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Studies on Internal Friction and
Vibration Fatigue.

NAVAL RESEARCH LABORATORY
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AUTHORIZATION:

1. This problem was authorized as an NRL problem by a Director's order dated 5 June 1928.

OBJECT:

2. The object of the experiments was to find out whether the method of experiment already devised by the writer could be used as a quick method of determining the endurance limit. Work was already being done elsewhere on the same problem by different methods. A secondary object, introduced later, was to find out something about the condition of forced vibrations in propellers, etc., and see if metals could be found for this purpose which would, while possessing desirable strength characteristics, at the same time possess enough internal friction to damp out forced vibrations.

KNOWN FACTS BEARING ON PROBLEM:

3. The known facts connected with the problem are as follows:

(a) Numerous workers, notably, B.P. Haigh in England¹, have

¹B.P.Haigh, Trans. Faraday Society, February, 1928

passed oil through hollow specimens underpoing fatigue tests, and studied the rate of heat evolution, and hence indirectly the internal friction, by means of the change in temperature of the oil produced by passing it through the specimen. In general the final onset of failure is signalized by a great increase in internal friction. The above method is not, however, very sensitive and suffers from other disadvantages. In some materials, at stresses only slightly above the endurance limit, heat evolution is at first rapid, but soon decreases and remains nearly constant for perhaps millions of cycles. Nevertheless failure does finally occur, with a preliminary warning burst of heat evolution. There is nothing in the early stages of the above experiment to indicate whether failure will ultimately occur or not, and the method could not therefore be used as a rapid endurance test. Of course the early heat evolution is only an accompaniment of plastic changes resulting from a certain amount of cold-working going on in the metal, and can equally well occur at stresses safely within the endurance range. In a later paragraph of this report the writer's own conclusions on this subject will be stated.

THEORETICAL CONSIDERATIONS:

4. Whenever a material is carried through a cycle of strain it exerts smaller stresses during the removal of the strain than it did during the application of the strain. If we plot the stresses against the strains as in Fig. 1, we find that instead of retracing the single straight line AOB as it would do if Hooke's Law were exactly obeyed, it traces a loop such as PQRS, which represents the symmetrical condition which exists after a number of strain-cycles

have been performed. Of course the area of the loop represents work absorbed by the specimen and not returned in the form of elastic energy. The whole picture bears an exact similarity to the hysteresis loop in magnetic materials, and in fact the term "elastic hysteresis" is often used to describe the phenomenon.

A fact that must be borne in mind from the outset is that the dissipative or nonelastic forces at play here are only associated with shearing strains. Even the most complex strain distribution can be divided uniquely into two parts; dilatation or change of volume, and distortion or change of shape. For instance, when a rod is simply stretched, the elastic energy associated with distortion is to the energy associated with dilatation in the ratio $E/(3N-E)$ where E is Young's modulus and N is the shearing modulus. For ordinary metals this ratio is about 5 to 1, so that even for simple tension the shear-strain plays a predominant role, and internal friction will be in evidence. On the other hand when a metal is subjected to hydrostatic pressure the strain is entirely dilatation and no internal friction has ever been proved to exist for such strains. In this respect internal friction in solids is quite analogous to viscosity in liquids, where, as is well-known, the frictional stress is proportional to the rate of change of shear strain.

For the above reasons most of the experiments described in this report were made in torsion, which involves only pure shearing stress.

Returning to the diagram of Fig. 1, the exact shape of the hysteresis loop is difficult to measure, since the width of the loop may correspond to a strain of a millionth of an inch per inch or less. What evidence exists points to a loop with nearly straight and parallel sides. Since most experiments, including those reported here, measure only the work absorbed or the area of the loop, it seems convenient to assume that the loop is a parallelogram like WXYZ. The half-width of the loop, f' , we call the friction stress, while its total height f we term the elastic stress or stress-amplitude. Suppose that as a result of an experiment we have found that in a stress-cycle such that w units of energy per unit of volume is stored up at either end of the swing, an amount of energy w' per unit of volume is dissipated. It is easy to verify that

$$w = f^2/2E \quad (1)$$

and
$$w' = 4ff'/E \quad (2)$$

where E is the proper elastic modulus. From these formulas it is easy enough to compute the corresponding values of f and f' .

This leads to a natural and simple way of plotting the results of experiments on internal friction - a way originating with the writer, and not used previously because other experimental methods are not delicate enough to indicate anything except the general form of the curve. The results are simply plotted with f' as ordinates and f as abscissae, and referred to as ' f' - f curves.' Examples of

such curves are shown in Fig. 2.

In some cases it is desired to express the relation of f' to f in the form of a coefficient. In case the f - f curve is a straight line through the origin, this can be done by defining a coefficient of internal friction ϕ by the following formula:

$$\phi = f'/f. \quad (3)$$

Subject to the above limitation, ϕ bears an exact relation to the logarithmic decrement of a pendulum or tuning fork made of the material. That is:

$$\delta = 4\phi \quad (4)$$

where δ is the logarithmic decrement of the free oscillation defined in the ordinary way by $A = A_0 e^{-nt\delta}$ where A is the amplitude at any time t , measured from the instant when A equalled A_0 , and n is the frequency.

In fact, other experimenters use the decrement defined above, and determined in the above way, to express the results of their work. As mentioned above, however, this coefficient is meaningless when the f - f curve is not linear.

NARRATIVE OF ORIGINAL WORK DONE AT THIS LABORATORY ON THE PROBLEM:

5. The original idea of this problem was used by the present writer in somewhat cruder form at the Johns Hopkins University, the results being published in the Physical Review⁽²⁾.

(2) R.H. Canfield: "Internal Friction in Metals," Phys. Rev. Vol. 32, No. 3, Sept. 1928, pages 520-530.

After setting up apparatus at this Laboratory, experiments were commenced in June 1928 and continued intermittently until October, 1932, at which time pressure of other duties and lack of a suitable assistant caused the work to become inactive. During this time the results were published in the form of two further papers⁽³⁾⁽⁴⁾.

(3) Proceedings Third International Congress of Applied Mechanics, Stockholm 1930 - "Internal Friction as a Physical Test of Materials".

(4) Transactions of the American Society for Steel Treating, Dec. 1932, pages 549 to 576, - "Internal Friction in Iron and Iron Alloys."

METHODS

6. The earliest experimenters on internal friction measured the rate of decay of elastic vibrations: either of torsion pendulums controlled by a wire made of the material under study, or of tuning forks

made of the material. Both of these methods are open to the same objections: 1-different parts of the specimen are stressed to different degrees; 2-during the process of getting the decrement the stress-range is changing. Both of these deficiencies lead to the same sort of inaccuracy- a smoothing out of the f' versus f curve so that it appears straighter and more uniform than it actually is.

The method used in the ensuing experiments is to make the specimen the elastic control of a large torsion pendulum which is maintained in a steady state of vibration by electromagnetic forces. These forces can be accurately estimated from the readings of ammeters. The apparatus is illustrated in Fig. 3.

The specimen itself is a fairly thin-walled tube so that if due allowance is made for the ends we may say that all parts of the specimen are going through the same stress-cycle. The stress f is determined from the frequency of vibration of the pendulum, its moment of inertia, the amplitude of the vibration, and the "section modulus," or physical dimensions of the specimens. The friction stress f' is determined from the currents flowing in the fixed and movable electromagnets, and the section modulus of the specimen. The present method of driving is illustrated in Fig. 3 and Fig. 4. Here P is the pendulum, with its windings. The main pendulum is coupled by light springs to a subsidiary very light pendulum Q carrying contacts C by means of which proper values of potential are applied to the grids of a bank of 28 vacuum tubes (type 71-A) connected in parallel. The plate current of these tubes passes through the primary of a transformer T , and the alternating component is passed on to the windings of the main pendulum from the secondary. By varying the plate voltage and number of tubes in parallel, a wide range of power is obtainable.

It is very important that the alternating current driving the main pendulum shall be in the correct phase relation to the motion of the pendulum, in order to secure maximum amplitude. This is accomplished in a very satisfactory manner by having vanes V attached to the movable part of pendulum Q and dipping into oil cups which are raised and lowered by a rack and pinion device controlled from the observing desk. By adjusting the height of these oil cups, the correct phase relation is easily realized. In this manner the pendulum drives itself at resonance frequency.

Currents supplying both the fixed magnets and the pendulum windings are measured by ammeters A . The frequency is measured by the specially designed tungsten-reed frequency meter F . The amplitude of the pendulum's vibration is measured by the width of the band of light formed by the image of a fixed lamp filament, formed by a concave mirror M attached to the pendulum, and focussed upon a ground glass scale in the observing desk.

THEORY OF EXPERIMENT:

7. We picture the pendulum acted on by a periodic torque equal to $L \sin 2\pi nt$ where L is the greatest value of the torque, n is the frequency and t the time. This assumes that the output of the

vacuum-tube power amplifier described above is a pure harmonic wave. Let the frequency be n and let the pendulum make pure harmonic vibrations of amplitude a , according to the equation

$$\theta = a \sin (2\pi nt - \alpha) \quad (5)$$

where θ = angular displacement, t is the time and α the lag in phase between the vibration and the torque imposed on the pendulum. Then the work done by the external couple in one complete cycle is

$$\text{Work} = \int_0^{2\pi} L d\theta = \pi L a \sin \alpha$$

and when the damping vanes are adjusted for maximum amplitude,

$$\sin \alpha = 1, \text{ and work} = \pi L a \quad (6)$$

Now from equation (2) we already know the internal work per unit volume. Since in a tubular specimen under torsion all parts are at essentially the same stress, the work absorbed is given by

$$\text{Work} = 4ff'V/E \quad (7)$$

where V is the volume of the specimen. Combining equations (6) and (7) we have

$$f' = L a E / f v \quad (8)$$

Now the theory of elasticity gives a formula for the twisting of a thin cylinder

$$a = T l / 2\pi r^3 t E \quad (9)$$

Where l is the length, r the mean radius and t the thickness of the tube, T is the torque, and a the angle of twist. Likewise the theory gives the mean stress in the tube as

$$f = t / 2\pi r^2 t \quad (10)$$

We now form the expression aE/fV from equations (9) and (10) remembering that $V = 2\pi r l t$.

$$\frac{aE}{fV} = \frac{1}{2\pi r^2 t}$$

Substituting this in equation (8) gives us

$$f' = L / 2r^2 t \quad (11)$$

A glance shows that equation (11), giving the friction stress, is identical with equation (10) for elastic stress except that πL is used for the torque in the former case. Equation (11) is the one actually used in computing results of experiments.

The elastic stress calculated from equation (10) with the following modification. Remembering that at the instant the pendulum

reverses its motion, no stress is being exerted on it by the magnets (this is the condition of resonance and follows from the fact that the lag ϕ is 90°), we see that the whole torque is due to the angular acceleration of the pendulum. This can be obtained by differentiating equation (5) twice with respect to time. Remembering that at the instant we are thinking of, $\sin(2\pi nt - \phi) = 1$,

$$\text{Acceleration} = \frac{d^2\theta}{dt^2} = 4\pi^2 n^2 a \quad (12)$$

Now the torque exerted is equal to the moment of inertia I of the pendulum, times the angular acceleration. Hence from equations (10) and (12)

$$T = \frac{2\pi n^2 a I}{r^2 t} \quad (13)$$

Equation (13) is the one used in calculating elastic stress. In the above derivations, t has been used both for time and for wall thickness, but in the final formulae appears only in the latter sense.

CONSTANTS AND CORRECTIONS

6. The moment of inertia of the pendulum for torsion is of fundamental importance. It was determined by two independent methods, involving nothing novel, and the result is considered correct to 0.2 percent.

Those constants which are the most difficult to determine, and perhaps the most doubtful, are those which determine the strength of the couple exerted when known currents pass through the windings. The method used was to measure photographically the amplitude of the static deflections produced by known currents. The results were a series of curves giving factors by which the product $I_1 I_2$ of the currents in the fixed and moving magnets is to be multiplied to obtain the torque exerted. This factor varied from about 1.3×10^6 to 2×10^6 dyne-cm per ampere squared. It should be noted that the readings of the A.C. ammeter in the circuit containing the moving magnets is the root-mean-square current and must be multiplied by $\sqrt{2}$ to obtain I_2 .

A complete study was made of losses due to air friction, eddy currents, and other losses outside the specimen, and these were found to be negligible.

The method of making an experiment is as follows: The specimen having been machined is firmly fastened in the pendulum by the use of a clamp and a tapered wedge. The lower end of the specimen is then similarly fixed in the base-bar of the machine, the slave pendulum is attached, and the electrical circuit energized. A tap of the finger starts the pendulum in vibration, and the oil cups are adjusted to give maximum amplitude. Care is exercised that the power supplied is small enough to prevent vibrations producing high stresses.

Now the currents in the fixed and moving magnets are increased by steps, taking an amplitude reading at each step. A frequency reading is taken after every few steps, and a check made of the oil cup setting. After readings have been carried to high enough amplitudes to answer the questions at issue, the results are computed in terms of f' and f and recorded as a curve.

DATA OBTAINED:

9. General. The curve f' versus f is far from being dependent only on the chemical nature of a metal or alloy. Instead, it is primarily a function of the physical condition of the specimen. Among the factors which influence the form of the curve are: 1- the space-lattice or crystal class of the metal, or of the various solid phases in the metal; 2- the grain-size of the metal; 3- the amount of intragranular strain or hardening, whether strain-hardening, precipitation-hardening, or solid-solution hardening; 4- effects of plastic deformation or fatigue, which disappear after a certain lapse of time and 5- effects due to condition of surface and existence of internal cracks or stress concentrations, which may be considered extraneous to the true properties of the metal itself, but which, nevertheless, must be guarded against.

Pure Unhardened Alpha Iron

It is proper to commence this report with the internal friction properties of alpha iron in its pure and unhardened state. The closest approach to this material that we have been able to obtain have been a few specimens made of Armco iron, subjected to a prolonged (48 to 120 hours) treatment in moist hydrogen at temperatures from 1100 to 1250 degrees Cent. (2010 to 2280 degrees Fahr.). The f versus f curve of one of these is given in curve (A), Fig. 5. This specimen had been hydrogen-purified for 92 hours at 1205 degrees Cent. (2200 degrees Fahr.), and cooled for 16 hours in the furnace. It had a grain size of about 3 millimeters and represents the extreme type of the pure alpha iron curve. Curve (B) in the same figure is the same specimen tested about 6 hours later. The change observed is due to hardening which resulted from making the previous experiment.

Knee Feature Characteristic of the Body-Centered Lattice

The knee marked f_{01} in the two curves seems to be a characteristic feature of the internal friction curve for metal with body-centered space lattices. The evidence for this is as follows: the knee is always present in pure alpha iron and to a lessening degree in carbon steels which contain the alpha iron phase. It is likewise present in stainless iron containing 13 per cent chromium, which is also an alpha solid solution. It is present in beta brass (curve C, Fig. 5), which is a body-centered solid solution. It is absent in austenitic steels such as the 18 and 8 type, also in 38 per cent nickel steel (Invar). It is also absent in alpha brass, which has a face-centered cubic lattice. It is absent in copper, zinc, aluminum, duralumin, phosphor-bronze, and in fact all the non-body-centered metals on which experiments have been made.

The f_1 -Point. Beyond the knee just described there occurs a range of stress where the friction f' remains almost unaltered or increases very slightly. This terminates very abruptly in alpha iron, but often more gradually in other materials, at a point marked f_1 in the diagrams. This point coincides roughly with the elastic limit, and appears to be the point at which true plastic deformation sets in. Lacking exact information on this question the author prefers to call it simply the " f_1 point." What is certainly true is that above this point the stress f' increases with a high power of f .

Grain-Size Determines Position of f_1 -Point. The stress at which the f_1 point occurs is an important property of the material, as it will be seen later that cyclic stresses of a greater amplitude than f_1 leave a permanent effect on the properties, while lower stresses can be repeated indefinitely without producing measurable effects. In pure or nearly pure iron, such as Armeo, the f_1 stress appears to depend mainly on the grain size. This is illustrated by Fig. 6, which shows curves for some purified and some unpurified Armeo iron of various grain diameters.

Effects of Cold-Work. In the early stages of experimentation with this apparatus, an accident occurred which led to some interesting observations. Through a mistake in making electrical connections a huge current passed momentarily through the pendulum windings. The result was to give the specimen of Armeo iron then in the machine a permanent twist of 4 degrees. The operator replaced the pendulum in its central position and at once proceeded to take data for a curve. The result was curve (B) of Fig. 7. Curve (A) was the curve for the specimen immediately prior to the accidental overstrain. The remaining curves show that the metal recovered its original condition within a period of 24 hours.

The next step was to determine what influence the amount of overstrain had on the curve. The result is illustrated in Fig. 8. It is seen that the slope of the main part of the curve is independent of the amount of the overstrain, varying from 7 to 36 degrees on specimens of two sizes.

SUMMARY OF EFFECTS OF OVERSTRAIN.

10. The above experiments refer to pure iron and very mild steel, but experiments on other metals bear out the same conclusions. The effects of overstrain are usually as follows:

- (1) An immediate steepening of the f' - f curve, i.e., an increase of internal friction.
- (2) The new f' - f curve is the same regardless of the amount of overstrain so long as it was definitely above the elastic limit.
- (3) During a period of rest following the overstrain the curve becomes lower and flatter again: the f_1 point may finally be higher than its original value.
- (4) In materials which "age", i.e., become hard during a period of rest after overstrain, the changes mentioned in item (3) take

place more rapidly than in materials which show little aging. In fact the internal friction phenomena can be used as delicate criteria of aging properties.

Further Properties of the f_1 -Stress. Existence of an f_2 -Stress.

The most important characteristic of the f_1 stress has yet to be described. It is as follows:

Stress cycles of lower amplitude than f_1 produce no change in the $f'-f$ curve or any other measurable physical property of the specimen, no matter how often repeated. Stress cycles of higher amplitude than f_1 do produce changes in the $f'-f$ curve.

These generalizations are supported by numerous experiments of the author's, both on ferrous and nonferrous metals. A few of these results are selected for presentation here.

Fig. 10 gives a series of $f'-f$ curves for normalized 0.25 per cent carbon steel, with readings taken first in ascending and then in descending order. Any displacement of the descending portion relative to the ascending is due to the effects of whatever number of stress-cycles of higher amplitude have been made in the course of taking data for the curve—perhaps 200 to 500 cycles for each plotted point. Curve (A) is the original curve (made on another similar specimen so as not to affect the remaining curves). Curve (B), which was not carried above the f_1 point, shows no difference outside the range of experimental error between ascending and descending branches. Curve (C) was carried to an amplitude above the f_1 point. The descending branch lies beneath the ascending one over a certain range, indicating a decrease in internal friction. Curve (D) was carried to a much higher amplitude. The descending branch now lies above the ascending branch and the internal friction has been increased. Curve (E) represents a still further increase over (D) due to carrying readings to still higher amplitudes. Finally curve (E) shows the effect of 2,700,000 cycles of a stress of about 1200 kg/cm^2 (17,000 pounds per square inch). It will be noted that curve (E) bears a strong likeness to the curves characteristic of freshly overstrained metal in Figs. 7, 8, and 9.

Again, Fig. 11 illustrates the effects of many cycles of stress above the f_1 point in 0.25 per cent carbon steel. Here curve (A) is the initial condition; curve (B) is after 5,000,000 cycles of 700 kg/cm^2 , a stress that is very close to f_1 . The result is a slight increase in the value of f_1 together with a decrease of the friction stress in the range beyond f_1 . The range below f_1 is unaltered. Curve (C) gives the effects of 2,700,000 cycles of 1000 kg/cm^2 . Curves (D) and (E) show the effects of recovery, the first during 3,000,000 cycles (about 34 hours) of a stress of 650 kg/cm^2 , the second an additional recovery period of 30 hours under no stress. The picture presented here is so similar to the recovery of iron from plastic deformation that it seems likely that the two effects are the same. It is to be especially noted that though the treatment resulting in curve (C) reduced the value of f_1 , the further cyclical stress of 650 kg/cm^2 , which is higher than the newly acquired f_1 ,

acted nevertheless is an inducement to recovery.

The data just cited point to the following conclusion: Cyclic stresses at amplitudes somewhat above f_1 result in a gradual change in the internal friction curve, the change consisting of an increase in the value of f_1 and a decrease in the internal friction. However, if the stress amplitude is too far in excess of f_1 , the reverse phenomena appear; the f_1 stress is lowered and there is an increase in the internal friction.

These two observations strongly suggest the presence of still another critical stress, higher than f_1 , which we shall call f_2 . In fact many of our curves, e.g., curve (A) of Fig. 10, indicate the existence of such a point; but such an effect might easily be the result of the finite wall thickness of the specimen, the second break marking the point where the f_1 stress reached the inner surface; for this reason the existence of an f_2 critical stress should not be supposed from the shape of the curve without confirmatory evidence. The existence of f_2 now seems well established in the light of another experiment about to be described. It is only to be noticed that according to the paragraph just above, cyclic stresses exactly equal to f_2 will cause the points f_1 and f_2 to fuse or coincide into one point. That such may be the case is shown by curves (A) and (B) of Fig. 12, curve (A) being the original and curve (B) following after.

An experiment on a specimen of S.A.S. 1010 steel, normalized, is shown in Fig. 13. The manner of taking these observations was as follows: On first attaining a given stress amplitude a reading was made; then the specimen was given 5000 cycles at this amplitude and a second reading taken; then another 5000 cycles and a third reading. Then the stress amplitude was increased and the same process repeated. The three sets of points form curves labelled (A), (B) and (C). Here we have plain evidence of the two ranges of progressive change—the range between f_1 and f_2 where the internal friction is decreased by the repetitions, and the range above f_2 where it is increased. The position of f_2 is quite accurately established by these curves at a value of 1080 kg/cm^2 (15,400 pounds per square inch).

The above described results are merely typical of dozens of similar experiments, of which an account would occupy too much space.

IDENTIFICATION OF ENDURANCE LIMIT FROM INTERNAL FRICTION EXPERIMENTS:

11. The results outlined above point to some conclusions regarding the use of the internal friction method as a way of determining endurance limits.

First of all, the f_1 point is certainly lower than the endurance limit, since stresses below f_1 produce no change in the curve or in any physical properties of the metal.

Second, stresses above f_1 but below f_2 , while they produce changes in the metal, do so in such a way as to decrease its internal friction and raise the f_1 stress. The change is therefore of such a nature as to oppose further change.

the oscillations began to shift; the specimen was acquiring a permanent set in compliance with the pull of the springs. Horizontal arrows are drawn from the end of each curve indicating the amount of this relief of stress. In each case where f exceeded 1900 kg/cm^2 the amount of this relief exactly equalled the amount of initial stress.

evidently the stress 1900 marks the commencement of plastic flow. This stress is definitely higher than the f_1 stress, and evidently answers the description of the f_2 stress introduced above.

A final experiment, made with the same apparatus, is designed to show how the internal friction curve behaves when small vibrations are superposed on a large static torque. For this purpose a free-machining stainless iron was selected - a material showing unusually high internal friction for high, but safe, stresses. Fig. 16 shows the original $f'-f$ curve of this metal, and superposed on it the short $f'-f$ curves obtained when the indicated value of f was applied as a static load. It will be perceived that the slopes of these short curves are much smaller than that of the parent curve at the corresponding mean stress. The significance of this is explained by the diagram, Fig. 17. Here ABCD is the hysteresis loop performed when going through the stress cycle of amplitude f . The actual hysteresis loop formed, when the small cyclic stress s is superposed on the static stress f , is the loop LMNP, not the loop QRST which might have been expected.

The above experiment answers the question as to how a propeller shaft may be expected to behave when near a speed which will set up critical vibrations. The most desirable material for a shaft intended to damp out such vibrations will be one for which the small superposed $f'-f$ curves have the steepest slope.

CONCLUSIONS AND RECOMMENDATIONS:

13.(a) The facts established by the above research are as follows:

(1) That the $f'-f$ curves of metals, as determined by the methods described, show critical points in certain cases, which are to be identified with changes in properties of the metal unrevealed by other tests.

(2) That there is in many cases a certain limiting stress f_1 , below which repetitions of stress produce no effect on the metal whatever.

(3) That there is another and higher limiting stress f_2 , above which repetitions of stress cause general increase of internal friction accompanied by plastic deformation and will ultimately lead to failure.

(4) That stress-ranges lying between the stresses f_1 and f_2 produce changes in the metal of such a kind as to increase the value of f_1 up to the stress-range, which is acting on the metal, thus decreasing its internal friction in that range and apparently producing

beneficial effects rather than the reverse.

(5) That with regard to vibrations superposed on static loads, the simple $f'-f$ curve gives no answer; but that a modified apparatus can be made to yield the required information.

(6) That highly cold-worked materials yield $f'-f$ curve that are steeper, i.e., show more internal friction, than heat-treated materials, in the useful stress-ranges.

(b) It is the opinion of the Laboratory that the apparatus and methods here described are capable of being used to study a property of metals which is not measured or revealed by other tests, and possesses many possibilities.

(c) The use of this apparatus and interpretation of results requires much special technical knowledge and a special training in its use, so that it would be unwise to attempt to install it in laboratories previously unacquainted with it. It is believed that the time of one man could be profitably occupied with a planned program of research by this method, with resulting benefits to the Navy and to the science of Metallurgy as well.

In particular, a well-planned study of the relation of this test to the standard endurance test is suggested. A further study of materials with a view to their damping properties when used for propeller shafts is suggested.

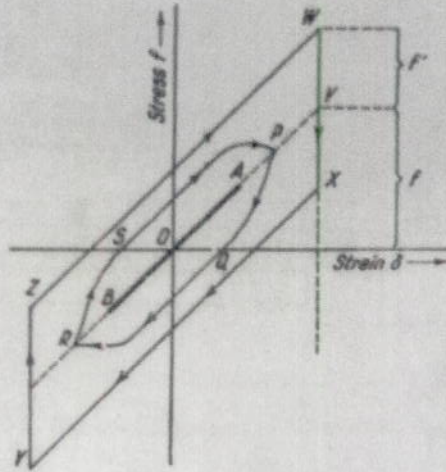


Fig. 1—Hysteresis Loops in Stress-Strain Cycles.

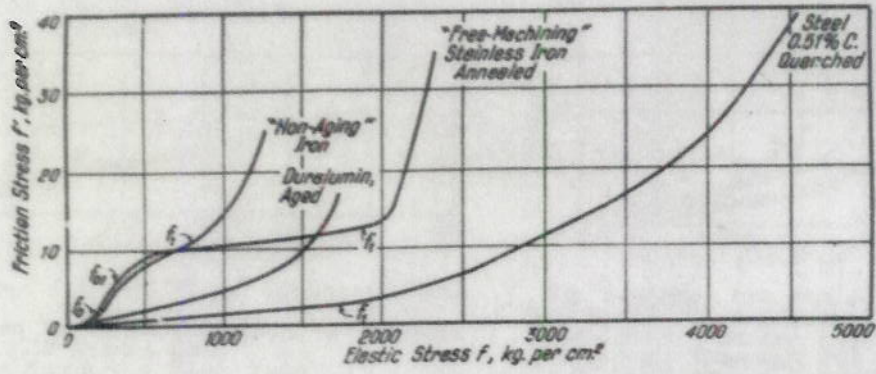


Fig. 2—Typical $f'-f$ Curves.

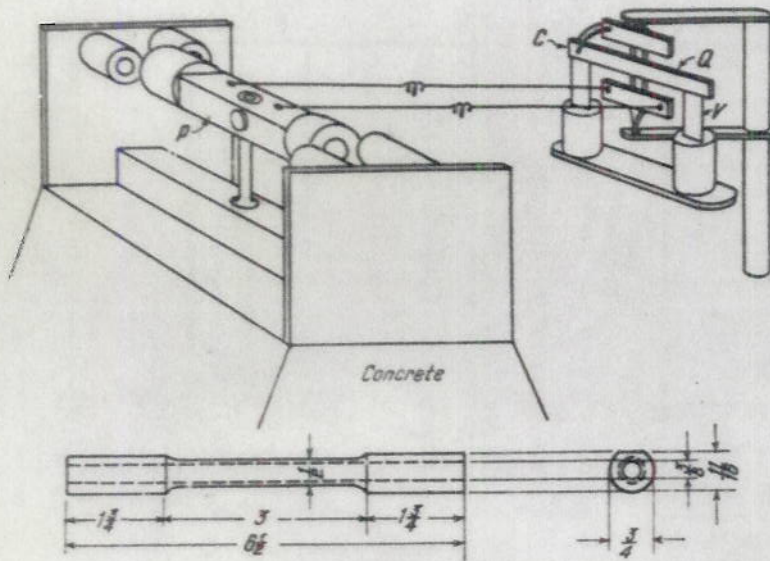


Fig. 3a—Sketch of Apparatus and Tubular Specimen.

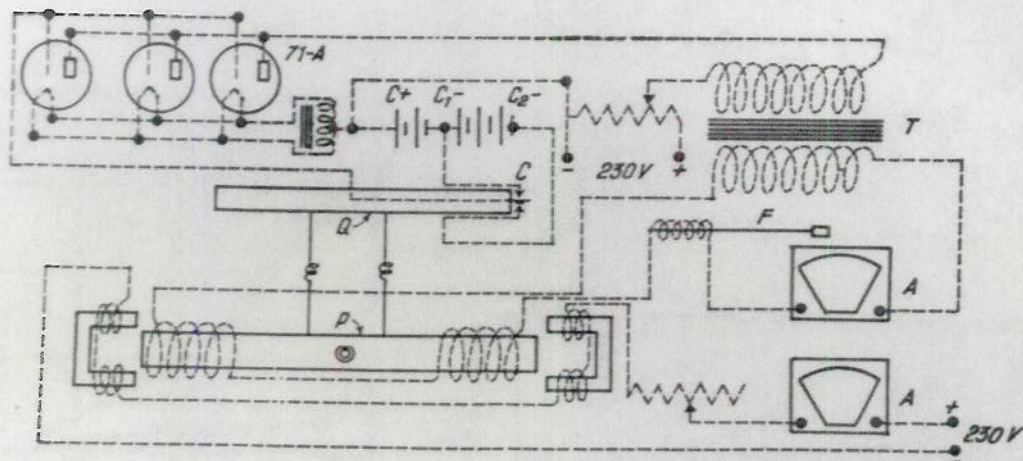


Fig. 4—Diagram of Electrical Circuit.

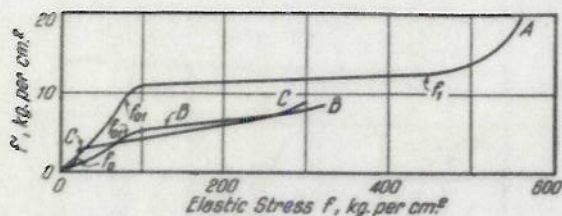


Fig. 5— f' - f Curves Typical of Body-Centered Lattice.
 A—Armco Iron Purified 92 hours in Hydrogen at 1200 Degrees Cent.
 B—Same Specimen 6 Hours Later.
 C—Cast Brass.

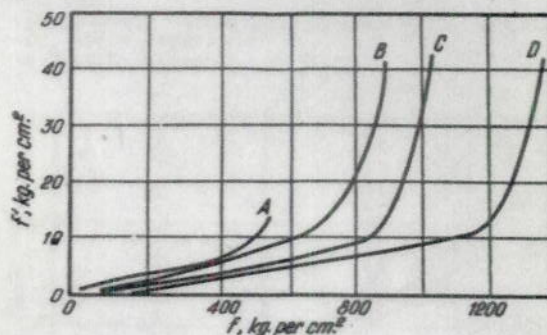


Fig. 6—Armco Iron Strain-Annealed to Produce Various Grain Diameters.
 A—Grain Diameter 1.0 Millimeter
 B—Grain Diameter 0.25 Millimeter
 C—Grain Diameter 0.065 Millimeter
 D—Grain Diameter 0.025 Millimeter

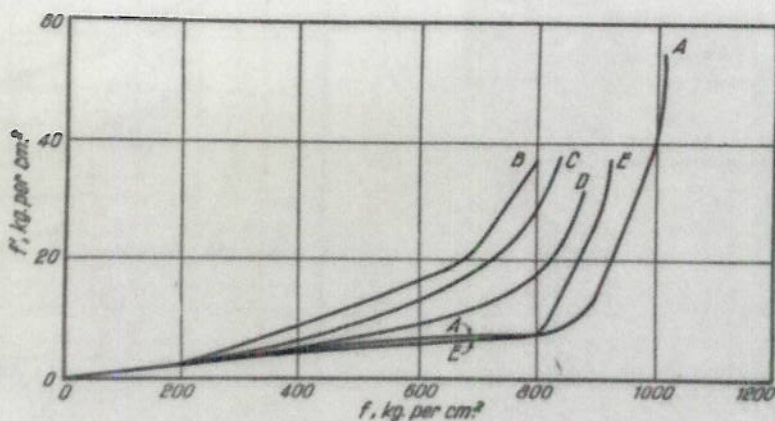


Fig. 7—Plastic Deformation and Recovery.
 A—Original Condition.
 B—Immediately After Overstrain.
 C—1 Hour Later.
 D—3 1/2 Hours Later.
 E—22 Hours Later.

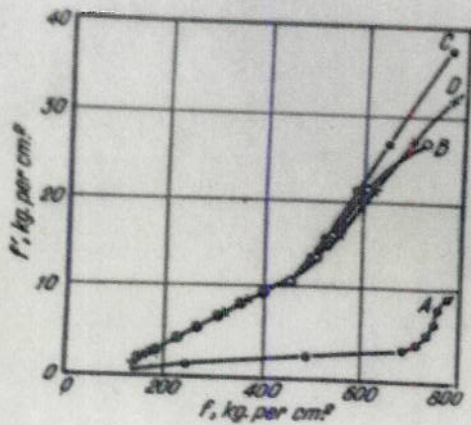


Fig. 8—Varying Amounts of Over-strain.

- A—Original Condition.
- B—4 Degrees Cold Twist.
- C—7 Degrees Cold Twist.
- D—10 Degrees Cold Twist.

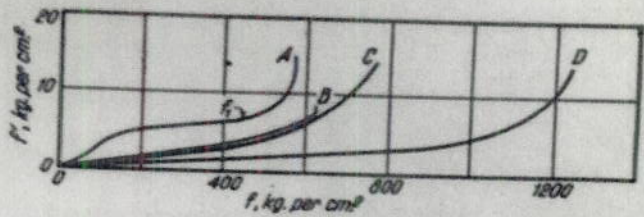


Fig. 9—Plastic Deformation and Recovery in Purified Iron.

- A—Original.
- B—Immediately After 180 Degrees Cold Twist.
- C—20 Hours Later.
- D—6 Months Later.

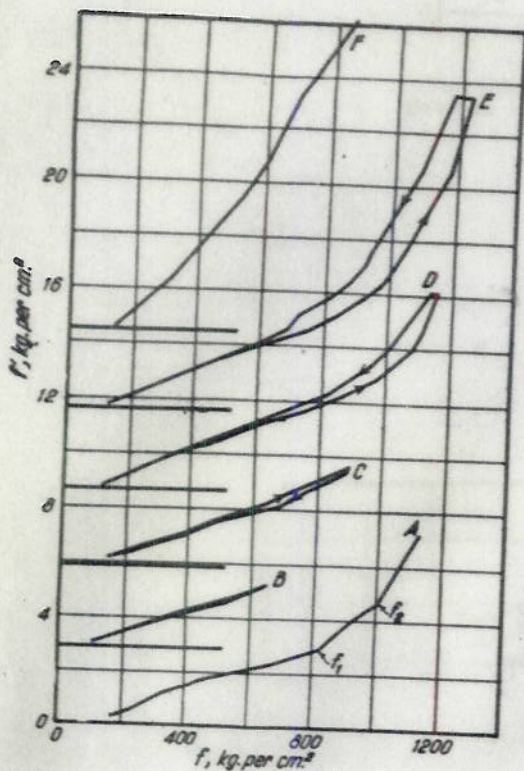


Fig. 10—Ascending and Descending Curves (0.25 per cent Carbon Steel).
 A—Original.
 B—C—D—E—Curves Carried to Indicated Amplitudes.
 F—Same After 2,700,000 Cycles at 1200 kg/cm.².

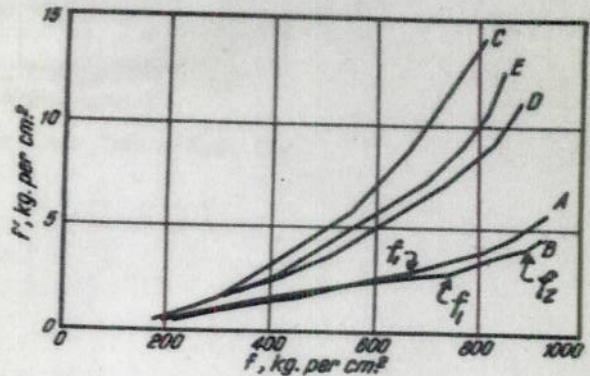


Fig. 11—0.25 Per Cent Carbon Steel.

- A—Original.
- B—After 5,000,000 Cycles at 700 kg/cm.².
- C—Same After 2,700,000 Cycles at 1000 kg/cm.².
- D—Same After 3,000,000 Cycles at 650 kg/cm.².
- E—Same After 30 Hours' Recovery.

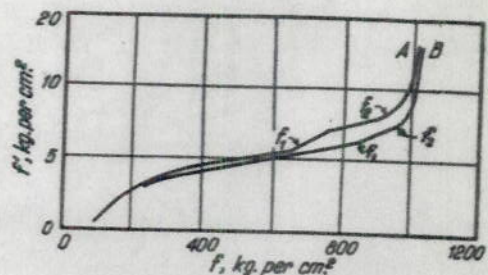


Fig. 12—Armco Iron as Rolled.

- A—First Curve.
- B—After Taking Data for Curve A.

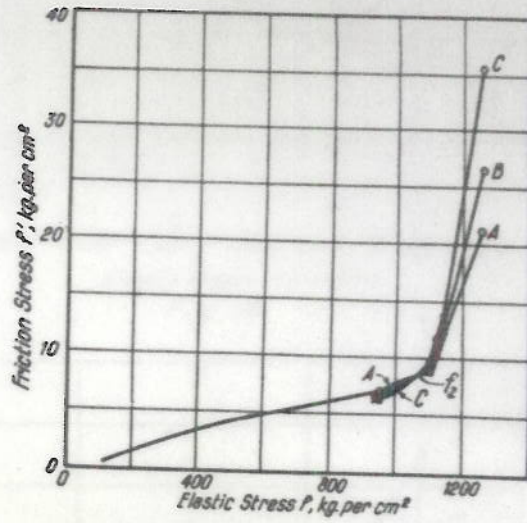


Fig. 18—0.10 Per Cent Carbon Steel (Explanation in Text).

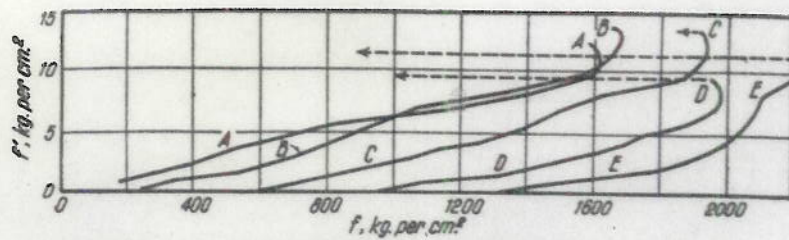


Fig. 18—0.10 Per Cent Carbon Steel with Initial Loadings.

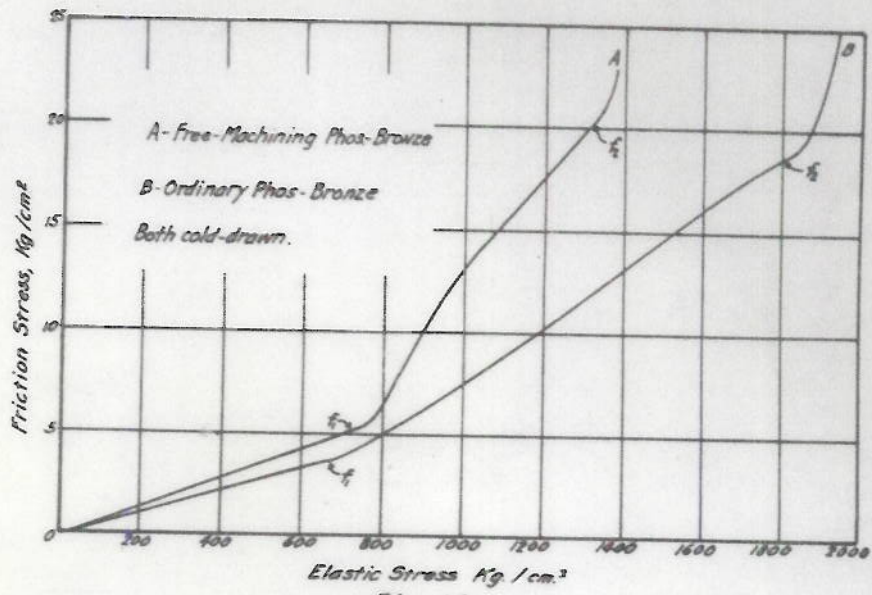


Fig. 14.

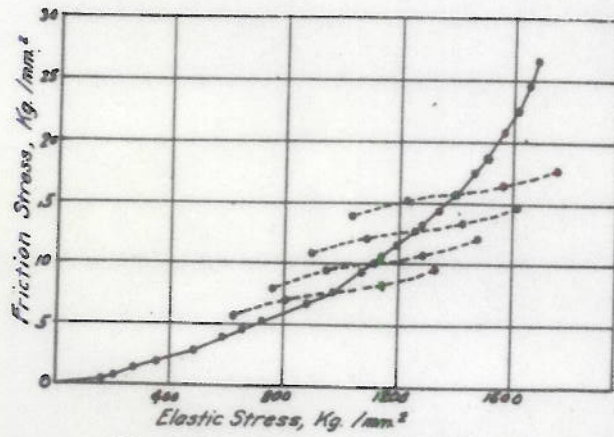


Fig. 16. "Free-Machining" Stainless Iron.

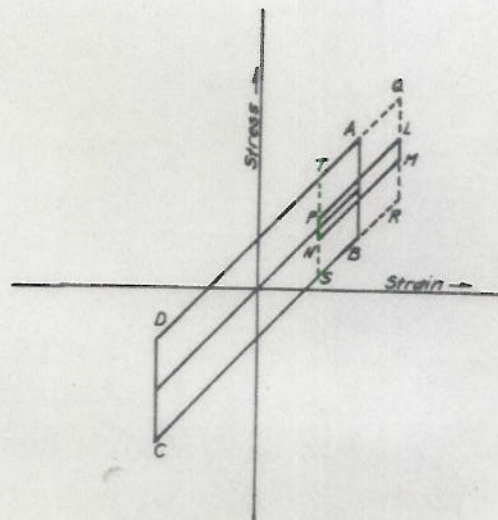


Fig. 17.