SURFACE FATIGUE OF SOFT STEEL

by

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and

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PART I

INTRODUCTION

The problem of surface fatigue has come into prominence in the present generation because of the ever increasing use of machinery. In every machine, parts are subjected to wear, and because of this wear, failure will ultimately occur in some form. It is therefore of great importance in building machinery to know what properties a machine part subjected to wear should have in order to minimize replacement and to obtain maximum life.

Consequently the problem of surface fatigue has become one of the important research problems of today. In writing this report on the surface endurance of soft steel we hope to aid in its solution.

The problem was first appreciated in 1922 when a special research committee of the A.S.M.E. started an investigation of the surface wear phenomena resulting from the engagement of two surfaces in rolling contact.

In 1932 the attention of this committee was focused on the endurance limit of materials. Professor Buckingham of the Massachusetts Institute of Technology was selected to take charge of the investigation. In order to further the investigation the testing machine used in these tests was designed by Professor Buckingham to determine the endurance limit of two surfaces engaged in either rolling or or sliding contact.

Mr. Guy Talbourdet who has done some very interesting and enlightening research work on the surface endurance limit of materials in various conditions of heat treatment and chemical composition has arrived at some very interesting conclusions. In order to show what has been done before along this line, we present the following conclusions which were derived by his efforts:-

1. That the influence of eccentric cylinders is negligible and does not affect the surface endurance limit of the materials.

2. That the effect of the rapidity of the repeated cycles for the range of R.P.M. does not influence the surface endurance limit of the cylinders in contact.

3. That the logarithmic plotting of the applied load vs. the number of repeated cycles required to cause failure of the surfaces in contact is the most favorable method of plotting because it makes it possible to plot on the chart, both the small and large values of the repeated cycles with the same degree of accuracy. Furthermore it indicates clearly because of the well defined shift line joining the plotted values, when the endurance limit is reached. When the endurance limit is reached, the plotted line becomes horizontal or approaches an asymptote.

The test specimens run under rolling contact used in in our tests were:-

1. Soft steel--heat treated.
2. Soft Steel--as cast.

DEFINITION OF TERMS

In order that this report may be clearly understood it is necessary to define some of the terms to be used in the following discussions.

When two cylindrical surfaces engage in rolling contact under pressure a form of failure called "pitting" occurs. This is a shearing out of small particles of metal from the surface as a result of compressive stresses, set up within the specimen. In the case of the soft steel rollers used in these tests "microscopic pitting" first occurred and then the pits increased in size until complete failure of the surface occurred when large particles of metal sheared out of the surface.

Because of the loading on a specimen, compressive stresses were set up, reaching a maximum value at some point beneath the surface, this point being called the "point of maximum compressive stress". A safe or "working compressive stress" then will be any stress less than the value of the maximum compressive stress causing failure of the surface.

Initial or "microscopic pitting" was found to form circumferential bands, usually near the edge of the specimen, and having a grayish appearance. These bands are called "ghost lines" and generally indicate the probable area of failure.

In some of the tests longitudinal "bands" or "waves" were noticed. These are probably due to the plastic flow of the metal near the surface of contact.

In plotting the load per inch of width of specimen against the number of cycles required to produce failure the curves were observed to approach asymptotically a load value below which the specimens would run indefinitely without surface failure occurring. This load value is called the "endurance limit" of the particular steel tested.

OUTLINE OF THEORY AND EQUATIONS

The problem of determining the stresses set up when two elastic bodies come in contact has long been recognized as an important and difficult one. Its importance has increased during the past few decades because of the increase in use of machinery involving parts rolling together under pressures. Considerable attention has been given to this subject by industrial firms manufacturing ball and roller bearings and wheels for street and railway cars with the result that empirical formulas have been developed which in general apply only to particular cases.

The attempt to solve the question has brought forth four distinct theories applicable to the conditions under which failure will occur in a body in which stress components are acting in more than one direction. These four theories may be outlined briefly as follows:

1. The Rankine theory of maximum stress, the most common theory assumes that failure will occur in a body when a stress is set up which exceeds the yield point of the particular material for that type of stress with no regard to the other types of stress existing at a given point at the same time.

2. The Saint Venant theory of maximum strain assumes that failure occurs because of the maximum deformation occurring from stresses acting at a point in the body.

3. The Coulomb theory of maximum shear stress assumes that failure will occur on some oblique plane along which the shear stress exceeds the shearing strength of the material.

4. The Mohr theory is based on the mathematical proof, that in any body subjected to stresses at right angles to each other failure will occur along a plane of maximum shearing stress, which plane makes an angle of forty-five degrees with the other two planes of stress.

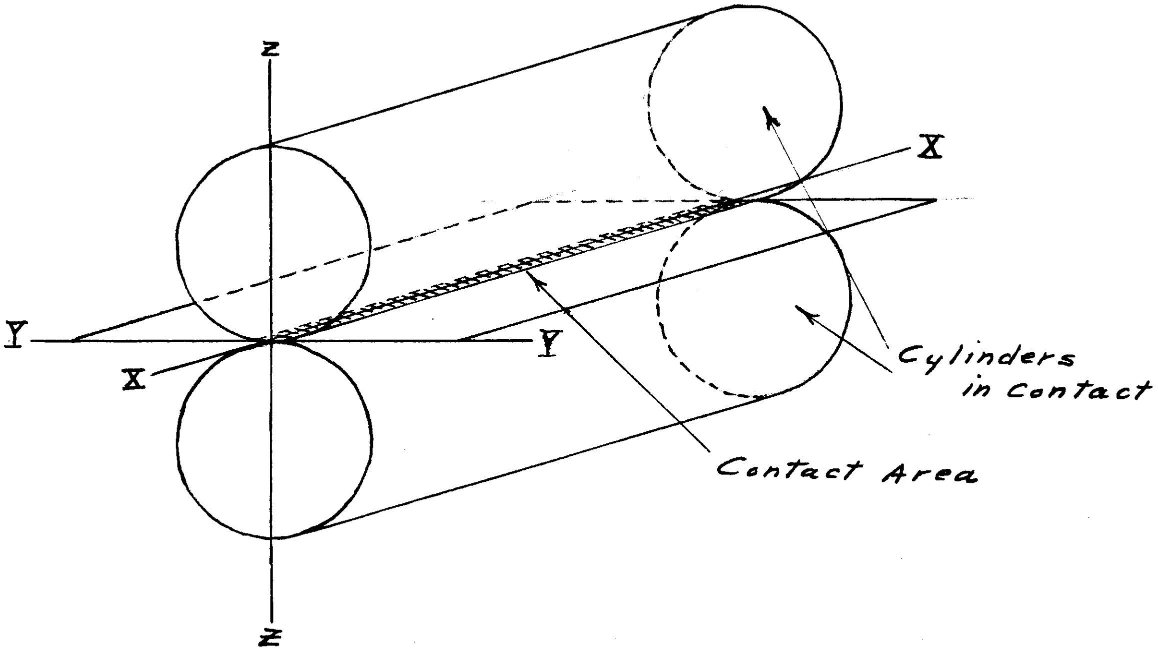
The first and second theories have been found to apply with sufficient accuracy only where the stress is almost entirely in one direction, while the fourth theory is merely an extended development of the third and had been found to give the highest degree of accuracy in the mathematical evaluation of stresses in bodies in contact. The discussions and calculations in this paper are all based on the maximum shear theory.

Winkler and Grashof were probably the first two men to attack this problem mathematically but they either arrived at approximate solutions or were forced to use some unknown empirical formula. However, in 1881, H. Hertz published a paper "On the Contact of Elastic Solids" and the following year brought out an extension of his studies in a paper entitled "On the Contact of Rigid Elastic Solids and on Hardness." Hertz's analysis has been the basis of solution of all such problems and has been developed by various mathematicians and adapted to numerous special cases.

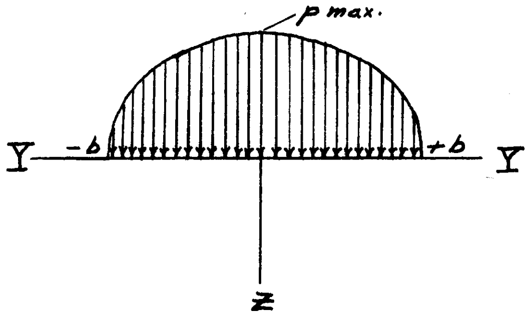
It is not the intention of the authors of this paper to attempt any mathematical derivation of the Hertzian equations for the case of two cylinders in rolling contact, but merely to outline very sketchily the theory involved and to present working formulae applicable to the particular tests made. These working formulae have been derived by numerous mathematicians and are generally accepted with various assumptions.

Two bodies are first considered to be in contact at a single point or line and then as pressure is applied contact occurs over a small area, called the area of contact. The Hertzian theory of stresses set up in two cylindrical bodies in contact is based on three assumptions; (1) the contacting bodies are perfectly elastic, (2) There are no shear stresses in the contact area, and (3) the radii of curvature of the two bodies are large in comparison with the dimensions of the area of contact.

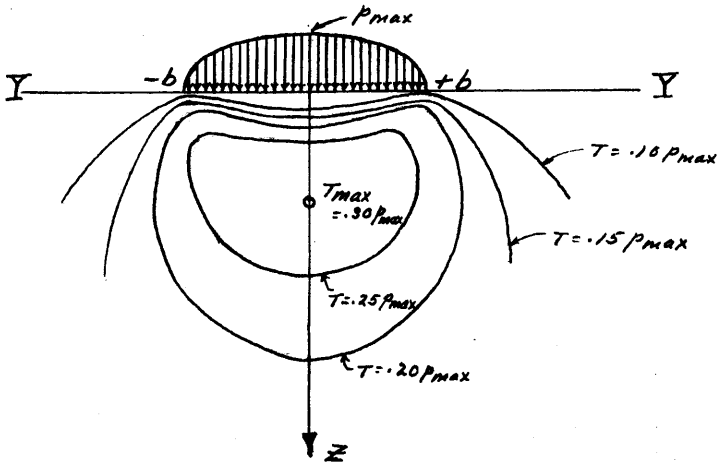
Assuming the two bodies to be perfectly elastic the area of contact will be in a plane $\overline{XY}$ perpendicular to a plane passing thru the longitudinal axes of the two cylinders, as shown in the figure below.



The stress concentrated over the area of contact may be expressed diagrammatically as below:



The principal stresses occurring beneath the area of contact have been determined from derivations of the general expressions of Hertz. Curves of principal stress have been plotted and confirmed by photoelastic pictures of bakelite cylinders in contact. Such curves of principal stress take the form indicated in the following diagram.



The maximum shear stress will then occur at a point beneath the area of contact. The depth of this point has been derived from the Hertzian Equations by Thomas and Hoersch in their paper on "Stresses Due to the Pressure of One Elastic Solid upon Another" for two steel cylinders in contact, and is given by the expression $z = 0.7861b$ where b is one half the width of the area of contact. This expression has been used by other experimenters as a means of determining the depth of the point of maximum shear stress in somewhat similar tests. However, this expression is derived under static conditions with no tangential thrust at the surface of the cylinders. It is the opinion of the authors of this paper that when the two cylinders engage in rolling contact the influence of this tangential thrust should not be neglected, and if taken into consideration will be found to exert considerable influence upon the depth of the point of maximum shear stress. In test 103HT the depth of the large sheared out section was measured and found to be 0.025" deep. The calculated depth of maximum shear stress was found to be 0.013". It is believed then that if the tangential thrust had entered into the calculations the theoretical depth of maximum shear stress would have approximated much more closely the depth of the actual sheared out section. As the derivation of such an expression would involve considerable time and study it has not been possible to present it in this paper due to the limitation of time, and the length of time spent in making the tests.

Mr. Guy Talbourdet, in performing similar tests at an earlier date, evaluated the general expressions of Hertz for this particular case. He used the following notations:

R_1 - R_2 = radii of the two cylinders in contact (in inches).

$2b$ = width of the area of contact (in inches).

L = length of the area of contact (in inches).

A = area of the area of contact (in sq. inches).

E_1 - E_2 = modulii of elasticity of the two cylinders in contact (in lbs. per sq. inch).

P = applied load (in lbs.).

S = maximum specific compressive stress (in lbs. per sq. inch).

S_A = average compressive stress (in lbs. per sq. inch).

The equations then become

$$b = 1.075 \frac{P\left(\frac{I}{E_1} + \frac{1}{E_2}\right)}{L\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

$$S = \frac{.35P\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}{L\left(\frac{1}{E_1} + \frac{1}{E_2}\right)}$$

$$A = 2b \times L$$

$$S_A = \frac{P}{A}$$

In all calculations the modulus of elasticity of steel was taken as 30,000,000 lbs. per sq. inch and, as the width of the face of the specimen was one inch in each case, L became unity.

The following set of sample calculations illustrates the above equations.

Test No. 103HT

$$b = 1.075 \sqrt{\frac{4750 \left(\frac{1}{30 \times 10^6} + \frac{1}{30 \times 10^6} \right)}{\left(\frac{1}{1.15} + \frac{1}{1.75} \right)}}$$

$b = .0159$ inches

width of area of contact = $2b = .0159 \times 2 = .0318$ in.

area of contact between roll and disk = A

$$= 2b \times L = .0318 \times 1 = .0318 \text{ sq. inches}$$

Average compressive stress = S_A

$$= \frac{P}{A} = \frac{4750}{.0318} = 149000 \text{ lbs./sq. in.}$$

Maximum specific compressive stress = S

$$= \sqrt{\frac{(.35)(4750)\left(\frac{1}{1.15} + \frac{1}{1.75} \right)}{\left(\frac{1}{30 \times 10^6} + \frac{1}{30 \times 10^6} \right)}}$$

= 189,700 lbs. per sq. in.

Depth of the point of maximum shearing stress

$$= 0.7861b = (0.7861)\left(\frac{.0319}{2}\right)$$

$$= 0.0125 \text{ inches}$$

PART II

DESCRIPTION OF TESTING MACHINE

The testing machine was designed by Professor Buckingham of the Massachusetts Institute of Technology in order to further the investigation of surface wear carried on by a special research committee on gears of the A.S.M.E. The machine is designed to run two cylindrical specimens together under different loads and at different rates of rotation and to test them thereby under either rolling or sliding contact. Tests may be made under rolling contact by having the same relation between the numbers of teeth on the two spur gears and the diameters of the disks. Tests under sliding contact may be made by having different ratios between the diameters of the disks.

The machine consists of a cast iron base, two jaws, a helical spring and dial gage, two shafts geared together, a dynamometer used as a driving motor, a torque balance and scale, and a lubrication system.

There are two jaws of "z" metal, one fixed and one movable, each of which supports a shaft. The fixed jaw is bolted to the frame and contains at opposite sides a plain bronze bearing used to support a shaft. The movable jaw is pivoted on an axle so that it may be swung toward and away from the fixed jaw. There are two plain bronze bushings in this jaw at opposite sides which support a second shaft.

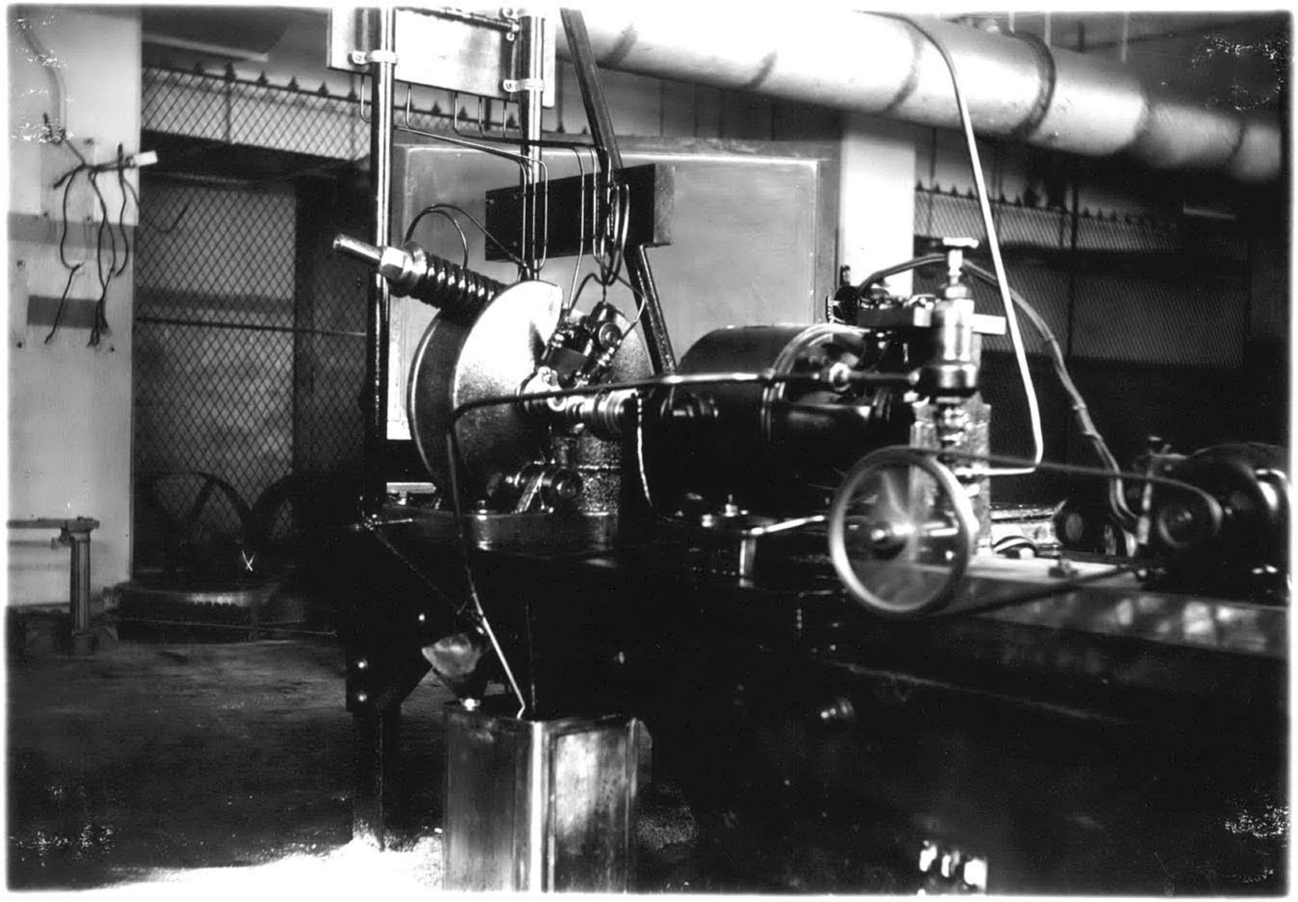
A helical spring, surrounding a threaded bar, fixed into the stationary jaw, passes through an opening in the movable jaw so that by screwing down a nut with a graduated dial on the free end of the bar the spring is compressed and the jaws are brought closer together.

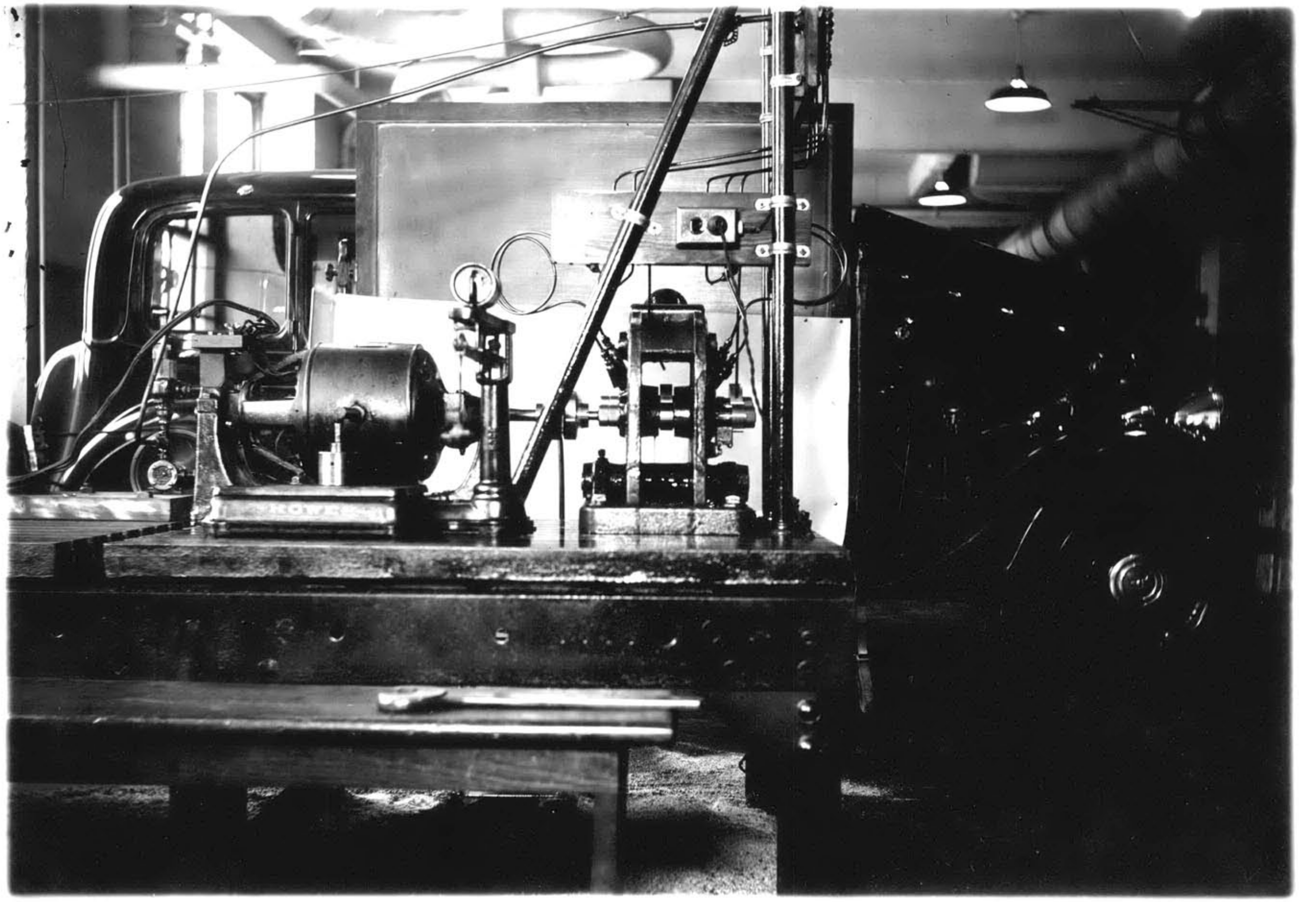
The fixed jaw contains a shaft coupled to a Sprague one horse power motor and has keyed on to it, between the jaws, a hardened steel roll and outside of the jaws, a fibre gear. This fibre gear meshes with a spur gear keyed at the extreme end of a shaft running in bronze bushings in the movable jaw. A specimen may be keyed on the second shaft between jaws so that its peripheral surface is in direct alignment with that of the steel roll contained between the fixed jaws. When the helical spring is compressed, the jaws carrying the two shafts are brought together so that the two disks have a load applied to them and may be run in contact with or without slipping under different loads and different rates of rotation.

The number of revolutions made by each shaft is automatically recorded on separate counters driven by a worm gearing having a ratio of twenty to one.

The driving motor is used as a dynamometer to measure the torque between the rolls, the torque being measured by a small balance scale mounted beside the motor.

Lubrication between the rolls for gearing and for bearings is supplied through a copper tubing by a rotary pump driven by a small motor. This pump supplies a small tank containing a pressure guage. The oil flows from this tank under a slight pressure and gravity thru copper tubing to the parts which require lubrication.

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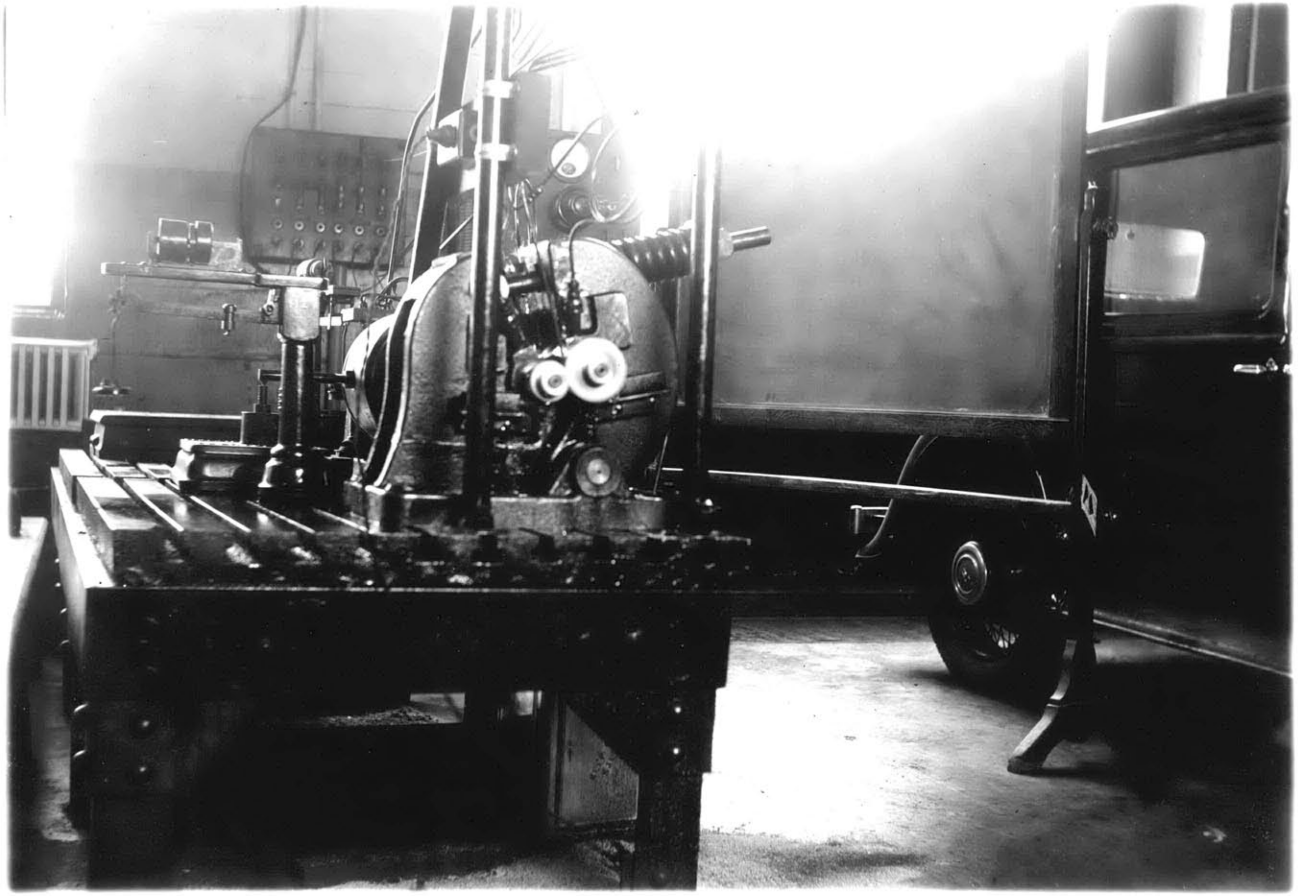


METHOD OF TESTING

The test is made by running a soft steel specimen against a hardened steel roll at a specific load and speed. After the steel specimen is keyed on a shaft between movable jaws and the shaft is installed in the machine, the zero reading on the spring is made by use of a bar opened wide and the motor started up under no load. The load is put on after the bearings have warmed up by screwing down a specific number of turns, the dial and nut on the threaded helical spring bar. Readings of revolution counter and torque scale are made and the oil pressure is noted.

At intervals during the test the machine is stopped and the specimen is examined for failure. Revolution counter and scale readings are taken. All changes microscopically visible on the surface of the specimen are recorded on the data sheet and the machine is started up at the same speed and the previous load is again applied.

To detect failure of the surfaces two methods are used:

(1) The surfaces of the two cylinders are wiped over with the fingers in order to feel any particles of metal which may have become sheared out.

(2) The surface of the test roll is carefully

wiped off and then examined with a microscope for pitting or any other changes which may occur.

DESCRIPTION OF TESTS

In the first test, No. 102AR, the specimen, a .50 carbon steel disk, 3.5 inches in diameter, in the "as received" condition was run against a 1.05 carbon heat treated steel roll 2.3 inches in diameter. A load of 3500 lbs. was applied, setting up a maximum compressive stress of 162,800 lbs. per sq. inch, while running the specimen at a speed of 1000 revolutions per minute. A little microscopic pitting was first observed at the end of 100,400 cycles. From this point on the microscopic pitting increased until it became evenly distributed over the entire surface. At the end of 500,750 cycles a band of microscopic pits about 1/8"inch wide had formed around the entire circumference of the disk about 1/8" in from one edge. After another 100,000 cycles a very slight chipping or flaking was noted at the above mentioned edge. The surface had by this time become well polished. Circumferential bands of microscopic pits now began to appear near the opposite edge of the disk becoming quite noticeable at 1,000,000 cycles. From this point on, no change was noted up to 3,000,000 cycles with the exception of a slight increase in the size of the pits. It was felt that the applied load was either at or very close to the endurance limit of the material and it was decided to discontinue the test and to repeat it at a higher load.

In test no. 106 AR the same steel disk was then turned down to 3.200" diameter and run against the same hardened steel roll used in the previous test. A load of 4580 lbs. was applied setting up a maximum compressive stress of 189,700 lbs. per sq. inch. The test specimen was run at a speed of 1000 r.p.m.. At the end of 52,500 cycles microscopic pitting had become plainly visible to the eye, there being several small pits about 1/16" in diameter and one pit about 1/8" in diameter. At 511,000 cycles the specimen was taken out of the machine. The surface contained several large pits and transverse cracks running across the face of the specimen.

In test no. 107AR a new disk 3.5" in diameter of the same "as received steel" was run against the same hardened steel roll used in the two previous tests. The test specimen was run at a speed of 1000 r.p.m., and a load of 4750 lbs. was applied, setting up a maximum compressive stress of 189,700 lbs. per sq. inch. After running 63,400 revolutions, a slight microscopic pitting was observed on the surface and at the end of 495,000 cycles failure occurred. In this test failure was evidenced by one large pit, crater-like and V-shaped in appearance, measuring about

3/16" across the widest part. Examinations of the surface showed three ghost lines around the circumference and waves or bands across the face of the specimen. These waves were 1/8" wide, spaced quite evenly about 1/8" apart around the entire circumference and were curved in the direction of motion. The surface of the disk was measured and it was found to have flattened, increasing in width from 1.248" to 1.262."

Test n. 103HT was run with 3½ inch diameter, .20 carbon heat treated steel disk at 1000 revolutions per minute, under an applied load of 4750 lbs. which caused a maximum compressive stress of 189,700 lbs. per sq. inch while running against a 2.3" diameter hardened steel roll. At the end of 227,300 cycles an intermittent dotted line had appeared along the center of the face of the specimen and microscopic pitting had started. The microscopic pitting continued and at the end of 384,370 cycles, pits about 1/16" wide were visible with the naked eye. A concentration of three of these large pits occurred near one edge. After the elapse of 531,940 cycles the pits had become enlarged to such an extent that one pit was about 3/32" long. The pits occurred near one edge of the test specimen and the smaller pits streamed out in a line from the larger pits. This streaming out may have been caused by the adherence of material to the large pit after the material had become sheared out and compressed between the rolls. At this stage waves also were visible . A ghost line or series of gray spots was visible around the circumference of the specimen. There was no change visible in the surface until a small section was sheared out at the end of 739,050 cycles. A few small sections sheared out when the specimen passed through 130,000 more cycles. Failure was evidenced at the end of 950,170 cycles by the shearing out of several small sections and a large section.

The cold working phenomena was partially responsible for a 4oz. decrease in torque scale reading over the initial reading. In test no. 108HT a .50 carbon steel roll subjected to a load of 4000 lbs or a maximum compressive stress of 177,200 lbs. per square inch was run against the same 1.05 carbon heat treated steel roll as used in the previous tests. At the end of 67,950 cycles, using Dr. De Forests' method of ~~work~~ crack detection, no cracks were observed on the specimen. However, slight microscopic pitting caused a light abrasive action as indicated by small gray lines or scratches. After 405,730 cycles, a ghost line was visible near one edge and also an intermittent line of scratches entirely around the circumference near one edge. The occurrence of waves was noted at the end of about 240,000 more cycles. These waves were not visible at the end of 995,080 total cycles.

After the specimen was run to 1,205,850 total cycles the surface had a grayish appearance and the microscopic pitting was well distributed over the surface. Pitting had occurred near one edge. No other changes were noticed until the end of 2,320,310 cycles at about which time a small piece, 1/8" long and 1/16" wide, chipped off one edge. A peculiar wavy effect near one edge was noted at the end of 2,726,790 cycles. When approximately 2,000,000 more cycles had elapsed six or eight bands had appeared in a group at one section. The specimen was run up to 2,934,940 cycles without failure occurring, when the test was discontinued due to lack of time.

PART III

DISCUSSION

Because of the limited amount of time available for making the tests it will be necessary to continue this work over a much longer period before sufficient data can be obtained to enable the determination of the surface endurance limit of soft steel. It is not possible, therefore, to present a complete discussion at this time. However, the results obtained give comparative values and indicate the probable surface endurance limit of the steels tested.

The material of the test roll was subjected to compressive stresses due to the applied load. As the test roll was run against a hardened steel roll, plastic deformation which was more severe on the test specimen than on the hardened steel roll took place. It is believed that this plastic deformation causes a reorientation of the crystals in the plastic material in such a way as to offer the least resistance to the plastic flow of the metal between the rolls. As the crystals change their position from the unstressed state, corners of the crystals are broken off, causing the microscopic pitting of the surface. As long as plastic deformation takes place the crystals are elongated in the direction of the microscopic pits and the pits are filled in under the cold working of the material.

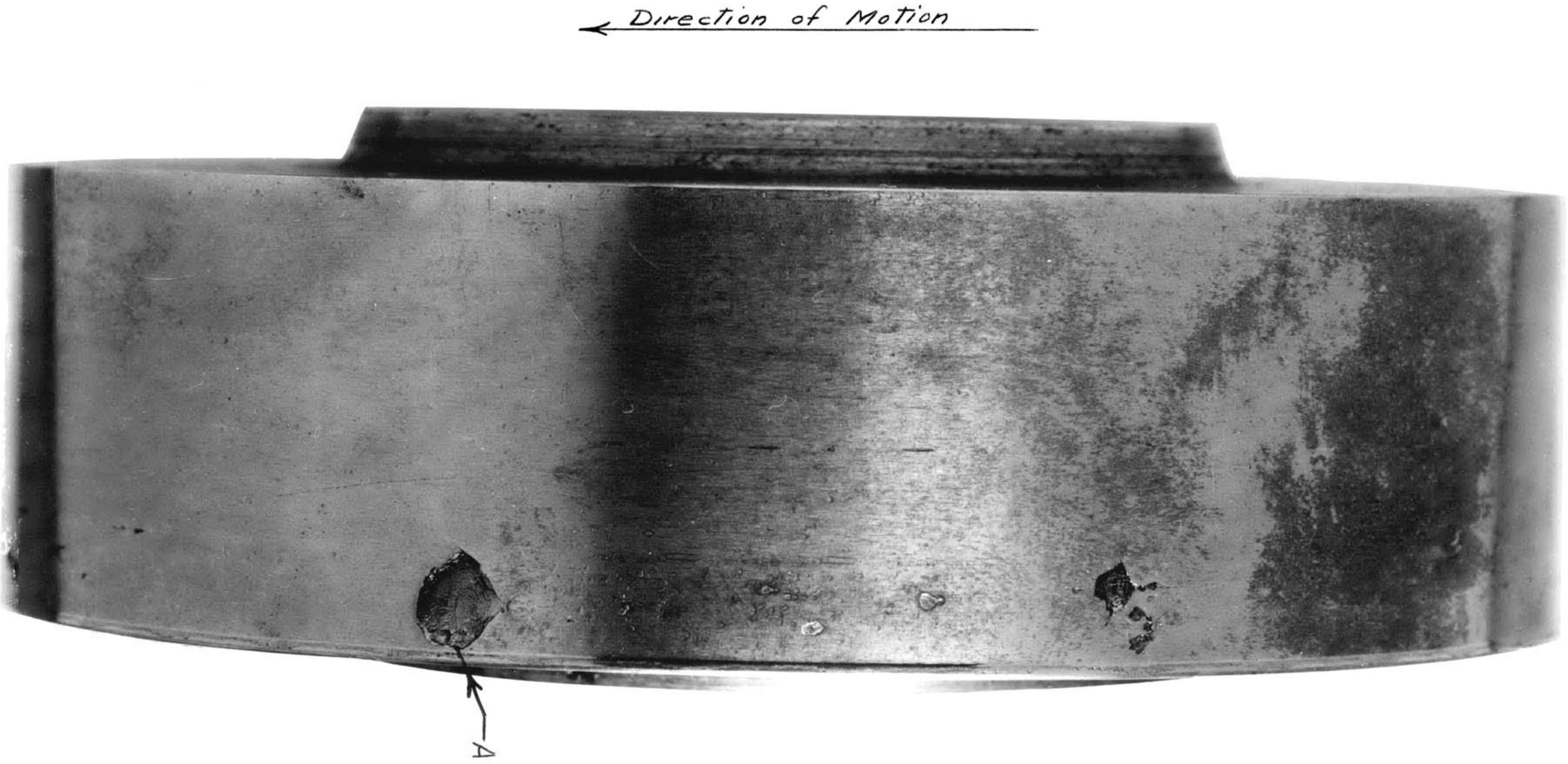
The plastic flow takes place in an outer ring of amorphous material in the surface of the specimen under rolling action. The outer ring of material is being continually pushed in the direction of rolling so that at some depth beneath the surface there must be a plane or planes of maximum slip. This plane of maximum slip is assumed to occur at the depth of maximum shear. A measure of the depth of maximum shear was obtained by measuring the thickness of the pit causing failure. Attempts to check the measured value by calculations derived from the Hertzian equations of plastic deformation proved unsuccessful. The reason the calculations did not check is thought to be due, as proved by photoelastic tests, to the omission of the torque between the rolls which occurs under actual running conditions. Hertz's equations hold true for static conditions but not for dynamic conditions. Photoelastic tests at the Massachusetts Institute of Technology have proved that materials subjected to torque and load were under a greater stress than those subjected to load only; the latter condition was assumed by Hertz in his derivations.

The surface material flows relatively to the material in the core in an outer band or ring around the circumference. The crystals are sheared or broken off from the core material along this cylindrical plane until a sufficient amount of amorphous material is formed between the sliding surfaces moving relatively to each other, to be squeezed out. As the amorphous metal is squeezed out, a crack will form beneath the surface. Since the crystal at which the crack takes place is no longer as strong as it was when supported by its neighbors, crystals in the vicinity of the crack spreads along the grain boundaries.

Under light loads if the crack takes place under a small group of crystals near the surface, the compressive force tends to shear it out leaving a small pit. Under heavy loads the crack may occur at such a depth beneath the surface that the compressive force is not enough to shear it out and the crack spreads beneath the surface. Under the repeated action of the compressive stress the crack will finally break through to the surface and produce a large pit.

A typical example of surface failure characteristic of soft steel may be seen in the accompanying photographs, which were taken at the end of test 103HT. The photographs show opposite sides of a specimen of .20 carbon heat treated steel. This disk was subjected to a load of

4750 lbs. The first indication of failure was observed at the end of 227,300 cycles, when a series of microscopic pits appeared on the surface. From this point on the pits increased both in number and size, (occurring in a group near one edge at the end of 384370 cycles). Close observation of the photographs will show groups of very small pits which result in larger more discernible pits. These larger pits likewise group together in twos and threes and are orientated in the direction of motion. The first large pit was noticed at the end of 390500 cycles. Service failure occurred at the end of 597610 cycles when a large section (marked A on photograph) sheared out. The section was fan shaped in appearance with the curved part of the fan in the direction of motion. This sheared out section demonstrates the four characteristic features of pits occurring in this type of material: (1) the boundary of the pit is composed roughly of two straight lines joined by a curved line forming a fan-shaped outline; (2) the pit extends in a nipple shaped extension at the vertex; (3) the pit is symmetrical about a circumferential line passing thru the vertex; (4) the bottom of the pit has a series of curved steps indicating a progressive fracture. These features



Test No. 103HT

Type HT steel - Applied load, 4750 lbs. - First large pit at the end of 390,500. cycles. - First sheared out section at the end of 597610 cycles Total cycles 808,730.

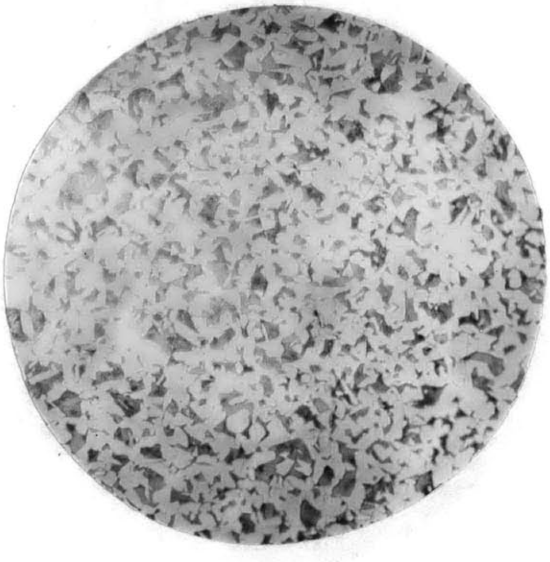
Test No. 103HT

Type HT steel - Applied load, 4750 lbs. - First large pit at the end of 390,500. cycles - First sheared out section at the end of 597610 cycles Total cycles 808,730.

are similar to those found by Stewart Way in somewhat similar tests.

An interesting phenomenon was the appearance of waves on the surface of a specimen of .50 carbon steel in the "as received" condition used in test no. 107AR. The waves were noticed at the end of 494700 cycles when failure occurred. These waves were curved across the face of the specimen, were 1/8" wide, and spaced evenly around the circumference 1/8" apart. The bands or waves appear to be caused by the displacement of the crystal layers. These crystal layers cause a rearrangement of the structure resulting in a finer grain. These waves seem to appear on a material of fine grain structure which follows the Slip Interference theory of hardening by a mechanical cold working. This theory assumes that cold working produces a structure similar to that of a very fine grained metal.

In the accompanying photomicrographs it can be seen that the .20 carbon steel type HT in the "as received" condition, (photograph No. 1) contains ferrite and pearlite in its structure and has evidently been annealed at the mill. The difference in the microstructure of this steel in the heat treated condition as compared with that in the "as received" condition may easily be observed.

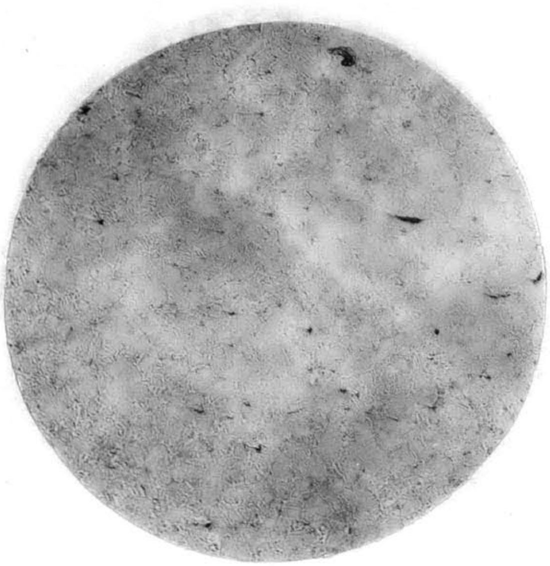


100X

Type HT Steel

As received

No. 1



100X

Type HT Steel

Heat treated

No, 2

100X

Type AR Steel

As received

No. 3

From photograph No. 2 it is apparent that the heat treatment has refined the grain structure probably resultin the formation of martensite since the Brinell hardness has been increased from 158 to 260.

From the third microphotograph of a .50 carbon steel in the "as received" condition it is evident that the structure is of sorbitic pearlite and ferrite and that it has likewise been annealed at the mill.

From our tests, although two steels of different composition were used it seems apparent that the effect of heat treating steel is to increase considerably its surface endurance. The effect of heat treatment on the material is comparable to the effect obtained by cold working, since in both cases the result obtained is an increase in hardness and it has been found in previous tests that a longer life results from an increasein hardness. This cold working action was observed to cause a reduction in torque scale reading. No exact analysis of the amount of cold working can be obtained ~~from~~ because of the friction of the bearings, friction in the gearing and friction between the rolls themselves.

Although the results plotted for the two types of steel will not bear much discussion and do not indicate definitely an Endurance Limit it seems apparent that the material will stand a maximum compressive stress somewhat above 163000 lbs. per sq. in.

CONCLUSIONS

It is apparent that considerable work must be done further in order to obtain sufficient information to determine the true surface endurance limit for types HT and AR soft steels. However, from the tests already made, the results indicate that for both steels the maximum allowable specific compressive stress lies somewhat above 163000 lbs. per sq. inch.

Although the two types of steel tested were of different chemical composition and physical properties, it is evident that heat treating the material is decidedly advantageous if the greatest surface wear resistance is desired. The tests indicated that the life of the heat treated steel was over twice that of the steel in the as received condition.

As in Nitralloy steels and cast iron materials, further tests will undoubtedly show that the grain structure, both of the core and the surface, as well as the hardness, exerts considerable influence upon the surface wear resistance of the material.

APPENDIX

CHEMICAL ANALYSIS OF TESTED STEELS

TYPE HT STEEL

Carbon	0.20
Manganese	1.05
Chromium	0.25
Silicon	0.10
Phosphorous	0.06
Sulphur	0.06
Nickel	0.41

TYPE AR STEEL

Carbon	0.45 - 0.55
Manganese	0.70 - 0.90
Chromium (residual)	0.15 max
Molybdenum	0.15 - 0.25
Phosphorous	0.045
Sulphur	0.08 - 0.11

PHYSICAL PROPERTIES OF TESTED STEELS

TYPE HT STEEL

As Received

Elastic Limit	36000 lbs/sq,in.
Yield Point	56200 lbs/sq,in.
Tensile Strength	86900 lbs/sq,in.
Elongation in 2"	31.2%
Reduction in area	63.8%
Hardness	158 BHN

Heat-Treated

Elastic Limit	95800 lbs/sq.in.
Yield Point	107700 lbs/sq.in.
Tensile Strength	123800 lbs/sq.in.
Elongation in 2"	21.7%
Reduction in area	58.8%
Hardness	260 BHN

TYPE AR STEEL

As Received

Elastic Limit	54500 lbs/sq.in.
Yield Point	78700 lbs/sq.in.
Tensile Strength	116800 lbs/sq.in.
Elongation in 2"	17.5%
Reduction in area	44.9%
Hardness	245 BHN

Test No. 102 AR

Material: 1.05 carbon heat treated steel roll 2.300" dia

0.50 carbon type AR steel disk 3.500" dia

zero reading at 0° mark

Load: 3500 lbs. = 8 turns + 135 divisions

R.P.M. Driv. Steel Roll	Rev. Counter Steel Roll	Torque Scale	Rev. Counter AR disk	Applied Load
1000	290306		416600	3500#
1000	305566	1# 15oz.	426640	3500#

Total revolutions of steel disk: 100400

Some microscopic pitting, no waves.

1400	320853	1# 14oz.	436667	3500#

Total revolutions of steel disk: 200670

Same microscopic pitting, no waves.

1550	336073	1# 14oz.	446669	3500#

Total revolutions of steel disk: 300690

Microscopic pitting increasing, evenly distributed.

1600	351292	1# 14oz.	456670	3500#

Increase in incipient pitting, pits slightly larger, no waves.

Total revolutions of steel disk: 400700

1800	366510	1# 14oz.	466670	3500#

Total revolutions of steel disk: 500700

A band of incipient pitting (about 1/8" wide) has formed around the entire circumference of the disk and about 1/8" in from one edge -- no waves.

1800 381729 1# 13oz. 476670 3500#

Total Revolutions of steel disk: 600700

The band of pitting is quite noticeable near the edge. Slight chipping or flaking near the same edge. Pitting now well distributed over entire surface. Surface well polished -- no waves.

1800 396962 1#13oz. 486682 3500#

Total revolutions of steel disk: 700820

No observable change.

1800 427272 1# 13oz. 506600 3500#

Total Revolutions of steel disk: 900000

The circumferential bands of pitting are plainly visible on the specimen. The pits are crater-like in shape. No bands have as yet been observable across the face of the specimen.

1800 457773 1# 12 oz. 526604 3500#

Total Revolutions of steel disk: 1,100,040

The band of pitting near the edge is widening. No sign of any bands across the face of the specimen. The surface does not seem to be as highly polished as on previous examinations. This is probably due to numerous pits which cut down the reflection of the light.

1800	503813	1# 12oz.	556898	3500#

Total revolutions of steel disk: 1,402,980

Increase in pitting. Circumferential band of of pits now appearing near the other edge of disk. Pits are slightly larger.

1800	549159	1# 12 oz.	586698	3500#

Total revolutions of steel disk: 1,700,980

Slight increase in concentration of pits.

1800	579446	1# 12oz.	606600	3500#

Total revolutions of steel disk: 1,900,000

A few ghost lines have now appeared.

1800	065949		926300	3500#
1800	143119	1# 13oz.	977013	3500#

Total Revolutions of steel disk: 2,407,130

Slight increase in size of pits. Pits in ghost line along edge have become noticeably enlarged and are located intermittently along this ghost line around the circumference.

1800	367899		124700	3500#
	376830		130570	3500#
1800	567564	1# 13oz.	253700	3500#
1800	648851	1# 13oz.	307117	3500#

Only light pitting over entire surface of steel disk at the end of 3,000,000 cycles.

No. of Rev. of AR steel disk: 3,000,000

No. of Rev. of hardened steel roll: 4,565,210

Tested Hardness of AR steel disk	Core 23-23-23 Rock "C" Bear. Surface 37-37-37 "

Test No. 103 HT

Material: 1.05 carbon heat treated steel roll 2.300" dia.

0.20 carbon type HT steel disk 3.500" dia

zero reading at 0° mark

Load: 4750 lbs. = 11 turns + 142 divisions

R.P.M. Driv. Steel Roll	R.E.V. Counter Steel Roll	Torque Scale	Rev. Counter HT disk	Applied Load
1000	928216		490700	
	941282	2# 7oz.	499286	4750#

Total revolutions of steel disk: 85,860

Sharp ridge appeared just inside the right hand edge.

1000	217819		668689	
	238812	1# 14oz.	682833	3000#

Total revolutions of steel disk: 227,300

Microscopic pitting and intermittent dotted line along center on specimen.

1000	435580		809519	
	4529-7	2# 1oz.	820912	4750#

Microscopic pitting well distributed over entire surface. A half dozen pits about 1/16" wide now observable without using the microscope. Three of these are bunched together near one edge.

1000	4753-4	2# 2oz.	835669	4750#

Total revolutions of steel disk: 531940

Pits have become considerably enlarged. One pit is about 3/32" long. Waves are visible. A series of gray spots have appeared also. The pits seem to be most prominent on the inside edge of the specimen. A series of smaller pits seem to string out from larger ones.

	491134	2# 2oz.	846025	3500#

Pits are growing larger. Five large pits on inside edge evenly spaced around circumference. Waves are still present.

1000	498888	2# 4oz.	851121	4750#

Total revolutions of steel disk: 684660

No change.

1000	722840		999037	
	731157	2# 4oz.	004476	4750#

Total revolutions of steel disk: 739050

The few large pits are increasing in size. One small section has sheared out.

1000	888926		098811	
	909330	2# 3oz.	112220	4750#

Pitting becoming quite noticeable over entire surface. A few very small sections have sheared out.

Total revolutions of steel disk: 873140

1000	909330	2# 3oz.	112220	
	921051	2# 3oz.	119923	4750#

Total revolutions of steel disk: 950170

Surface failed. Several small sections sheared and one large section. Depth of large section= 0.025"

Test No. 106 AR

Material: 1.05 carbon heat treated steel roll 2.300" dia
0.50 carbon type AR steel disk used in test #102
and turned down to 3.200" dia.

zero reading at zero mark

Load: 4580 lbs. = 11 turns + 62 divisions

R.P.M. Driv. Steel Roll	Rev. Counter Steel Roll	Torque Scale	Rev. Counter HT disk	Applied Load
1000	921051		119923	4580#
	928358	2# 6oz.	125174	4580#

Total revolutions of steel disk: 52,510

Microscopic pitting started. Pits are well distributed.

1000	342387		372831	4580#
	388945	2# 6oz.	405971	4580#

Total revolutions of steel disk: 383,910

Enlarged pitting. One large pit about 1/8" dia. Several small pits 1/16" dia.

1000	398779	2# 6oz.	412996	4580#
1000	406662	2# 6oz.	418677n	4580#

Total revolutions of steel disk: 510,970

Several large pits present. Cracks visible across face of specimen.

Test No. 1o7AR

Material: 1.05 carbon heat treated steel roll 2.300"dia
0.50 carbon type AR steel disk 3.500" dia
zero reading at 0° mark

Load: 4750 lbs. = 11 turns + 142 divisions

R.P.M. Driv. Steel Roll	Rev. Counter Steel Roll	Torque Scale	Rev. Counter AR disk	Applied Load
1000	410044	3# 12oz.	420646	4750#
1000	419688	2# 5oz.	426983	4750#

Total revolutions of steel disk: 63370

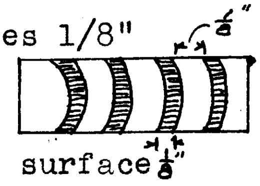
Slight microscopic pitting.

1000	790250	2# 8oz.	654100	4750#
1000	855890	1#13oz.	697233	4750#

Total revolutions of steel disk: 494700

Specimen failed, evidenced by one large pit.
Crater-like and V-shaped about 3/16" wide.

Three ghost lines show on specimen.
Waves all around circumference -- waves 1/8"
width and slightly curved as shown.



Surface flattened increasing width of surface
from 1.248" to 1.262".

Test 108HT

Material: 1.05 carbon heat treated steel roll 2.300" dia.
0.20 carbon type HT steel disk 3.500" dia.
zero reading at 0° mark

Load: 4000 lbs. = 10 turns + 106 divisions

R.P.M. Driv. Steel Roll	Rev. Counter Steel Roll	Torque Scale	Rev. Counter AR disk	Applied Load
1000	855890	1# 15oz.	697233	4000#
1000	866229	1# 15oz.	704028	4000#

Total revolutions of steel disk: 67950

No cracks detected on surface with Dr. De Forest's method. Slight microscopic pitting causing light abrasive action as shown by numerous gray lines or scratches.

1000	361853	2# 2oz.	010662	4000#
1000	413254	1#12oz.	044440	4000#

Total revolutions of steel disk: 405370

Ghost line quite noticeable near each edge - no waves - intermittent line of scratches entirely around circumference near right edge - scratches and spacings about 3/16" long.

1000	413254	1#12oz.	044440	4000#
1000	448730	1#12oz.	067752	4000#

Total revolutions of steel disk: 638850

Many waves are visible - pitting near each edge has become much larger - gray streaks are still visible -- two ghost lines are still there also.

1000	871264	2#13oz.	331305	4000#
1000	906934	2#	367928	4000#

Total revolutions of steel disk: 995080

Nothing now noticeable except a slight chipping near each edge -- no waves visible.

1000	000500		410228	4000#
1000	041774	1#13oz.	437305	4000#

Total revolutions of steel disk: 1,265,850

Surface has a very gray appearance, slight pitting near one edge.

1000	070000	1#13oz.	455893	4000#

Total revolutions of steel disk: 1,451,730

Microscopic pitting well distributed over entire surface.

1000	214523	1#13oz.	545732	4000#
1000	236650		560291	4000#

Total revolutions of steel disk: 1,597,320

No change.

1000	284853	2# 3oz.	587991	4000#
1000	369855	1#13oz.	643850	4000#

Total revolutions of steel disk: 2,155,910

One small pit near edge -- microscopic pitting well distributed over entire surface.

1000	448700	3# 2oz.	690552	4000#
1000	473756	3#	706992	4000#

Total revolutions of steel disk: 2,320,310

Small piece has chipped off of one edge, otherwise no change.

1000 491255 3# 718490 4000#

Total revolutions of steel disk: 2,435,290.

No change.

500 535583 2# 6oz. 747640 4000#

Total revolutions of steel disk: 2,726,790.

Peculiar wavy effect near one edge.

600 561800 2# 4oz. 764908 4000#

Total revolutions of steel disk: 2,899,470.

Six or eight bands have appeared in a group at one section -- no other changes.

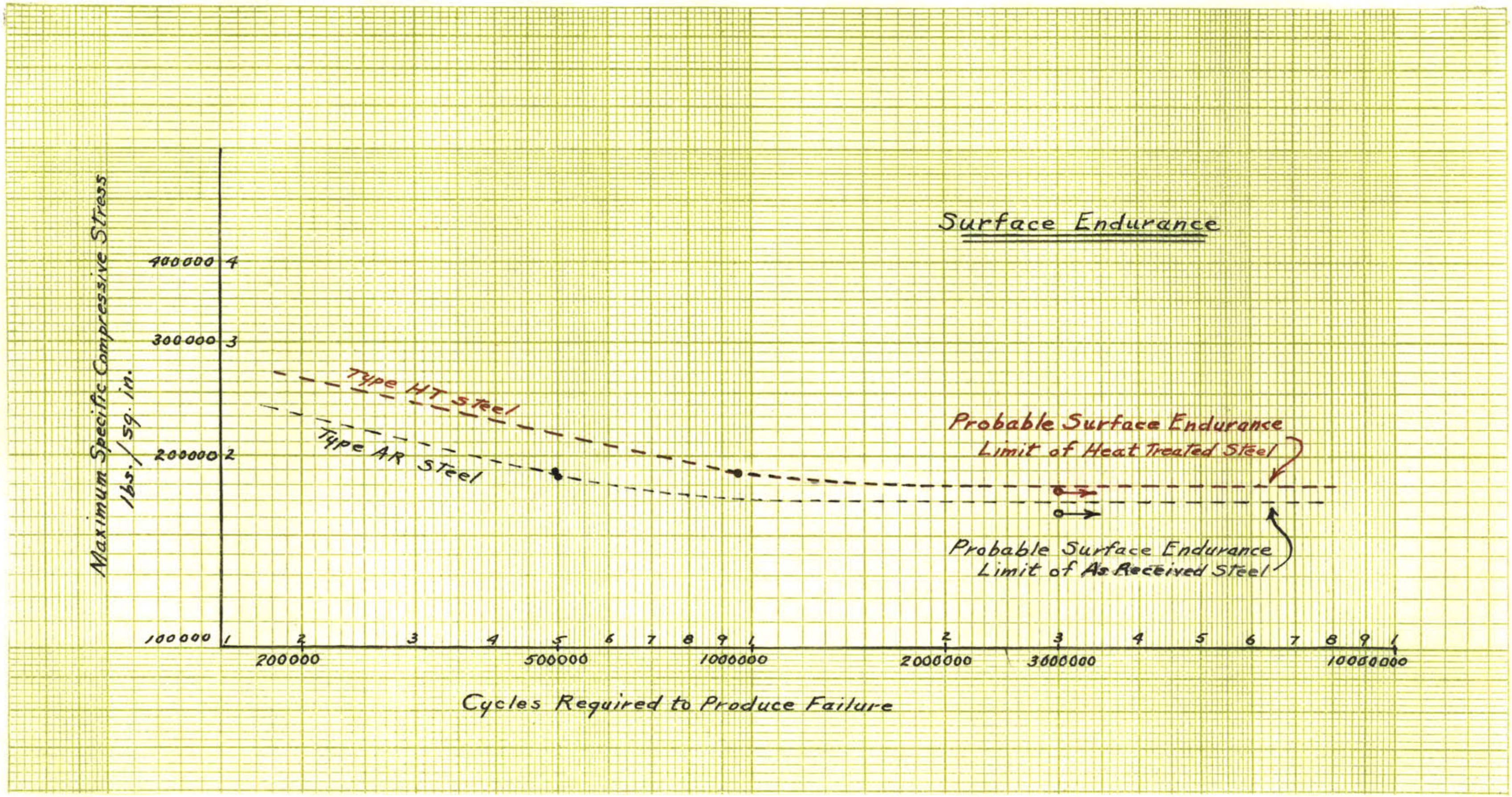
700 570301 2# 4oz. 770455 4000#

Total revolutions of steel disk: 2,934,940.

No change.

Table of Results

Test No.	102AR	103HT	106AR	107AR	108HT
Max. Spec. Compr. Stress lbs./sq.in.	162800	189700	189700	189700	177200
Av. Spec. Compr. Stress lbs./sq.in.	128000	149000	147000	149000	137000
Depth of point of max. Compr. Stress in inches	.0108	.0125	.0121	.0125	.0115
Width of area of contact in inches	.0137	.0159	.0154	.0159	.0146
Area of contact in sq. in.	.0274	.0318	.0312	.0318	.0292


Surface Endurance
Maximum Specific Compressive Stress lbs./sq. in.
400000 4
300000 3
200000 2
100000 1
Type HT Steel
Type AR Steel
Probable Surface Endurance Limit of Heat Treated Steel
Probable Surface Endurance Limit of As Received Steel
2
3
4
5
6
7
8
9
1
200000
500000
1000000
2000000
3000000
10000000
Cycles Required to Produce Failure

CALCULATIONS FOR MAXIMUM SPECIFIC COMPRESSIVE STRESS FOR TESTED STEELS

- -

In the following calculation the moduliis of elasticity of steel is taken as 30,000,000 lbs. per sq. inch.

TEST NO. 102AR

$$S^2 = \frac{.35 \quad 3500 \left(\frac{1}{1.15} + \frac{1}{1.75}\right)}{\frac{1}{30000000} + \frac{1}{300000000}}$$

S = 162,800 lbs. per sq. inch

TEST NO. 103HT

$$S^2 = \frac{.35 \quad 4750 \left(\frac{1}{1.15} + \frac{1}{1.75}\right)}{\frac{1}{30000000} + \frac{1}{30000000}}$$

S = 189,700 lbs. per sq. inch

TEST NO. 106AR

$$S^2 = \frac{.35 \quad 4580 \left(\frac{1}{1.15} + \frac{1}{1.60}\right)}{\frac{1}{30000000} + \frac{1}{30000000}}$$

S = 187,700 lbs. per sq. inch

TEST NO. 107AR

$$s^2 = \frac{.35 \quad 4750 \left(\frac{1}{1.15} + \frac{1}{1.75}\right)}{\frac{1}{30000000} + \frac{1}{30000000}}$$

$S = 189{,}700$ lbs. per sq. inch

TEST NO. 108HT

$$s^2 = \frac{.35 \quad 4000 \left(\frac{1}{1.15} + \frac{1}{1.75}\right)}{\frac{1}{30000000} + \frac{1}{30000000}}$$

$S = 177{,}200$ lbs. per sq. inch

CALCULATIONS FOR AVERAGE COMPRESSIVE STRESS OVER AREA OF CONTACT

TEST NO. 102AR

$$S_A = \frac{3500}{.0274} = 128{,}000 \text{ lbs. per sq. in.}$$

TEST NO. 103HT

$$S_A = \frac{4750}{.0318} = 149{,}000 \text{ lbs. per sq. in.}$$

TEST NO. 106AR

$$S_A = \frac{4580}{.0312} = 147{,}000 \text{ lbs. per sq. in.}$$

TEST NO. 107AR

$$S_A = \frac{4750}{.0318} = 149{,}000 \text{ lbs. per sq. in.}$$

TEST NO. 108HT

$$S_A = \frac{4000}{.0292} = 137{,}000 \text{ lbs. per sq. in.}$$

CALCULATIONS FOR DEPTH OF THE POINT OF MAXIMUM SPECIFIC COMPRESSIVE STRESS

TEST NO. 102AR

$z = 0.7861 \times .0137 = .0108$ in.

TEST NO. 1o3HT

$z = 0.7861 \times .0159 = .0125$ in.

TEST NO. 106AR

$z = 0.7861 \times .0154 = .0121$ in.

TEST NO. 107AR

$z = 0.7861 \times .0159 = .0125$ in.

TEST NO. 108HT

$z = 0.7861 \times .0146 = .0115$ in.

CALCULATIONS FOR AREA OF CONTACT
BETWEEN ROLL AND DISK

- -

In the following calculations the moduliis of elasticity of steel is taken as 30,000,000 lbs. per sq. inch.

2b = width of contact area

L = length of contact area = 1 inch

A = area of contact area = 2b × L

TEST NO. 102AR

$$b = 1.075 \sqrt{\frac{3500\left(\frac{1}{30000000} + \frac{1}{30000000}\right)}{\left(\frac{1}{1.15} + \frac{1}{1.75}\right)}}$$

b = .0137 =

2b = 2 × .0137 = .0274 in.

A = .0274 × 1 = .0274 sq. in.

TEST NO. 103HT

$$b = 1.075 \sqrt{\frac{4750\left(\frac{1}{30000000} + \frac{1}{30000000}\right.}{\left(\frac{1}{1.15} + \frac{1}{1.75}\right)}}$$

b = .0159 in.

2b = 2 × .0159 = .0318 in.
A = .0318 × 1 = .0318 sq. in.

TEST NO. 106 AR

$$b = 1.075\sqrt{\frac{4580\left(\frac{1}{30000000}+\frac{1}{30000000}\right)}{\left(\frac{1}{1.15}+\frac{1}{1.60}\right)}}$$

b = .0154 in.

2b = 2 × .0156 = .0312 in.

A = .0312 × 1 = .0312 sq. in.

TEST NO. 107AR

$$b = 1.075\sqrt{\frac{4750\left(\frac{1}{30000000}+\frac{1}{30000000}\right)}{\left(\frac{1}{1.15}+\frac{1}{1.75}\right)}}$$

b = .0159 in.

2b = 2×.0159 = .0318 in.

A = .0318 × 1 = .0318 sq. in.

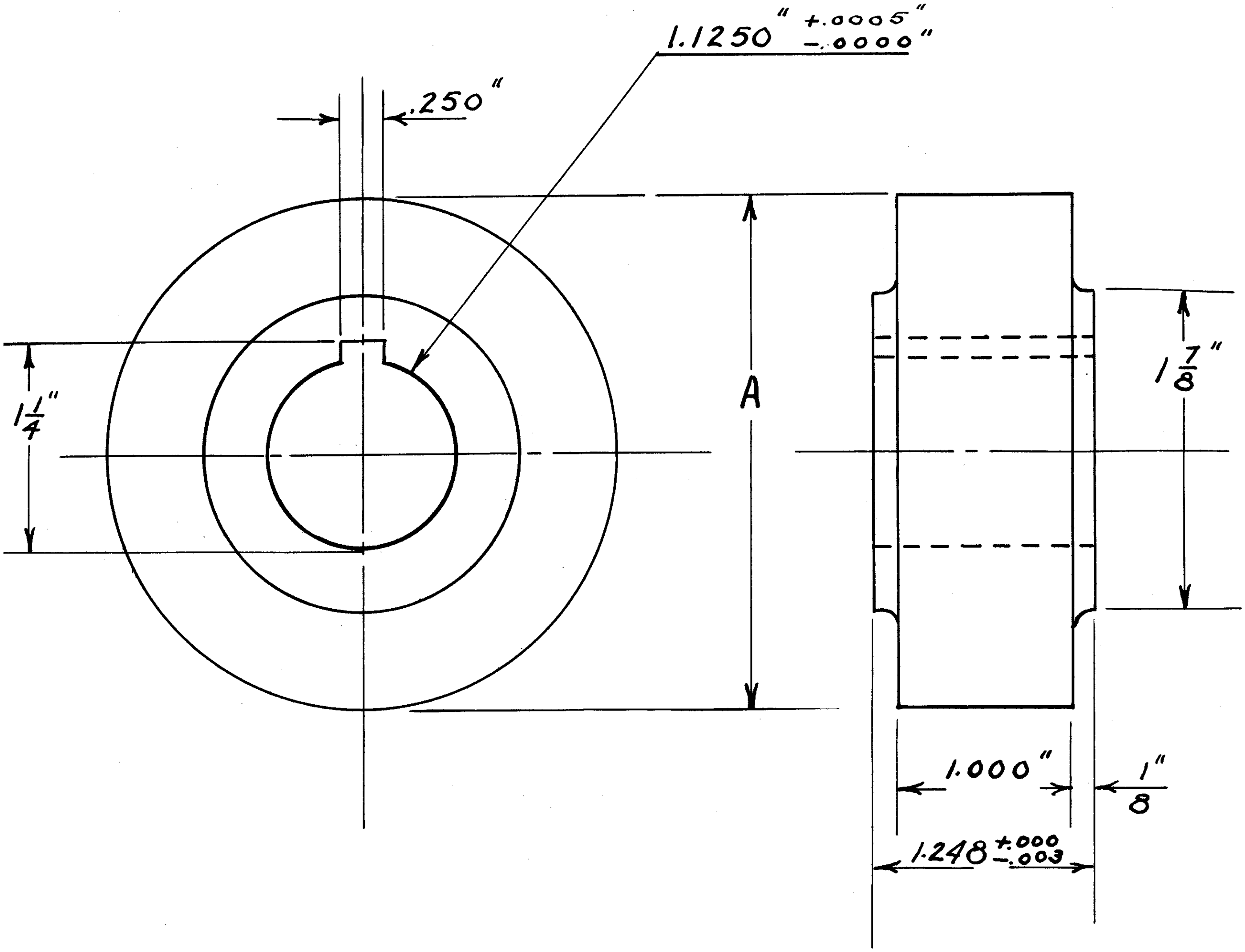
TEST NO. 108HT

$$b = 1.075\sqrt{\frac{4000\left(\frac{1}{30000000}+\frac{1}{30000000}\right)}{\left(\frac{1}{1.15}+\frac{1}{1.75}\right)}}$$

b = .0146 in.

2b = 2 × .0146 = .0292 in.

A = .0292 × 1 = .0292 sq. in.



Test Disc "f" All Over

TEST SPECIMEN

SURFACE FATIGUE

Shewbridge and Griffin

1936

Testing Machine

SPRING CALIBRATION

Height inches	Load lbs.
9 9/16	Free
9 7/16	280
9 5/16	550
9 3/16	860
9 1/16	1170
8 15/16	1480
8 13/16	1800
8 11/16	2110
8 9/16	2430
8 7/16	2740
8 5/16	3100

Solid at 8.22 inches

Threaded Rod

12 threads per inch, .0833" pitch

BIBLIOGRAPHY

Buckingham, E.-- A Study of Surface Failure Due to Rolling Contact. Progress Report of the A.S.M.E. Special Research. Committee on the Strength of Gears.--1935

Talbourdet, G.-- An Investigation of the Surface Endurance Limit of Materials--M.I.T. Thesis 1935.

Moore and Kommers--Fatigue of Metals--1927.

Nadai, A. Plasticity--1931.

Timoshenko Strength of Materials, Vol. 2 --1930.

T. H. Grant and W. Nixon,-- Surface Fatigue of Metals-- M. I. T. Thesis, 1931.

French, H. J. --Fatigue and the Hardening of Steels. Extract from "Metals and Alloys" Vol. 4, Page 170

Von Heydekampf G. S. -- Cold Rolling Raises Fatigue or Endurance Limit. Reprint from "Iron Age". Sept. 18 and Oct. 2, 1930.

Moore, H. F. -- Crackless Plasticity. Reprint from Iron Age. Sept. 10, 1931.

Way, Stewart -- Pitting Due to Rolling Contact. Transactions of the A.S.M.E. --1935.

H. R. Thomas and V. A. Hoersch -- Stresses Due to the Pressure of One Elastic Solid Upon Another. University Bulletin --July 15, 1930.