were not worn in. They were extremely bright and shiny where worn. B-29 had more shiny places than B-28 and was very slightly ridged. The rings looked about the same as after the previous runs.

No. 221 After this run the rings looked the same. The specimens were worn all over and were extremely well polished. B-29 was slightly ridged.

No. 222. The rings were slightly ridged and slightly galled. The appearance of galling may again be due to the nature of the nitrided surface. The specimens were mirror bright and very slightly ridged.

No. 223. 224. 225. New N specimens were run on B rings. The latter were smoothed with #280 paper. After the run the specimens were not worn in. They were slightly ridged and mirror bright where worn. The rings were very smooth, but ridged slightly.

No. 226. After this run the rings looked about the same. Specimen N-4 had galled. This again may be due to the fact that the nitrided surface is not very thick and with wear may become thin enough to flake off. Specimen N-3 looked the same as after previous runs, namely, slightly ridged and mirror bright.

ORIGINAL AND COMPUTED DATA

Run No.	Spec. No.	Ring No.	Load $\#/in^2$	Area $in.^2$	Speed Ft/min	Travel Feet	Wear Grams	Wear $Gms/in^2/ft$ $X10^{-8}$	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
12	B-9 B-10	B-3 B-4	1030	.206 .200	393	98000	.070 .016	350 82	.11	.10	.06
14	B-9 B-10	B-3 B-4	250	.206 .200	393	198000	.001 .002	2 5	.12	.07	.07
15	B-9 B-10	B-3 B-4	250	.206 .200	393	196000	.002 .001	5 3	.10	.09	.09
17	A-1 A-2	A-1 A-2	300	.210 .210	393	131000	.002 .006	7 22	.12	.10	.10
18	A-1 A-2	A-1 A-2	300	.210 .210	393	1020000	.010 .010	4.7 4.7	.10	.03	.03
19	A-1 A-1	A-1 A-1	300	.210 .210	393	660000	.002 .003	1 2	.11	.02	.02
20	A-1 A-2	A-1 A-2	300	.210 .210	393	654000	.001 .003	0.8 2	.10	.002	.002
21	B-11 B-12	A-1 A-2	300	.210 .210	393	2000000	.001 .002	0.2 0.5	.10	.00-	.00-
22	B-11 B-12	A-1 A-2	300	.210 .210	393	2780000	.001 .001	0.2 0.2	.10	.00-	.00-
23	B-11 B-12	A-1 A-2	600	.210 .210	393	1970000	.001 .002	0.2 0.5	.08	.00-	.00-
24	B-11 B-12	A-1 A-2	600	.210 .210	393	1960000	.004 .006	1 1	.06	.00-	.00-

Run No.	Spec. No.	Ring No.	Load $\#/in^2$	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear $Gms/in^2/ft$ $\times 10^{-8}$		Coefficient of Friction Start	End	Low
25	B-11 B-12	A-1 A-2	600	.210 .210	393	1980000	.002 .003	0.5 0.7		.09	.02	.02
16	C-1 C-2	A-1 A-2	300	.171 .166	393	9850	.389 .206	23100 12600		.22	.14	.14
26	A-3 A-4	A-1 A-4	300	.208 .210	393	35700	.013 .011	180 150	Dry test	.27	.37	.27
27	A-3 A-4	A-1 A-4	300	.208 .210	393	13100	.014 .038	510 1400	Dry test	.31	.37	.31
28	B-13 B-14	B-5 B-6	700±	.179 .179	393	2620000	.005 .005	1 1		.07	.00-	.00-
29	B-13 B-14	B-5 B-6	700±	.179 .179	393	3980000	.001 .000	0.1 0		.08	.00-	.00-
30	B-13 B-14	B-5 B-6	700±	.179 .179	393	4050000	.000 .000	0 0		.02	.00-	.00-
31	WC-1 Wc-2	Wc-1 WC-2	400 600	.220 .220	393	1160000	.002 .002	0.8 0.8		.09	.00-	.00-
32	WC-1 WC-2	WC-1 WC-2	500±	.220 .220	393	1960000	.001 .001	0.2 0.2		.02	.00-	.00-
33	WC-1 WC-2	WC-1 WC-2	400±	.220 .220	393	1920000	.001 .001	0.2 0.2		.08	.00-	.00-
34	WC-1 WC-2	WC-1 WC-2	300 450±	.220 .220	786	1960000	.015 .007	3.5 1.7		.11	.02-	.00-

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^{2}ft X 10^{-8}	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
35	B-15 B-16	B-5 B-6	300	.177 .175	786	2040000	.0075 .0005	2.1 0.1	.07	.00-	.00-
36	B-15 B-16	B-5 B-6	300	.177 .175	786	1970000	.001 .0005	0.3 0.1	.06	.02	.02
37	ST-1 ST-2	ST-1 St-2	300	.181 .181	786	983000	.073 .0805	41 45	.19	.03	.03
38	ST-1 ST-2	ST-1 ST-2	300	.181 .181	786	985000	.123 .0635	69 36	.19	.03	.03
39	ST-3 ST-4	B-5 B-6	300	.177 .180	786	983000	.010 .009	5.7 5.1	.08	.02	.02
40	ST-3 ST-4	B-5 B-6	300	.177 .180	786	1000000	.004 .002	2.2 1.1	.09	.02	.02
41	ST-3 ST-4	B-5 B-6	300	.177 .180	786	995000	.002 .0015	1.1 0.8	.13	.00-	.00-
42	B-17 B-18	ST-3 ST-4	300 375	.179 .179	786	1010000	.0435 .004	24 2.2	.13	.00-	.00-
43	B-17 B-18	ST-3 ST-4	300	.179 .179	786	1090000	.045 .0015	2.3 0.8	.13	.00-	.00-
44	B-17 B-18	ST-3 ST-4	300	.179 .179	786	995000	.0045 .002	2.5 1.1	.08	.00-	.00-
45	WC-3 WC-4	B-7 B-8	500± 550±	.225 .225	786	3960000	.005 .002	0.6 0.2	.12	.00-	.00-

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft X10-8	Coefficient of Friction Start	End	Low
46	WC-3 WC-4	B-7 B-8	375± 425±	.225 .225	786	3940000	.001 .0005	0.1 0.06	.05	.00-	.00-
47	WC-3 WC-4	B-7 B-8	375± 425±	.225 .225	786	3940000	.001 .0005	0.1 0.06	.04	.00-	.00-
48	B-19 B-20	B-7 B-8	300 High	.178 .178	1180	321000	.016 .001	28 1.7	.08	.05	.05
49	B-19 B-20	B-7 B-8	300 600±	.178 .178	1180	1310000	.009 .002	3.9 0.9	.08	.02	.02
50	B-19 B-20	B-7, B-8	300 600±	.178 .178	1180	1310000	.009 .002	3.9 0.9	.05	.00-	.00-
51	WC-5 WC-6	WC-3 WC-4	300	.224 .225	1180	655000	.006 .005	4.0 3.4	.09	05	.05
53	B-21 B-22	B-9 B-10	300	.177 .176	1180	1340000	.0075 .002	3.2 0.9	.11	.07	.07
54	B-21 B-22	B-9 B-10	300	.177 .176	1180	1310000	.005 .000	2.1 0	.10	.05	.05
55	B-21 B-22	B-9 B-10	300	.177 .176	1180	2620000	.0155 .000	3.3 0	.07	.02	.02
56	WC-7 WC-8	B-11 B-12	1200± 300	.225 .225	1180	3925000	.002 .0055	0.2 0.6	.09	.01	.01
57	WC-7 WC-8	B-11 B-12	375± 300	.225 .225	1180	3940000	.001 .009	0.1 1.0	.15	.02	.02

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear		Coefficient of Friction		
							Grams	Gms/in^2/ft X 10^{-8}	Start	End	Low
58	WC-9 WC-10	WC-5 WC-6	300	.209 .209	1180	657000	.003 .002	2.2 1.5	.09	.01	.01
59	WC*9 WC-10	Wc-5 WC-6	300	.209 .209	1180	692000	.001 .0003	0.7 0.2	.08	.00-	.00-
60	WC-9 WC-10	WC-5 WC-6	300	.209 .209	1180	1340000	.002 .0012	0.7 0.4	.10	.01	.01
61	B-23 B-24	WC-7 WC-8	300	.182 .182	1180	2620000	.004 .0025	0.8 0.5	.11	.02	.00-
63	WC-11 Wc-12	WC-9' WC-10	300	.228 .228	1180	676000	.002 .000	1.3 0	.11	.02	.02
64	WC-11 WC-12	WC-9 WC-10	300	.228 .228	1180	1336000	.0105 .0015	3.5 0.5	.09	.03	.03
65	C-3 C-4	B-17 B-18	600	.187 .187	197	3292	.510 .681	83000 111000	.19	.16	.16
66	C-3 C-4	B-17 B-18	600	.187 .187	197	672	.063 .085	50000 67500	.17	.17	.17
67	C-5 C-6	B-17 B-18	300	.187 .187	197	6560	.005 .005	406 406	.12	.07	.07
68	C-5 C-6	B-17 B-18	300	.187 .187	197	6550	.001 .001	82 82	.06	.06	.06
69	C-5 C-6	B-17 B-18	300	.187 .187	197	6540	.000 .000	0 0	.08	.08	.08

Run No.	Spec. No.	Ring No.	Load #/in²	Area in²	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in²/ft X 10^{-8}	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
70	C-5 C-6	B-17 B-18	300	.187 .187	197	13100	.000 .000	0 0	.09	.09	.09
71	C-7 C-8	B-17 B-18	300	.185 .185	393	3290	.202 .719	33200 118000	.10	.10	.10
72	C-7 C-8	B-17 B-18	300	.185 .185	393	1340	.201 .284	81000 115000	.12	.12	.12
73	C-9 C-10	B-17 B-18	300	.188 .188	393	1320	.195 .388	78600 156000	.13	.09	.09
74	C-9 C-10	B-17 B-18	300	.188 .188	393	1190	.163 .220	73000 98000	.13	.10	.10
75	C-11 C-12	B-17 B-18	300	.188 .188	393	1350	.337 .476	133000 188000	.09	.08	.08
76	C-11 C-12	B-17 B-18	300	.188 .188	393	1331	.299 .440	120000 176000	.09	.09	.09
77	C-17 C-18	B-17 B-18	96	.380 .380	393	1310	.062 .069	12400 13800	.07	.09	.07
78	C-17 C-18	B-17 B-18	96	.380 .380	393	1310	.187 .165	37500 33000	.09	.09	.09
79	C-17 C-18	B-17 B-18	96	.380 .380	393	1330	.448 .390	89000 77000	.12	.12	.12
80	C-17 C-18	B-17 B-18	96	.380 .380	393	1310	.395 .396	79500 79600	.11	.11	.11

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft X 10^{-8}	Coefficient of Friction Start	End	Low
81	C-17 C-18	B-17 B-18	96	.380 .380	393	1340	.520 .479	102000 94000	.10	.12	.10
82	C-19 C-20	B-17 B-18	33	.381 .381	393	3330	.057 .044	4500 3500	.32	.23	.23
83	C-19 C-20	B-17 B-18	33	.381 .381	393	3220	.006 .003	490 240	.35	.32	.32
84	C-19 C-20	B-17 B-18	33	.381 .381	393	6570	.001 .000	40 0	.29	.29	.29
85	C-19 C-20	B-17 B-18	33	.381 .381	393	13800	.001 .0005	19 9.5	.20	.16	.16
86	C-19 C-20	B-17 B-18	33	.381 .381	786	3160	.000 .0255	0 2000	.38	.29	.29
87	C-19 C-20	B-17 B-18	33	.381 .381	786	9900	.0225 .014	580 370	.67	.45	.45
88	C-19 C-20	B-17 B-18	33	.381 .381	786	13600	.006 .007	115 135	.65	.42	.42
89	C-19 C-20	B-17 B-18	33	.381 ?381	786	14400	.0025 .002	45 36	.45	.45	.45
90	C-19 C-20	B-17 B-18	96	.381 .381	786	1330	.044 .051	8700 10000	.30	.18	.18
91	C-19 C-20	B-17 B-18	96	.381 .381	786	1490	.045 .038	7900 6900	.13	.13	.13

Run No.	Spec. No.	Ring No.	Load #/in2	Area in2	Speed Ft/min	Travel Feet	Wear		Coeffieient of Friction		
							Grams	Gms/in2/ft X 10^{-8}	Start	End	Low
92	C-19 C-20	B-17 B-18	70	.381 .381	786	3310	.010 .008	780 620	.21	.18	.18
93	C-19 C-20	B-17 B-18	70	.381 .381	786	6700	.019 .008	730 310	.21	.20	.20
94	C-19 C-20	B-17 B-18	70	.381 .381	786	6530	.0145 .014	570 550	.35	.16	.16
95	C-19 C-20	B-17 B-18	130	.381 .381	786	690	.3575 .350	135000 131000	.36	.36	.36
96	C-19 C-20	B-17 B-18	130	.381 .381	786	810	.226 .251	72000 80000	.36	.36	.36
97	C-19 C-20	B-17 B-18	130	.381 .381	786	604	.377 .359	161000 153000	.35	.35	.35
98	C-23 C-24	B-15 B-16	70	.382 .382	393	32700	.000 .001	0 8	.14	.13	.13
99	C-23 C-24	B-15 B-16	70	.382 .382	393	29500	.000 .0005	0 0.4	.14	.11	.11
100	C-23 C-24	B-15 B-16	96	.382 .382	393	6550	.000 .0015	0 60	.06	.10	.10
101	C-23 C-24	B-15 B-16	96	.382 .382	393	10060	.000 .000	0 0	.08	.07	07
102	C-23 C-24	B-15 B-16	150	.382 .382	393	6370	.000 .001	0 40	.08	.08	.08

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft X 10^{-8}	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
103	C-23 C-24	B-15 B-16	150	.382 .382	393	6570	.449 1.787	17900 71100	.09	.19	.09
104	C-23 C-24	B-15 B-16	150	.382 .382	393	678	.322 .182	124000 70300	.14	.14	.14
105	C-23 C-24	B-15 B-16	150	.382 .382	393	695	.222 .179	80000 67500	.14	.14	.14
106	C-23 C-24	B-15 B-16	150	.382 .382	393	658	.245 .198	97500 78800	.14	.14	.14
107	C-23 C-24	B-15' B-16	200	.382 .382	393	653	.356 .292	143000 117000	.13	.13	.13
108	C-23 C-24	B-15 B-16	200	.382 .382	393	653	.347 .298	139000 119000	.13	.13	.13
109	G-1 G-2	B-15 B-16	300	.234 .234	1180	632	.706 6525	478000 441000	.27	.27	.27
110	G-3 G-4	B-13 B-14	155	.235 .235	1180	1515	.158 .097	44300 27200	.31	.37	.31
111	G-5 G-6	B-13 B-14	155	.234 .234	786	743	.582 .532	335000 306000	.12	.12	.12
112	G-7 G-8	B-19 B-20	155	.234 .234	786	678	.275 .2535	173500 160000	.12	.12	.12
113	G-7 G-8	B-19 B-20	155	.234 .234	786	683	.259 .233	162500 146000	.11	.11	.11

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
								X 10^{-8}			
114	G-7 G-8	B-19 B-20	155	.234 .234	786	696	.295 .270	181000 166000	.11	.11	.11
115	G-9 G-10	F-1 F-2	155	.234 .234	786	665	.2755 .0795	177000 51100	.10	.10	.10
116	G-9 G-10	F-1 F-2	155	.234 .234	786	734	.410 .1405	239000 81700	.10	.12	.10
117	G-9 G-10	F-1 F-2	155	.234 .234	786	746	.486 .1425	278000 81600	.10	.11	.10
118	G-11 G-12	F-3 F-4	155	.232 .233	786	703	.307 .256	188000 155500	.11	.11	.11
119	G-11 G-12	F-3 F-4	155	.232 .233	786	671	.252 .2235	161600 142000	.11	.11	.11
120	G-11 G-12	F-3 F-4	155	.232 .233	786	675	.310 .2545	198000 160800	.11	.11	.11
121	G-13 G-14	E-1 E-2	155	.234 .232	786	683	.132 .176	82500 111000	.09	.09	.09
122	G-13 G-14	E-1 E-2	155	.234 .232	786	705	.188 .221	114000 137300	.09	.09	.09
123	G-13 G-14	E-1 E-2	155	.234 .232	786	734	.153 .230	89000 135200	.09	.09	.09
124	G-15 G-16	E-3 E-4	155	.234 .234	786	671	.191 .224	121600 142600	.11	.11	.11

Run	Spec.	Ring	Load	Area	Speed	Travel	Wear		Coefficient of Friction		
No.	No.	No.	#/in^2	in^2	Ft/min	Feet	Grams	Gms/in^2/ft	Start	End	Low
								X 10^{-8}			
125	G-15 G-16	E-3 E-4	155	.234 .234	786	721	.215 .256	127600 152000	.10	.10	.10
126	G-15 G-16	E-3 E-4	155	.234 .234	786	716	.238 .253	142000 151000	.09	.10	.09
127	E-3 E-4	B-21 B-22	300	.234 .231	786	5860	.076 .054	5530 3940	.15	.06	.06
128	E-3 E-4	B-21 B-22	300	.234 .231	786	6580	.007 .011	455 715	.14	.04	.04
129	E-3 E-4	B-21 B-22	300	.234 .231	786	6650	.0655 .0395	4210 2540	.21	.08	.08
130	E-3 E-4	B-21 B-22	300	.234 .231	786	6600	.002 .0015	131 99	.08	.08	.08
131	E-5 E-6	B-21 B-22	300	.234 .234	786	6710	.055 .038	3500 2420	.23	.07	.07
132	E-5 E-6	B-21 B-22	300	.234 .234	786	6540	.0005 .0545	33 3560	.16	.07	.07
133	E-5 E-6	B-21 B-22	300	.234 .234	786	6470	.0065 .0095	429 627	.07	.07	.07
134	E-5 E-6	B-21 B-22	300	.234 .234	786	6600	.000 .0415	0 2690	.18	.09	.09
135	F-1 F-2	B-13 B-14	300	.234 .234	786	13100	.0035 .006	114 196	.08	.05	.05

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear		Coefficient of Friction		
							Grams	Gms/in^2/ft	Start	End	Low
								X 10^{-8}			
136	F-1 F-2	B-13 B-14	300	.234 .234	786	32800	.0005 .0005	6 6	.07	.06	.06
137	F-1 F-2	B-13 B-14	300	.234 .234	786	131000	.000 .000	0 0	.06	.02	.02
138	F-1 F-2	B-13 B-14	300	.234 .234	786	621000	.000 .009	0 6	.05	.02	.02
139	E-7 E-8	B-13 B-14	300	.234 .234	786	16370	.005 .006	131 157	.08	.05	.05
140	E-7 E-8	B-13 B-14	300	.234 .234	786	16370	.005 .0345	131 900	.10	.05	.05
141	E-7 E-8	B-13 B-14	300	.234 .234	786	16410	.0055 .137	143 3560	.14	.05	.05
142	C-13 C-15	B-23 B-24	400	.187 .188	197	987	.0005 .204	271 110500	.10	.10	.10
143	C-13 C-15	B-23 B-24	400	.187 .188	197	690	.001 .153	775 118500	.07	.07	.07
144	C-13 C-15	B-23 B-24	400	.187 .188	197	705	.108 .133	81900 101000	.12	.11	.11
145	C-13 C-15	B-23 B24	400	.187 .188	197	643	.129 .1365	108200 113000	.12	.12	.12
146	C-13 C-15	B-23 B-24	400	.187 .188	197	661	.1375 .1275	111000 103000	.08	.10	.08

Run No.	Spec. No.	Ring No.	Load #/in²	Area in²	Speed Ft/min	Travel Feet	Wear		Coefficient of Friction		
							Grams	Gms/in²/ft X 10^{-8}	Start	End	Low
147	C-13 C-15	B-23 B-24	500	.187 .188	197	674	.1545 .140	123000 111000	.14	.14	.14
148	C-13 C-15	B-23 B-24	500	.187 .188	197	656	.150 .121	122000 93600	.14	.14	.14
149	C-13 C-15	B-23 B-24	500	.187 .188	197	649	.114 .091	85700 75000	.12	.12	.12
150	C-13 C-15	B-23 B-24	500	.187 .188	197	680	.084 .050	66000 39400	.14	.12	.12
151	C-13 C-15	B-23 B-24	600	.187 .188	197	705	.067 .020	50800 15200	.15	.13	.13
152	C-13 C-15	B-23 B-24	600	.187 .188	197	684	.055 .012	43000 9380	.14	.11	.11
153	C-13 C-15	B-23 B-24	600	.187 .188	197	1300	.0255 .0005	10680 206	.11	.10	.10
154	C-13 C-15	B-23 B-24	600	.187 .188	197	3260	.0155 .000	2620 0	.09	.08	.08
155	CH-1 Ch-2	CH-1 CH-2	300	.186 .186	786	6610	.0127 .0195	1030 1582	.24	.04	.04
156	CH-1 CH-2	CH-1 CH-2	300	.186 .186	786	13100	.007 .0015	283 62	.24	.06	.06
157	CH-1 CH-1	CH-1 CH-1	300	.186 .186	786	20900	.0055 .0035	141 90	.30	.04	.04

Run No.	Spec. No.	Ring No.	Load $\#/in^2$	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	 Gms/in²/ft X 10^{-8}	Coefficient of Friction Start	 End	 Low
158	CH-1 CH-2	CH-1 CH-2	300	.186 .186	786	20100	.002 .003	53 80	.26	.04	.04
159	CH-1 CH-2	CH-1 CH-2	300	.186 .186	786	19600	.0005 .0015	14 41	.13	.07	.07
160	CH-1 CH-2	CH-1 CH-2	300	.186 .186	786	39300	.001 .006	14 82	.16	.00-	.00-
161	CH-1 CH-2	CH-1 CH-2	300	.186 .186	786	39300	.0005 .003	7 41	.00-	.00-	.00-
162	CH-3 CH-4	B-25 B-26	300	.186 .186	786	6500	.0055 .002	455 105	.06	.03	.03
163	CH-3 CH-4	B-25 B-26	300	.186 .186	786	32700	.001 .0005	16 8	.06	.00-	.00-
164	CH-3 CH-4	B-25 B-26	300	.186 .186	786	65400	.0005 .0005	4 4	.06	.00-	.00-
165	CH-3 CH-4	B-25 B-26	300	.186 .186	786	5700000	.0004 .0005	0.04 0.05	.04	.00-	.00-
166	C-25 C-26	B-27 B-28	300	.383 .383	197	978	.2895 .234	77300 62500	.12	.09	.09
167	C-25 C-26	B-27 B-28	300	.383 .383	197	657	.1365 .1175	54200 46500	.10	.10	.10
168	C-25 C-26	B-27 B-28	300	.383 .383	197	653	.166 .135	66300 54000	.10	.10	.10

Run No.	Spec. No.	Ring No.	Load $\#/in^2$	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear $Gms/in^2/ft$ $X\ 10^{-8}$	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
169	C-25 C-26	B-27 B-28	300	.383 .383	197	668	.1135 .095	44300 37100	.13	.11	.11
170	C-25 C-26	B-27 B-28	300	.383 .383	197	1315	.189 .146	37500 29000	.12	.12	.12
171	C-25 C-26	B-27 B-28	300	.383 .383	197	1310	.151 .0535	30100 10660	.13	.11	.11
172	C-25 C-26	B-27 B-28	300	.383 .383	197	3270	.4155 .0003	33200 24	.10	.10	.10
173	C-27 C-28	B-27 B-28	300	.383 .383	197	13100	.1097 .1702	2170 3400	.14	.06	.06
174	C-27 C-28	B-27 B-28	300	.383 .383	197	19620	.023 .108	306 1441	.12	.05	.05
175	C-27 C-27	B-27 B-27	300	.383 .383	197	19620	.003 .0848	40 1130	.11	.06	.06
176	C-27 C-28	B-27 B-28	600	.383 .383	197	1352	.405 .399	78200 77000	.--	.14	
177	C-27 C-28	B-27 B-28	600	.383 .383	197	662	.298	90200	.12	.12	.12
178	C-29 C-30	B-27 B-24	300	.383 .383	295	1305	.728 .760	145600 152000	.13	.11	.11
179	C-29 C-30	B-27 B-24	300	.383 .383	295	656	.329 325	131000 129500	.13	.11	.11

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear		Coefficient of Friction		
							Grams	Gms/in^2/ft	Start	End	Low
								X 10^{-8}			
180	C-29 C-30	B-27 B-24	300	.383 .383	295	654	.251 .319	100300 127500	.12	.12	.12
181	C-29 C-30	B-27 B-24	300	.383 .383	295	658	.2625 .351	112500 139500	.13	.11	.11
182	C-29 C-30	B-27 B-24	450	.383 .383	295	556	.474 .633	220000 298000	.13	.11	.11
183	C-29 C-30	B-27 B-24	450	.383 .383	295	677	.661 .840	256000 320000	.13	.11	.11
184	C-31 C-32	B-27 B-24	200	.383 .383	295	1320	.1585 .3695	31000 73000	.15	.11	.11
185	C-31 C-32	B-27 B-24	200	.383 .383	295	1310	.180 .3115	36000 62000	.11	.11	.11
186	C-31 C-32	B-27 B-24	200	.383 .383	295	1320	.306 .424	60400 83700	.14	.11	.11
187	C-31 C-32	B-27 B-24	200	.383 .383	295	1330	.360 .391	70500 76500	.14	.11	.11
188	C-31 C-32	B-27 B-24	200	.383 .383	295	1330	.292 .369	57300 72500	.14	.12	.12
189	C-33 C-34	B-27 B-24	96	.383 .383	295	6530	.0913 .036	3650 1440	.11	.03	.03
190	C-33 C-34	B-27 B-24	96	.383 .383	295	6540	.0037 .010	148 400	.08	.03	.03

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft X 10^{-8}	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
191	C-33 C-34	B-27 B-24	96	.383 .383	295	6540	.0005 .0002	20 8	.05	.03	.03
192	C-33 C-34	B-27 B-24	96	.383 .383	295	26200	.0055 .0018	55 18	.06	.03	.03
193	C-33 C-34	B-27 B-24	96	.383 .383	295	26350	.0015 .000	15 0	.05	.02	.02
194	C-37 C-38	B-27 B-24	450	.383 .383	295	705	1.367 1.501	520000 570000	.13	.11	.11
195	C-37 C-38	B-27 B-24	450	.383 .383	295	635	1.036 1.201	437000 508000	.13	.13	.13
196	C-39 C-40	B-27 B-24	450	.383 .383	295	441	1.106 .745	670000 453000	.13	.13	.13
197	C-39 C-40	B-27 B-24	450	.383 .383	295	807	1.068 .781	354000 259000	.13	.13	.13
198	C-39 C-40	B-27 B-24	450	.383 .383	295	660	.834 .674	338000 275000	.11	.11	.11
199	C-41 C-42	B-27 B-24	300	.383 .383	393	711	1.198 .997	451000 376000	.13	.13	.13
200	C-41 C-42	B-27 B-24	300	.383 .383	393	776	1.037 .964	357000 332000	.13	.13	.13
201	C-41 C-42	B-27 B-24	300	.383 .383	393	790	1.283 1.149	436000 390000	.12	.12	.12

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
								X 10^{-8}			
202	C-43 C-44	B-27 B-24	200	.383 .383	393	821	.738 .566	241000 185000	.14	.12	.12
203	C-43 C-44	B-27 B-24	200	.383 .383	393	709	.661 .589	250000 223000	.13	.13	.13
204	C-43 C-44	B-27 B-24	200	.383 .383	393	699	.551 .542	211000 208000	.12	.12	.12
205	B-26 B-26	CH-1 CH-2	300	.187 .187	786	20200	.002 .0015	54 40	.09	.06	.06
206	B-25 B-26	CH-1 CH-2	300	.187 .187	786	131000	.0015 .0008	6.1 3.3	.12	.02	.02
207	B-25 B-26	CH-1 CH-2	300	.187 .187	786	805000	.002 .0017	1.3 1.1	.09	.03	.03
208	B-25 B-26	CH-1 CH-2	300	.187 .187	786	1012000	.0035 .0005	1.8 .3	.11	.03	.03
209	FA-1 FA-2	FA-1 B-29	300	.187 .187	786	17700	.5035 -.0015	15200	.13	.19	.13
210	FA-1 FA-2	FA-1 B-29	300	.187 .187	786	2850	.078 .000	14700	.200	.19	.19
211	B-18 FA-2	FA-1 B-26	300	.179 .187	786	55700	.004 .0035	40 34	.10	.01	.01
212	B-18 FA-2	FA-1 B-26	300	.179 .187	786	124100	.0025 .000	11	.11	.04	.04

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Gms.in^2/ft X 10^{-8}	Coefficient of Friction Start	End	Low
213	B-18 FA-2	FA-1 B-26	300	.179 .187	786	167200	.0015 .000	5	.05	.02	.02
214	B-18 FA-2	FA-1 B-26	300	.179 .187	786	831000	.001 .000	0.7	.07	.00-	.00-
215	B-18 FA-2	FA-1 B-26	300	.179 .187	786	1800000	.002 .0035	0.6 *	.09	.00-	.00-
216	N-1 N-2	N-1 N-2	300	.188 .188	786	295000	.002 .002	3.6 3.6	.08	.00-	.00-
217	N-1 N-2	N-1 N-2	300	.188 .188	786	852000	.0015 .000	0.9 0	.00-		
218	N-1 N-2	N-1 N-2	300	.188 .188	786	1120000	.0145 .004	6.9 1.9	.06	.00-	.00-
219	N-1 N-2	N-1 n-2	300	.188 .188	786	946000	.004 .004	2.2 2.2	.04	.00-	.00-
220	B-28 B-29	N-1 N-2	300	.234 .234	786	1278000	.001 .003	0.3 1.0	.05	.00-	.00-
221	B-28 B-29	N-1 N-2	300	.234 .234	786	3130000	.003 .001	0.4 0.1	.04	.00-	.00-
222	B-28 B-29	N-1 N-2	300	.234 .234	786	3320000	.001 .0025	0.1 0.3	.02	.00-	.00-

* Wear of FA-2 on B-26 is based on the sum of runs 212, 213, 214, and 215
Travel was 2922300 feet Wear value is 0.64

Run No.	Spec. No.	Ring No.	Load #/in^2	Area in^2	Speed Ft/min	Travel Feet	Wear Grams	Wear Gms/in^2/ft	Coefficient of Friction Start	Coefficient of Friction End	Coefficient of Friction Low
								X 10^{-8}			
223	N-3	B-23	300	.188	786	92600^0	.011	6.3	.25	.00-	.00-
	N-4	B-25		.188			.008	4.6			
224	N-3	B-23	300	.188	786	1800000	.0145	4.3	.12	.00-	.00-
	N-4	B-25		.188			.0005	0.2			
225	N-3	B-23	300	.188	786	2295000	.0025	0.6	.12	.00-	.00-
	N-4	B-25		.188			.0025	0.6			
226	N-3	B-23	300	.188	786	2530000	.0025	0.5	.10	.00-	.00-
	N-4	B-25		.188			.004	0.8			

Xray Investigation

From the "Strukturbericht" by P.P. Ewald and C. Herman, the crystal structure of Fe-α, Fe_3C, FeO, Fe_2O_3, and Fe_3O_4 were found.

Alpha iron, Fe-α, is of the A-2 type, which is a body centered cubic lattice. The length of one side of the unit cube is 2.86 angstroms. For a cubic crystal the interplaner distance is given by the following relation:;

$$d_{hkl} = \frac{a_w}{\sqrt{h^2+k^2+l^2}}$$

where h, k, and l are the indices of the planes, and a_w is the length of one side of the unit cube.

For a body centered cubic lattice, planes with $h_1+h_2+h_3$ odd do not appear.

The angle of reflection is related to the wave length of the xray and the interplaner distance by the relation, $n\lambda = 2d\sin\theta$. If a circular film is used having a radius R, the angle θ times R is equal to the distance to a reflection from the spot at which the xray beam hits the film with no interference. By measuring the film distance, it is a simple matter to determine the interplaner distance of the planes causing the reflection. By comparing these values of d_{hkl} with those computed for various values of h, k, and l from the first relation given above, it is possible to identify the reflections.

Tables have been made up which give the values of $Q = 1/d^2$ for all planes which can reflect up to angles of about $\theta = 45^\circ$. The values for Q were determined by the use of the "International Tables for the Determination of Crystal Structures", Berlin 1935, Vol. II.

Cementite, Fe_3C, is an orthorhombic crystal. $a=4.52\text{Å}$, $b=5.08\text{Å}$, and $c=6.73\text{Å}$. Only the length of the lattice constants are known for this compound. Therefore, the values of Q for all planes were calculated. The value of Q is determined from the lattice constants and values for h, k, and l by the following relation:

$$Q = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}$$

FeO is a face-centered cubic crystal of the B-1 type. $a_w = 4.28\text{ Å}$ In a face centered cubic lattice only those planes in which h, k, and l are all odd or all even will appear.

Fe_2O_3 is a hexagonal crystal of the D-54 type. $a = 5.42\text{ Å}$ and $\alpha = 55^\circ 17'$. When calculated on the basis of rhombohedral axes, the relation is as follows:

$$Q = \frac{\cos^2\frac{\alpha}{2}}{a^2\sin\frac{\alpha}{2}\sin\frac{3\alpha}{2}}\left[(h^2+k^2+l^2)-(1-tg^2\frac{\alpha}{2})(kl+lh+hk)\right]$$

Fe_3O_4 is a face-centered cubic crystal of the H-11 type. $a_w = 8.4$ Å

Values of Q have been calculated for all reflecting planes up to values of θ equal to about 45°. These have been listed in a table which appears on the following pages. The indices of the plane are given and the value of Q for the plane is also given, in order of increasing values of Q. This table gives all planes which might possibly appear. All will not appear, however, due to differences in intensities of the different planes. Only strong lines will appear on the film.

Three pictures were taken of WC-11. This was a white cast iron wear specimen. On one surface a layer of worked material was found as described in the thesis. WC-11-1 and WC-11-3 were taken with the Mo-Kα xray beam directed at the layer. The beam hit the layer with a glancing angle of about 5 or 10°. WC-11-2 was taken in the same way on the back of the specimen, where there was no worked material. The measurements and calculated values for Q as determined from the films are given in the table. By comparing the values of Q as determined by the film measurements with those calculated from the lattice constants, the reflecting planes were identified. The reflections were broad and not very strong so that the accuracy is not too good. The table shows that practically all lines are without a doubt due to Fe_3C or Fe-α, which agrees with the conclusions of the metallographic investigation.

Table of Values of Q

(calculated from the lattice constants)

Fe_3C		Fe-α		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
001	0.0221								
010	0.0387								
						111	0.04252		
				111	0.0477				
100	0.0489								
						200	0.05669		
				100	0.0581				
011	0.0608								
101	0.0710								
				110	0.0741				
110	0.0876								
002	0.0883								
111	0.1097								
						220	0.11338		
012	0.1270								
102	0.1372								
				211	0.1377				
020	0.1550								
						311	0.15589		
				$1\bar{1}0$	0.1582				
								111	0.16377
						222	0.17007		
112	0.1759								
021	0.1771								
				221	0.1855				
				222	0.1910				
200	0.1957								
003	0.1987								
120	0.2039								
				210	0.2060				
				$1\bar{1}\bar{1}$	0.2162				
201	0.2178								
								200	0.21836
121	0.2260								
						400	0.22675		
				200	0.2325				
210	0.2344								
013	0.2374								
022	0.2433								
		110	0.2445						
103	0.2476								
211	0.2565								
						331	0.26927		
						420	0.28344		

Fe_3C		Fe-α		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
202	0.2840								
113	0.2863								
122	0.2922								
				220	0.2960				
				322	0.3125				
212	0.3227								
						422	0.34013		
				311	0.3435				
030	0.3487								
220	0.3507								
004	0.3532								
023	0.3537								
031	0.3708								
221	0.3728								
				$\bar{2}10$	0.3745				
						511	0.38265		
						333	0.38265		
				$2\bar{1}1$	0.3905				
014	0.3919								
				$33\bar{2}$	0.3925				
203	0.3944								
130	0.3976								
104	0.4021								
123	0.4026								
131	0.4197								
				333	0.430				
213	0.4331								
								220	0.43673
032	0.4370								
222	0.4390								
300	0.4404								
114	0.4428								
						440	0.45352		
				310	0.454				
301	0.4625								
				331	0.471				
				$\bar{2}11$	0.4755				
310	0.4791								
132	0.4859								
		200	0.4890						
						531	0.49604		
311	0.5012								
				320	0.5015				
024	0.5082								
						600	0.51021		
						442	0.51021		
				300	0.5225				
				$22\bar{1}$	0.5225				

Fe_3C		Fe-α		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
302	0.5287								
230	0.5444								
033	0.5474								
204	0.5489								
223	0.5494			422	0.5505				
005	0.5520								
231	0.5665								
						620	0.56689		
312	0.5674								
				433	0.584				
				432	0.588				
015	0.5907								
320	0.5954								
133	0.5963								
								311	0.6005
105	0.6009								
				533	0.60941				
040	0.6100								
				622	0.62358				
041	0.6321								
232	0.6327								
				$2\bar{2}0$	0.633				
303	0.6391								
115	0.6396								
								222	0.65509
140	0.6589								
				330	0.666				
				411	0.666				
313	0.6778								
				421	0.680				
						444	0.68028		
141	0.6810			$3\bar{1}1$	0.681				
322	0.6837								
214	0.6876								
				$\bar{2}21$	0.692				
				443	0.695				
042	0.6983								
034	0.7019								
224	0.7039								
025	0.7070								
				$\bar{3}10$	0.707				
				$\underline{43}1$	0.709				
				321-	0.7125				
321	0.7175								
		211	0.7335			551	0.7228		
						711	0.7228		
						640	0.73697		
				442	0.7415				
233	0.7431								
142	0.7472								
205	0.7477								

Fe_3C		Fe-α		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
134	0.7508								
125	0.7559								
400	0.7830								
215	0.7864								
330	0.7891								
304	0.7936								
						642	0.79366		
323	0.7941								
006	0.7948								
401	0.8051								
240	0.8057								
043	0.8087								
331	0.8112								
				410	0.817				
410	0.8217								
				420	0.824				
				655	0.826				
241	0.8278								
314	0.8323								
016	0.8335								
						731	0.83618		
						553	0.83618		
106	0.8437								
411	0.8438								
				$\bar{3}11$	0.850				
				533	0.853				
143	0.8576								
				$\overline{22}2$	0.866				
402	0.8713								
								400	0.87346
332	0.8774								
116	0.8826								
242	0.8940								
234	0.8976								
				532	0.900				
035	0.9007								
225	0.9027								
				522	0.904				
				441	0.904				
						800	0.90703		
412	0.9100								
				543	0.9225				
				400	0.929				
				430	0.946				
324	0.9486								
						733	0.94955		
139	0.9496								
026	0.9498								
				544	0.950				

Fe_3C		Fe-α		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
421	0.9601								
044	0.9632								
						820	0.96372		
						644	0.96372		
				$3\bar{2}1$	0.966				
050	0.9688								
		220	0.9779						
				$33\bar{1}$	0.978				
403	0.9817								
333	0.9878								
206	0.9905								
051	0.9909								
305	0.9924								
126	0.9987								
243	1.0044								
				$\underline{6}65$	1.007				
				$\bar{3}20$	1.009				
				542	1.012				
144	1.0121								
150	1.0177								
413	1.0204					822	1.02039		
						660	1.02039		
				521	1.025				
422	1.0263								
216	1.0292								
								331	1.0372
151	1.0398								
				$\bar{3}21$	1.050				
340	1.0504								
052	1.0571								
						751	1.06291		
						555	1.06291		
				531	1.063				
341	1.0727								
						662	1.07708		
007	1.0819								
				$4\bar{1}1$	1.088				
								420	1.0918
				$5\underline{5}4$	1.093				
				410	1.100				
				511	1.104				
152	1.1060								
315	1.1311								
430	1.1317								
						840	1.13378		
				$42\bar{1}$	1.136				
404	1.1362								
342	1.1387								
				754	1.141				
334	1.1423								
226	1.1455								
431	1.1538								

Fe_3C		Fe-a		Fe_2O_3		Fe_3O_4		FeO	
hkl	Q	hkl	Q	hkl	Q	hkl	Q	hkl	Q
				$3\bar{2}2$	1.156				
244	1.1589								
250	1.1645								
053	1.1675								
414	1.1749								
						911	1.17630		
						753	1.17630		
251	1.1866								
153	1.2164								
				541	1.218				
				321	1.219				
432	1.2200								
		310	1.2224						
500	1.2234								
423	1.2367								
501	1.2455								
343	1.2491								
252	1.2528								
510	1.2621								
511	1.2842								
424	1.2912								
350	1.3092								
								422	1.31018
502	1.3117								
				$\bar{3}22$	1.328				
				411	1.341				
520	1.3784								
				$3\bar{3}0$	1.422				
				551	1.442				

Identification of Reflecting Planes

WC-11-3 (layer)

Line	x	Q	Refl. Plane
1	1.48	0.1752	Fe_3C 112
2	1.58	0.1968	Fe_3C 003
3	1.68	0.2232	Fe_3C 121
4	1.73 1.79)	0.2368 0.2536)(	Fe_3C 103,013, 022; Fe-α 110
5	1.91	0.2888	Fe_3C 113,122?
6??	2.00	0.3168	Fe_3C 212?
7	2.11	0.3528	Fe_3C 004
8	2.24	0.3944	Fe_3C 203
9	2.37	0.4416	Fe_3C 300,114
11	2.53	0.5000	Fe_3C 311
12?	2.70	0.5704	Fe_3C 312
13	2.95	0.6776	Fe_3C 313
14	3.14	0.7640	Fe_3C 125?
15	3.23	0.8040	Fe_3C 401
16	3.69	1.042	Fe_3C 151?

WC-11-1 (layer)

Line	x	Q	Refl. Plane
1	1.50	0.177	Fe_3C 021
2	1.59	0.200	Fe_3C 003
3	1.77	0.249	(Fe_3C 103 Fe-α 110
4	1.92	0.292	Fe_3C 122
5	2.12	0.354	Fe_3C 023
6	2.27	0.405	Fe_3C 123?
7	2.38	0.446	Fe_3C 114?
8	2.48	0.480	Fe_3C 310?
9	2.56?	0.512	Fe_3O_4 600?
10	2.62	0.537	Fe_3C ?
11	2.74??	0.583	Fe_2O_3 433?
12	3.15	0.769	Fe_3C 125?
13	3.24	0.809	Fe_3C 043
14	3.74	1.071	Fe_3C 341

WC-11-2 (back)

Line	x	Q	Refl. Plane
1	1.50	0.1776	Fe_3C 021
2	1.59	0.1992	Fe_3C 003
2a	1.68?	0.2232	Fe_3C 121
3	1.73 1.79)	0.2368 0.2536)	(Fe_3C 013,103 022; Fe-α 110
4	1.94	0.2976	?
5	2.14	0.3592	Fe_3C 023?
6?	2.20	0.3800	?
7?	2.27	0.4048	Fe_3C 123?
8	2.38	0.4456	Fe_3C 114?
9	2.49 2.54)	0.4880 0.5080)(	Fe_3C 311 Fe-α 200
10?	2.68	0.5616	?
11	3.09 3.14)	0.7392 0.7632)(	Fe-α 211, Fe_3C ?
12	3.26	0.8192	Fe_3C 410? Fe_2O_3 410?
13	3.62	1.002	Fe_3C 243 Fe-α 220?

Original and Computed Data on Scratch Investigation

Run No.	Date	Spec. No.	Etch	Load gms.	Voltage volts	Instrument Reading Max.	Instrument Reading Min.	Instrument Reading Aver.	Aver. Force gms.	Width of Scratch Max.	Width of Scratch Min.	Width of Scratch Aver.	Average Microns	Energy* gm.cm./cm.^{3}
53	5-21-35	Armco	4%Nitric in Amyl. alcohol 15 sec.	2.7	113.5	9	0	6	0.06			1.05	8.4	8.5
				6.0	113.5	100	0	20	0.30			1.10	8.8	39.5
				9.5	113.5	300	180	200	2.25			1.29	10.3	236
				12.9	113.5	600	480	500	4.70			1.57	12.6	316
				16.3	113.8	680	680	680	5.95			1.85	14.8	270
54	5-22-35	Brass	10% H_2O_2 in NH_4OH 10 sec.	2.7	113	12	2	7	0.07			1.26	10	8.4
				6.0		75	0	10±	0.10			1.13	9.0	20.8
				9.5	114	200	80	120	1.50			1.40	11.2	123
				12.9	114	350	280	300	3.15			1.70	13.6	170
				16.3	114	570	530	550	5.10			2.28	18.2	155
55	5-23-35	B-4	4%Nitric in Amyl alcohol 30 sec.	6.0	112.5	5	0	0.5	0.005					
				9.5	112.3	8	0	2	0.02					
				12.9	112.2	120	30	60	0.90			0.48	3.8	473
				16.3	112.0	200	130	160	1.90			0.72	5.8	546
				19.7	112.3	280	180	220	2.40			0.98	7.8	608
				23.1	112.5	690	670	680	5.95			1.16	9.3	620
56	5-24-35	C-14	" 10 sec.	6.0	114.0	30	0	10	0.10			1.10	8.8	20.4
				9.5	114.4	200	30	100	1.32			0.94	7.5	220
				12.9	114.4	350	100	200	2.25			1.11	8.9	285
				16.3	114.2	450	200	280	2.95			1.25	10.0	295
				19.7	114.5	500	350	400	3.95			1.33	10.6	324
				23.1	114.0	750	750	750	6.20			1.54	12.3	420
57	5-24-35	WC-13	" 30 sec.	9.5	113.8	100	0	40	0.60	0.99	0.45	0.72	5.8	178
				12.9	114.0	140	80	100	1.32	1.15	0.50	0.83	6.6	270
				16.3	113.5	250	150	200	2.25	1.21	0.50	0.85	6.8	396
				19.7	114.5	300	250	280	2.95	1.32	0.91	1.11	8.9	522
				23.1	115.0	760	760	760	6.25	1.44	1.04	1.24	9.9	638

Run No.	Date	Spec. No.	Etch	Load gms.	Voltage volts	Instrument Reading Max.	Instrument Reading Min.	Instrument Reading Aver.	Aver. Force gms.	Width of Scratch Max.	Width of Scratch Min.	Width of Scratch Aver.	Average Microns	Energy* gm.cm./cm.^{3}
58	5-25-35	N-2	4%Nitric in Amyl alcohol 30 sec.	9.5	114.5	8	2	3	0.03			0.67	5.4	10.3
				12.9	114.5	95	30	40	0.60			0.73	5.8	178
				16.3	114.8	180	130	150	1.82			0.86	6.9	368
				19.7	114.0	320	250	280	2.95			0.99	7.9	578
				23.1	114.0	780	750	770	6.30			1.07	8.6	953
59	5-25-35	CH-6	"	9.5	114.0	100	0	10	0.10			0.89	7.1	19.8
				12.9	113.8	200	140	150	1.82			1.04	8.3	258
				16.3	113.6	270	240	250	2.70			1.66	11.3	215
				19.7	113.5	350	330	340	3.46			2.00	16.0	150
				23.1	114.0	770	750	760	6.30			2.41	19.3	165
				9.5	114.0	10	0	1	0.001			1.05	8.4	
				16.3	113.7			100	1.32			1.00	8.0	
60	5-25-35	A-5	4%Nitric in Amyl alcohol 30 sec.	9.5	114.2	100	0	20±	0.30	0.95	0.37	0.66	5.3	114
				12.9	114.4	200	50	100	1.32	1.06	0.44	0.75	6.0	236
				16.3	114.1	180	140	160	1.90	1.16	0.68	0.92	7.4	374
				19.7	114.0	280	250	260	2.76			1.03	8.2	530
				23.1	114.5	740	600	650	5.77			1.17	9.4	652
61	5-25-35	St-4	10%NaOH,10%HCl electrolytic	9.5	112.5	2	0	0.5±	0.005			0.70	5.6	1.6
				12.9	112.5	5	0	3	0.03			0.85	6.8	7.2
				16.3	112.5	120	40	60	0.88			0.88	7.0	149
				19.7	112.5	270	180	200	2.25			1.09	8.7	304
				23.1	112.5	700	600	650	5.77			1.21	9.7	613

* In calculating the energy required to scratch, the values of force and width used in the formula, $E = F/W2$, were taken from the curves in Figures 11 and 12, respectively.

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