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A STUDY OF THE IKEDA SHORT-TIME (ELECTRICAL RESISTANCE) TEST FOR FATIGUE STRENGTH OF METALS

BY

HERBERT F. MOORE

AND

SEICHI KONZO

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I. Introduction

1. *Proposed Short-Time Tests for Fatigue Strength.*—The determination of the endurance limit of a metal under repeated stress by the regular long-time method involves the testing of at least six specimens. The time required for a fatigue test of ferrous metals is about one week, and for some non-ferrous metals as much as a month or more. Various short-time tests have been proposed to determine this valuable physical property.

Short-Time High Stress Tests:—It has been frequently proposed to evaluate the comparative fatigue strength of a number of metals by subjecting samples to cycles of high stress which will produce failure in a short time. The endurance under this arbitrary high stress is taken as a measure of fatigue resistance. This method is utterly unreliable for determining resistance to working stresses. If the metals are arranged in order of merit as shown by this test, and the fatigue strength is then determined by a long-time test, the order of merit of the metals as determined by this latter test will, in general, be quite different.

Rise-of-Temperature Test:—The rise-of-temperature test was developed by Stromeyer,* and later by Putnam and Harsch.† In this test a specimen is subjected to cycles of repeated stress for a few moments and the temperature measured. The stress is then raised and after another short run the temperature is measured again. The process is repeated until there is a distinct break in the stress-temperature curve. The stress at which this break occurs is taken as the endurance limit of the metal. Where delicate thermocouple measurements have been used, the method has worked fairly well for ferrous metals. It has not been satisfactory for all of the non-ferrous metals tested.

Running Deflection Test:—This test has been developed by Gough.‡ In it the deflection of the running specimen is carefully measured and as the load is increased on the specimen the stress-deflection curve is

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*Memo. Chief Engr., Manchester (England) Steam Users Assn., 1913.

†"An Investigation of the Fatigue of Metals," Univ. of Ill. Eng. Exp. Sta. Bul. 124, 1921. See also Gough, "The Fatigue of Metals," chap. X; Moore and Kommers, "The Fatigue of Metals," p. 148.

‡"Improvements in Methods of Fatigue Testing," The Engineer (London), Aug. 12, 1921, p. 159.

plotted. The stress at which this curve can be seen to deviate from a straight line is taken as the endurance limit of the metal. This test has also been fairly satisfactory for ferrous metals, but has not been satisfactory for certain non-ferrous metals.

Power Input Test:—This method has been developed by Lehr.* It consists in driving a fatigue testing machine with a motor so small that it is loaded nearly to capacity by the machine. A watt-meter measures the input to the motor and, as the load is increased on the specimen, a curve is plotted with stress as ordinates and watts input (less watts consumed in friction) as abscissas. The break of the curve is taken to locate the endurance limit. A number of tests comparing long-time test results with the results of power-input tests are reported, and a fair agreement is found for quite a number of ferrous and non-ferrous metals. The test seems to be of considerable promise.

2. *Difficulties with Short-Time Tests.*—The difficulty with all of the tests previously named, except possibly the power-input test, seems to be that they detect *slip* rather than the starting of a fatigue *crack.* Numerous experiments† have shown that at present no clear relation is known between the beginning of slip, with consequent mechanical hysteresis, and the start of a fatigue crack. In the case of the wrought ferrous metals slip seems to precede the starting of a fatigue crack and to occur at a stress but little below that corresponding to the starting of this crack. Hence, for wrought ferrous metals, the rise-of-temperature test and the running deflection test usually give values fairly close to those obtained by long-time tests, and on the safe side.

In the case of certain non-ferrous metals a fatigue crack apparently starts before there is any appreciable amount of slip. For such metals neither the rise-of-temperature test nor the running deflection test give any indication of structural damage until after fatigue cracks have started and slip begins.

Moreover, these tests, again with the possible exception of the power-input test, depend for their indications on the general behavior of an appreciable mass of metal in the specimen. They may be said to be tests of the average behavior of an appreciable amount of the metal. A fatigue crack affects only a very minute amount of metal. It is not a phenomenon of *average* properties of the metal, but tends to be a phenomenon of minimum strength.

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*Engineering (London), Feb. 18, 1927, p. 212. See also Lehr's Doctor's thesis (1925) at the Technical High School, Stuttgart.

†See B. P. Haigh, "Hysteresis in Relation to Cohesion and Fatigue," Trans. Faraday Soc. vol. XXIV, part 2, Feb., 1928; also Moore and Kommers, "The Fatigue of Metals," chap. III and IV.

3. *The Electrical Resistance Method for Determining Fatigue Limit.*—The measurement of change of electrical resistance under repeated stress seems to be worthy of study. It would appear reasonable to suppose that the opening up of an actual fatigue crack would affect the resistance of a piece of metal fully as much as would the phenomenon of slip without fracture, and that a distinct change in resistance might be expected due to fatigue cracks in their early stages. The general principle of measurement of electrical resistance has been used with marked success by Sperry* to detect incipient fissures in steel rails, and by Ikeda† as a short-time test for endurance limit. Ikeda's method, as carried out in a slightly modified form by Suzuki, is described in some detail in the appendix to this bulletin.

4. *Division of Work.*—In the winter and spring of 1928 Dr. M. Suzuki of the Japanese Imperial Government Railways spent some time as a visitor at the University of Illinois. He was familiar with the Ikeda test, and using a slightly modified apparatus, carried out some tests on steel and monel metal in the Fatigue of Metals Laboratory. His results checked fairly closely the results of the long-time tests. Upon his departure Mr. Konzo took up the further study of the Ikeda tests as a thesis for the degree of Master of Science in Mechanical Engineering. He worked under the general direction of PROF. H. F. MOORE, who is in charge of the Fatigue of Metals Laboratory. The fatigue machine used was designed by Professor Moore, who also kept in close touch with all the developments of the tests. Mr. Konzo carried out the actual work of testing and wrote his M. S. thesis. The material in that thesis has been used in the preparation of this bulletin by Professor Moore and Mr. Konzo in collaboration.

5. *Acknowledgments.*—Acknowledgment is made to the Mechanical Engineering Laboratory for the use of the delicate potentiometer required for the investigation, and to PROF. A. P. KRATZ for his very helpful suggestions concerning the use of the potentiometer. MR. M. MOZUMDAR, graduate student, also gave valuable assistance in connection with the tests of tool steel.

This study has been carried on as a part of the work of the Engineering Experiment Station of the University of Illinois, and has been under the general administrative direction of DEAN M. S. KETCHUM,

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*Iron Age, Nov. 15, 1928, p. 1214.

†Jour. Soc. of Mechanical Engineers of Japan, vol. XXXI, no. 136, 1928. Shoji Ikeda is on the staff of the Research Office of the Imperial Japanese Railways, and his tests were made in coöperation with Tohoku Imperial University, Sendai, Japan.

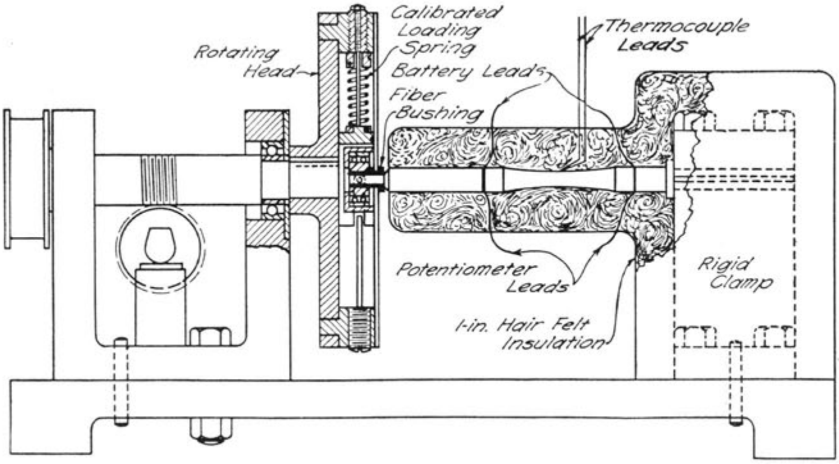

FIG. 1. ROTATING-SPRING TESTING MACHINE FOR REPEATED-STRESS TESTS

director of the Station. The work has been carried on as a joint activity of the Department of Mechanical Engineering, of which PROF. A. C. WILLARD is head, and of the Department of Theoretical and Applied Mechanics of which PROF. M. L. ENGER is head.

II. APPARATUS AND TEST METHODS

6. *Testing Machine.*—The testing machine used in these tests is described in Bulletin 136* (see Fig. 1). The specimen is firmly clamped at one end, and the load is transmitted to the other end by a ball bearing race attached to the rotating head of the machine. The applied load is determined by a spring, the deflection of which is measured by a strain gage fitted with a micrometer dial. The test specimen is stationary and is subjected to a flexural, cantilever-beam stress that varies at any one point on the specimen from full tension to full compression during each revolution of the rotating head.

The speed of the machine is approximately 1500 r.p.m. and does not vary appreciably from the no-load to the maximum-load condition.

Ikeda in his tests used a rotating-beam specimen, and made connection to his resistance measuring apparatus by means of thin flanges forming part of the specimen and dipping in mercury as the specimen rotated. This moving contact introduces difficulty in avoiding changes

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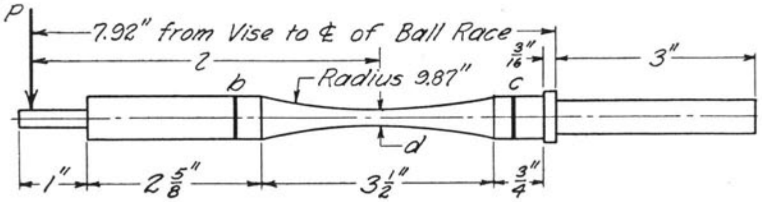
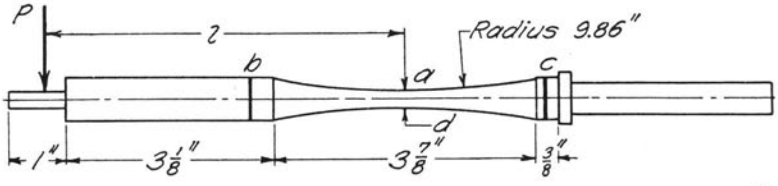
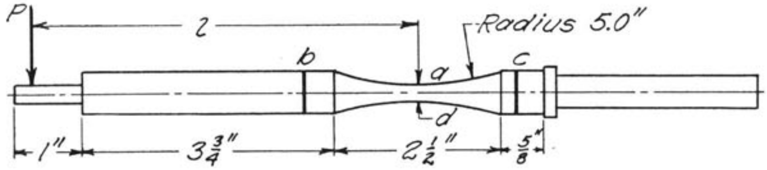
*"An Investigation of the Fatigue of Metals, Series of 1922," Univ. of Ill. Eng. Exp. Sta. Bul. 136, Appendix A, 1922.



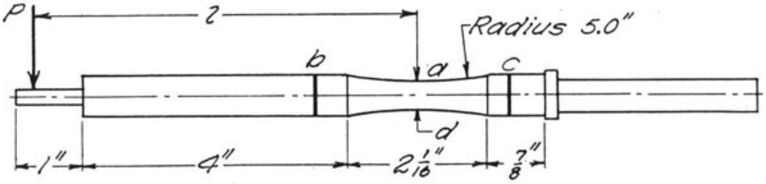
Armco Iron and S.A.E. 1020 Specimen d = 0.3"



Tool Steel Specimen, d = 0.25; Monel Specimen, d = 0.3"



Brass Specimen, d = 0.3"



Copper Specimen d = 0.4"

l = Lever Arm. d = dia. at Point of Maximum Stress

FIG. 2. SPECIMENS FOR ELECTRICAL RESISTANCE TESTS

of contact resistance, and in the present study a stationary specimen was used with contacts soldered to it. The necessity of stopping the testing machine in order to change load is a drawback of the stationary-specimen method, but it was not considered to be as great as the drawback of variable contact resistance on a rotating specimen.

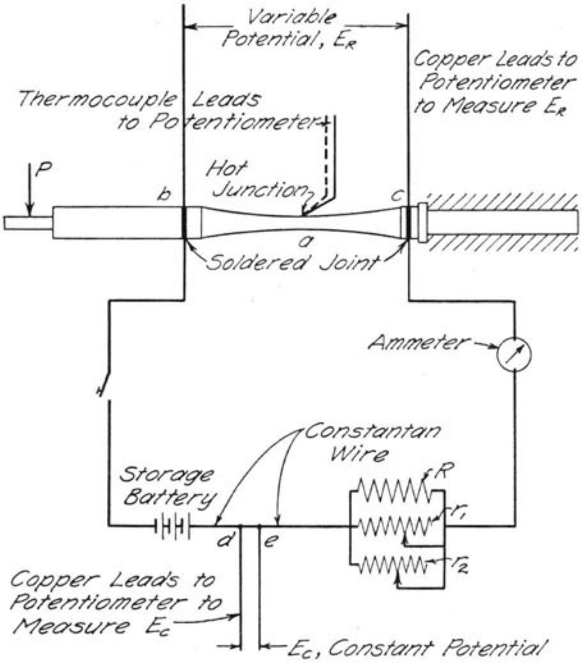


FIG. 3. WIRING DIAGRAM FOR ELECTRICAL RESISTANCE MEASURING APPARATUS

7. *Test Specimen.*—The dimensions of the test specimen are given in Fig. 2. The diameter at *a*, the smallest section, was 0.3 in. except for the tool steel specimen, for which it was 0.25 in., and for the copper specimen, for which it was 0.4 in.

The maximum stress in the specimen occurs at the least diameter at point *a* (Fig. 2), and is numerically equal to

$$S = \frac{32PL}{\pi d^3}$$

where S = stress in pounds per square inch
P = load applied at rotating head in pounds
L = distance from the load to point *a* in inches
d = diameter at point *a* in inches.

8. *Wiring Diagram.*—The measurement of resistance between two given points on the specimen (one on each side of the section of maximum stress) was made by the drop of potential method with a constant current in the specimen. The wiring diagram for the apparatus

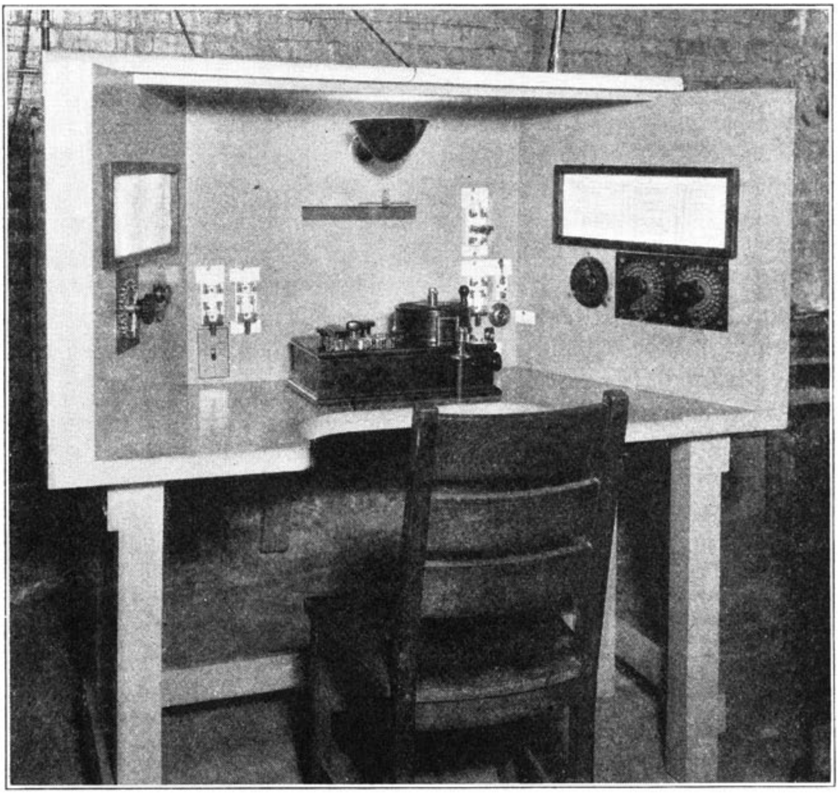


FIG. 4. POTENTIOMETER AND SWITCHBOARD

is shown in Fig. 3. By means of a 6-volt storage battery a flow of current was obtained through the test specimen between points b and c. The current was regulated by means of parallel resistances R, r_1, and r_2. An ammeter A was placed in the circuit, but was read only for approximate current adjustment. For finer current regulation the potential difference between points d and e (Fig. 3) on the constantan wire was balanced on the potentiometer and was kept constant throughout a test by means of the slide-wire resistances, r_1 and r_2. Since the resistance of the constantan wire is practically unaffected by the small temperature changes in the laboratory, if the potential drop E_c is kept constant, the current I for the circuit will also be constant. This method of current regulation is much more sensitive than that by means of an ammeter alone.

The potential drop E_R between the points b and c (Fig. 3) on the specimen is also measured on the potentiometer. The potentiometer used was a Leeds and Northrup instrument of the type catalogued by the makers as type K, in which drop of potential is balanced against the voltage of a Weston Standard cell. The general appearance of the potentiometer set-up is shown in Fig. 4.

The millivolt readings of two copper-constantan thermocouples used for temperature measurements were determined by the same potentiometer. The galvanometer measurement used in balancing the potentiometer is the null-deflection method, and has the advantage that the deflection is independent of the magnitude of the current flowing through the galvanometer circuit.

The current I was adjusted to approximately 5 amperes, which produced an e.m.f. reading on the potentiometer varying from about 1.500 to 5.500 millivolts, depending upon the material of the specimen and the location of the connecting lead wires b and c.

9. *Temperature Measurements.*—The temperature of the test specimen at point a was measured by means of a copper-constantan thermocouple made of No. 22 B. and S. gage wire with the hot junction of the wires tied securely to the surface of the specimen at the section of maximum stress. A thin sheet of waxed paper was interposed between the thermocouple and the metal surface. The thermocouple was calibrated against a standard thermometer.

To minimize the effect of sudden temperature changes in the laboratory the test specimen and stationary head were wrapped with hair felt insulation, as shown in Fig. 1. The air temperature of the laboratory was read by means of a thermocouple placed about ten inches away from the test specimen. The maximum temperature variation of the laboratory was about 2 deg. F. during the period of a single test, and the use of the hair felt insulation made the change in electrical resistance of the specimen due to this small temperature change in the laboratory negligible. Temperature readings of the laboratory were recorded, however, and note was made of any extreme variations.

10. *Test Procedure.*—The procedure followed during a test is given in outline form as follows:

(a) A load is applied on the rotating end of the specimen and the motor to the machine started. The constant potential E_c is adjusted on the potentiometer scale to a desired value, usually at 2.600 millivolts, by means of the resistances r_1 and r_2. After an interval of five minutes from the time of starting of the motor the potential drop

TABLE 1

CHEMICAL COMPOSITION AND HEAT TREATMENT OF METALS TESTED

Metal	Approximate Chemical Composition, per cent	Heat Treatment
1. Ferrous Metals		
Armco Iron	Carbon 0.02; silicon 0.02; manganese 0.03; phosphorus 0.005; sulphur 0.042.	Box annealed by manufacturer.
0.20 Carbon Steel (S.A.E. 1020)	Carbon 0.25; manganese 0.45; phosphorus 0.040; sulphur 0.05.	As rolled by manufacturer.
0.52 Carbon Steel	Carbon 0.52; silicon 0.24; manganese 0.56; phosphorus 0.037; sulphur 0.029.	Normalized at 1550° F.; heated to 1450° F. and quenched in water; reheated to 1200° F. and cooled in air.
Tool Steel	"Ryolite" brand of carbon tool steel.	Heated to 2300° F. and quenched in kerosene; reheated to 1100° F. and cooled in air.
2. Non-ferrous Metals		
Brass	Copper 60.25; zinc 39.61; lead 0.02; iron 0.02.	Treatment by manufacturer; cast in 6⅞ in. billet; heated to 1435° F.; cooled to 1290° F.; extruded to 1 in. round; reheated to 1020° F.; drawn to ¾ in. round; reheated to 1020° F.; cooled in air.
Monel Metal "111"	Nickel 68.95; copper 27.29; iron 2.22; manganese 1.38; carbon 0.20; silicon 0.08; phosphorus 0.019; sulphur 0.019.	Hot rolled by manufacturer.
Monel Metal "K"	Nickel 75.33; copper 18.79; iron 1.33; manganese 0.28; carbon 0.16; aluminum 3.87.	Heated to 1500° F.; quenched in water.
Copper	Copper 99.98.	Treatment by manufacturer; extruded at 1380° F. to 1 in. round; drawn to ⅞ in. round; annealed at 1290° F. in oxydizing atmosphere; drawn cold to ¾ in. round; annealed at 1290° F. in oxydizing atmosphere.

TABLE 2
MECHANICAL PROPERTIES OF METALS TESTED

Metal	Proportional Elastic Limit* lb. per sq. in.	Tensile Strength lb. per sq. in.	Brinell Number	Elongation in 2 in. per cent	Reduction of Area per cent	Endurance Limit by Long-time Test lb. per sq. in.
1. Ferrous Metals						
Armco Iron	16 100	42 400	69	48.3	76	22 000
0.20 Carbon Steel (S.A.E. 1020)	34 400	60 200	104	38.8	66	28 000
0.52 Carbon Steel	80 300	111 400	227	21.9	57	55 000
Tool Steel	......	......	...	....	..	130 000†
2. Non-ferrous Metals						
Brass	23 600	66 000	90	48.1	40	29 000
Monel Metal "111"	49 600	89 800	169	40.4	69	32 000
Monel Metal "K"	27 600	93 200	134	47.9	72	40 000
Copper	3 200	32 400	47	56.4	72	10 000

*Proportional elastic limit determined by modification of Method II of A.S.T.M. 1929 Tentative Standards. Modification consists in locating limit at stress where rate of strain has increased 25 per cent above its initial value, rather than 50 per cent.

†Approximate.

TABLE 3
TYPICAL SET OF TEST DATA FOR DETERMINATION OF ENDURANCE LIMIT BY RESISTANCE METHOD

Test No. 5. Metal, brass. Specimen 103 A 49.

Dimensions of specimen (See Fig. 2), l = 5.81 in., d = 0.308 in.

Constants of Electrical Circuit (See Fig. 3) E_c = 2.650 millivolts, I_c = 5.1 amperes.

Constants for Testing Machine (See Fig. 1) Spring, 60-lb. Tabor indicator spring. Each increment of load remained on specimen 5 minutes. See Fig. 9 for graphical data.

Reading	Load on Specimen lb.	Computed Stress in Outer Fibers of Specimen lb. per sq. in.	Drop of Potential between b and c (Fig. 3) E_R millivolts	Temperature of Specimen deg. F.	Temperature of Laboratory Air deg. F.
1	0.0	0	1.658	75.5	74.5
2	6.0	12 100	1.678	75.8	74.6
3	8.9	17 900	1.685	76.0	74.3
4	12.2	24 600	1.695	76.1	74.4
5	14.4	29 000	1.708	76.2	75.6
6	16.2	32 500	1.729	76.4	74.3
7	17.5	35 300	1.738	76.5	74.3
8	19.2	38 800	1.752	77.2	75.2
9	21.7	43 700	1.775	79.4	75.0
10	24.0	48 400	1.796	83.7	75.1

across points b and c is read on the potentiometer. Temperature readings of the air and of the test specimen are also obtained by the thermocouple readings on the potentiometer.

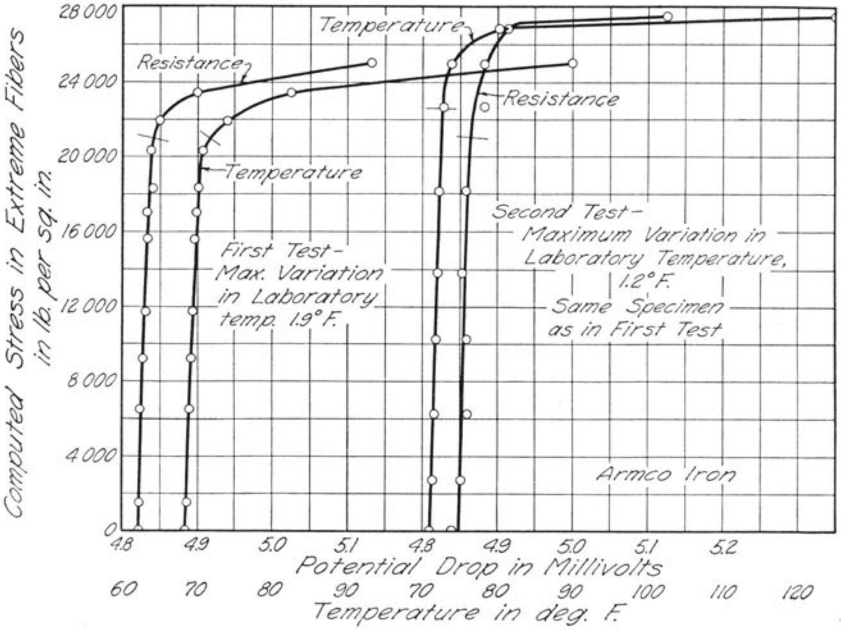


Fig. 5. Graph of Resistance and Temperature Tests—Armco Iron

(b) When the potential drop and thermocouple readings have been taken for the given load, the motor is stopped, a greater stress applied,* and the process repeated. Note that the current is regulated at each reading immediately before taking the measurement E_R.

(c) A curve is plotted during the test, and the increments of compression of the load spring of the testing machine are taken in smaller steps when the change in slope of the curve becomes apparent. The test is stopped when a definite break in the curve has been obtained.

III. Test Data and Results

11. *Metals Tested.*—The approximate chemical composition and the heat treatment of the metals tested are given in Table 1. The physical properties are given in Table 2. The value of the endurance limit by the long-time test was obtained in most cases from values previously determined for the particular bar of metal in the course of the regular work of the Fatigue of Metals Laboratory.

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*In order to minimize the time that the machine was stopped while changing load it was the practice to give a slight turn to the screw controlling the pressure of the loading spring (Fig. 1) and then to read the load on the spring by means of the strain gage. To adjust the spring carefully to a given load would require much more time.

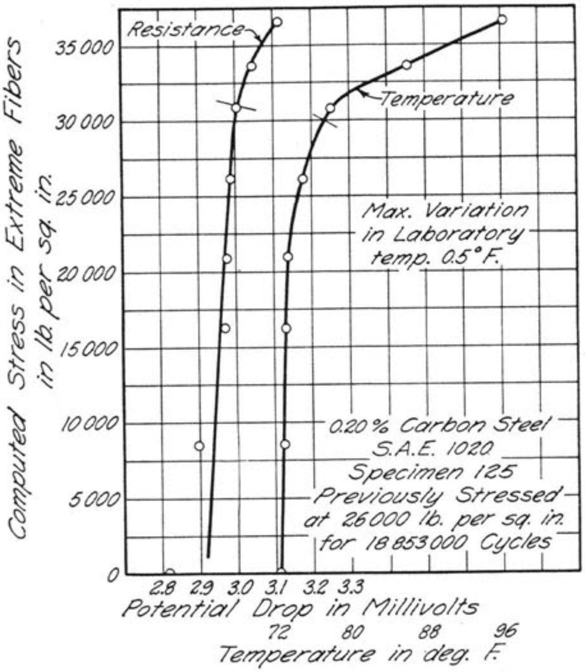

FIG. 6. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—0.20 CARBON STEEL

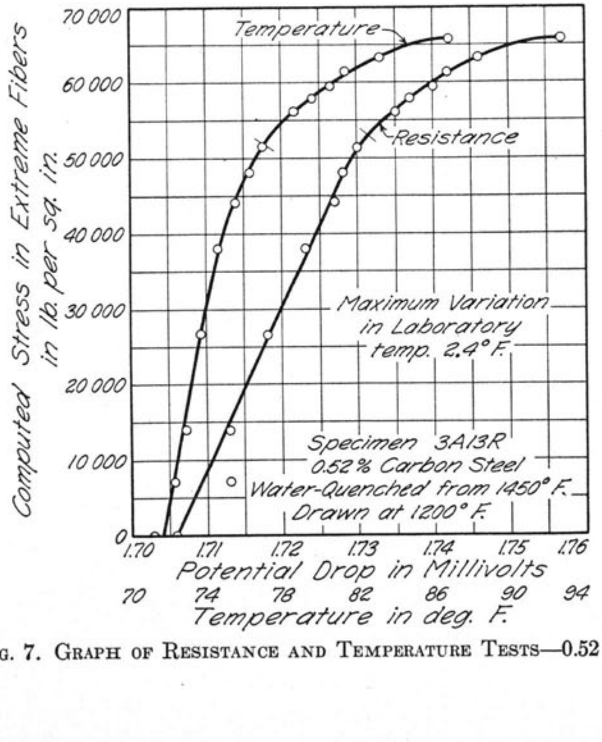

FIG. 7. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—0.52 CARBON STEEL

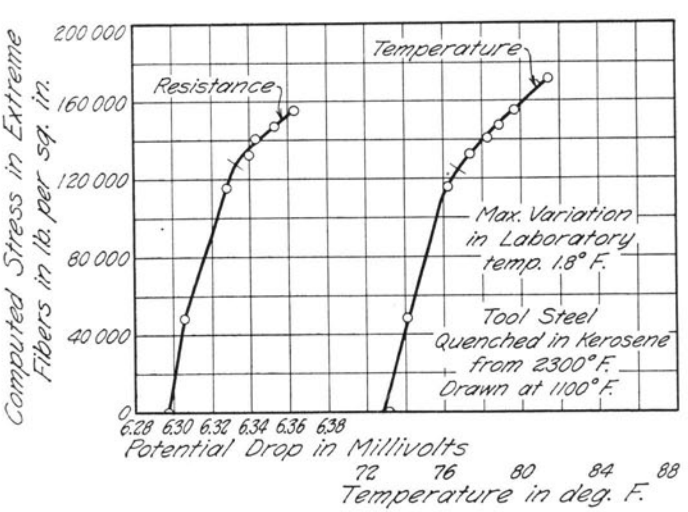

FIG. 8. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—TOOL STEEL

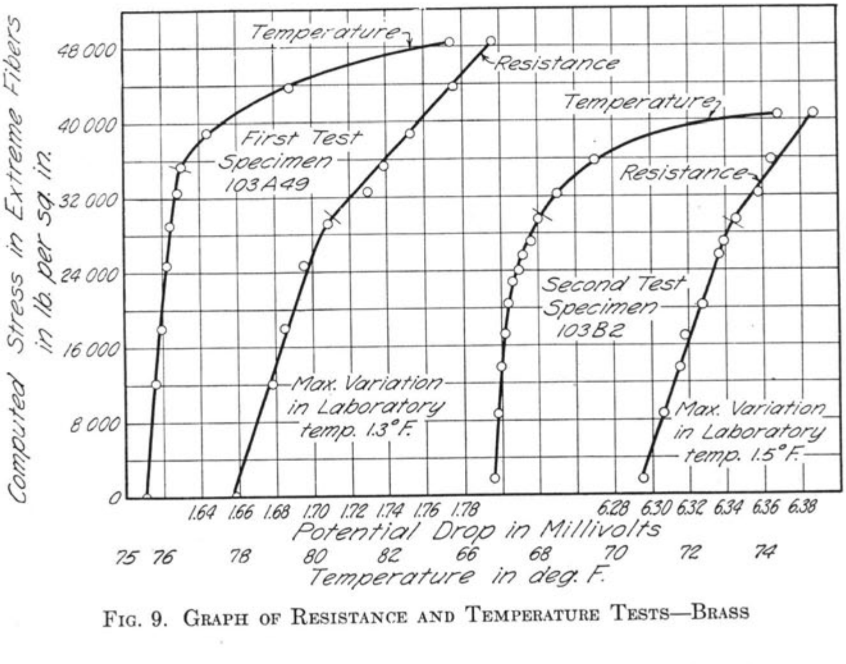

FIG. 9. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—BRASS

12. *Test Data and Results.*—Table 3 gives a typical set of test data for a test by the resistance method described on pages 8 to 15, inclusive. Figures 5 to 11, inclusive, give graphical test data for the

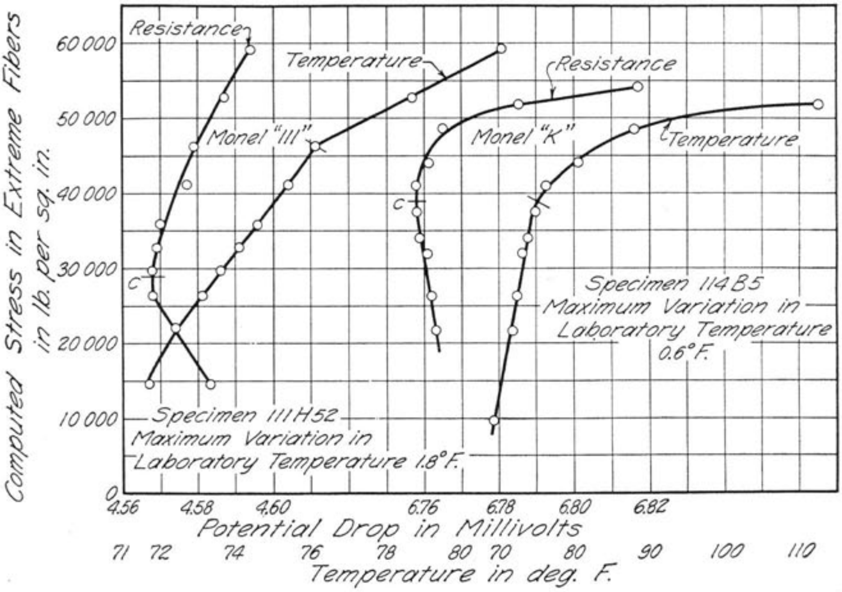

FIG. 10. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—MONEL METAL

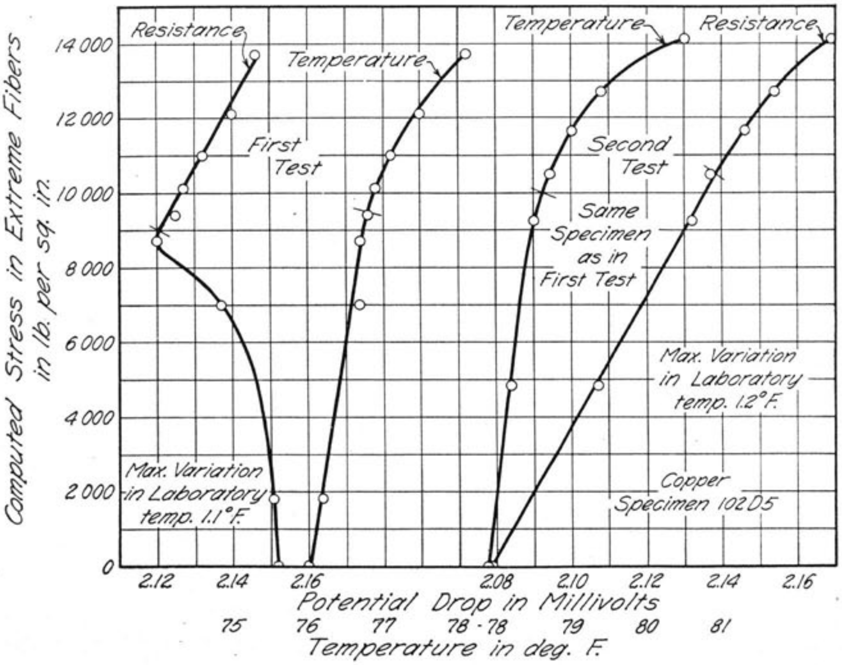

FIG. 11. GRAPH OF RESISTANCE AND TEMPERATURE TESTS—COPPER

tests by the resistance method. It will be noted that the use of a thermocouple to measure the temperature of the specimen made possible the trying out of the rise-of-temperature method for determining endurance limit. Table 4 gives a comparison of the endurance limits determined by the long-time test, by the rise-of-temperature test, and by the resistance method. Figures 12 and 13 show the *S–N* (stress-cycle) diagrams for the long-time fatigue tests.

The average total time required to make a combined resistance and temperature test was about 2¼ hours. With practice and a systematized routine it should be possible to make a resistance test in much less time.

IV. Discussion of Results

13. *Correlation of Results of Short-Time and Long-Time Fatigue Tests.*—Table 4 shows at a glance the correlation between endurance limit as determined by (a) the rise-of-temperature test, (b) the Ikeda resistance test, and (c) the ordinary long-time fatigue test. The results of the test of 0.20 carbon steel require special explanation. The specimen subjected to the resistance test and to the rise-of-temperature test had been previously subjected to some 18 000 000 cycles of stress just a little below the long-time endurance limit. This "coaxing" treatment would have the effect of raising the endurance limit appreciably.* Hence the fact that the resistance test and the rise-of-temperature test give slightly higher values for endurance limit than do the long-time tests is evidence for the reliability of these tests rather than the reverse.

For most of the metals other than the 0.20 carbon steel the results of both the resistance test and the rise-of-temperature test show fair correlation with the results of the long-time tests. The resistance test in all cases gives slightly lower values for endurance limit than the long-time test, that is, the results of the resistance test are on the "safe" side. The rise-of-temperature test results show fair correlation with the results of the long-time test with the exception of the results on monel metal "111", in which the rise-of-temperature value for endurance limit is very much on the "danger" side of the long-time endurance limit. The endurance limit for the brass is slightly on the "danger" side. Former tests of the rise-of-temperature method gave results on the "danger" side of long-time results for cold-drawn copper, cold-drawn bronze, and cold-drawn brass.†

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*"An Investigation of the Fatigue of Metals, Series of 1923," Univ. of Ill. Eng. Exp. Sta. Bul. 142, p. 13 and pp. 27-31.

†"An Investigation of the Fatigue of Metals, Series of 1925," Univ. of Ill. Eng. Exp. Sta. Bul. 152, p. 61.

TABLE 4

ENDURANCE LIMITS DETERMINED BY LONG-TIME TESTS, BY RISE-OF-TEMPERATURE TESTS, AND BY RESISTANCE TESTS

Metal	Long-time Test Maximum Number of Cycles of Stress	Endurance Limit—lb. per sq. in.			Deviation from Long-time Test Result—per cent	
		Long-time Test	Rise-of-Temperature Test	Resistance Test	Rise-of-Temperature Test	Resistance Test
1. Ferrous Metals						
Armco Iron	30 025 000	22 000	20 500*	20 600*	− 6.8†	− 6.4†
0.20 Carbon Steel (S.A.E. 1020)	21 100 000	28 000	30 000‡	31 000‡	+ 7.0‡	+10.5‡
0.52 Carbon Steel	108 987 000	56 000	52 000	53 000	− 7.3	− 5.5
Tool Steel	5 273 000	134 000§	125 000	128 000	− 6.6	− 4.5
2. Non-ferrous Metals						
Brass	400 000 000	30 000	32 500*	29 500*	+ 2.0	− 1.6
Monel Metal "111"	700 000 000	32 000	46 000	29 000	+43.8	− 9.4
Monel Metal "K"	450 000 000	40 000	39 000	39 000	− 3.3	− 3.3
Copper	400 000 000	10 000	9 800*	9 800*	− 2.0	− 2.0

*Average of two tests.

†A negative deviation indicates a result on the "safe" side.

‡Specimen tested by resistance and rise of temperature had previously been subjected to some 18 000 000 cycles of stress at 26 000 lb. per. sq. in., thus raising the endurance limit above the value determined by the long-time test.

§Estimated.

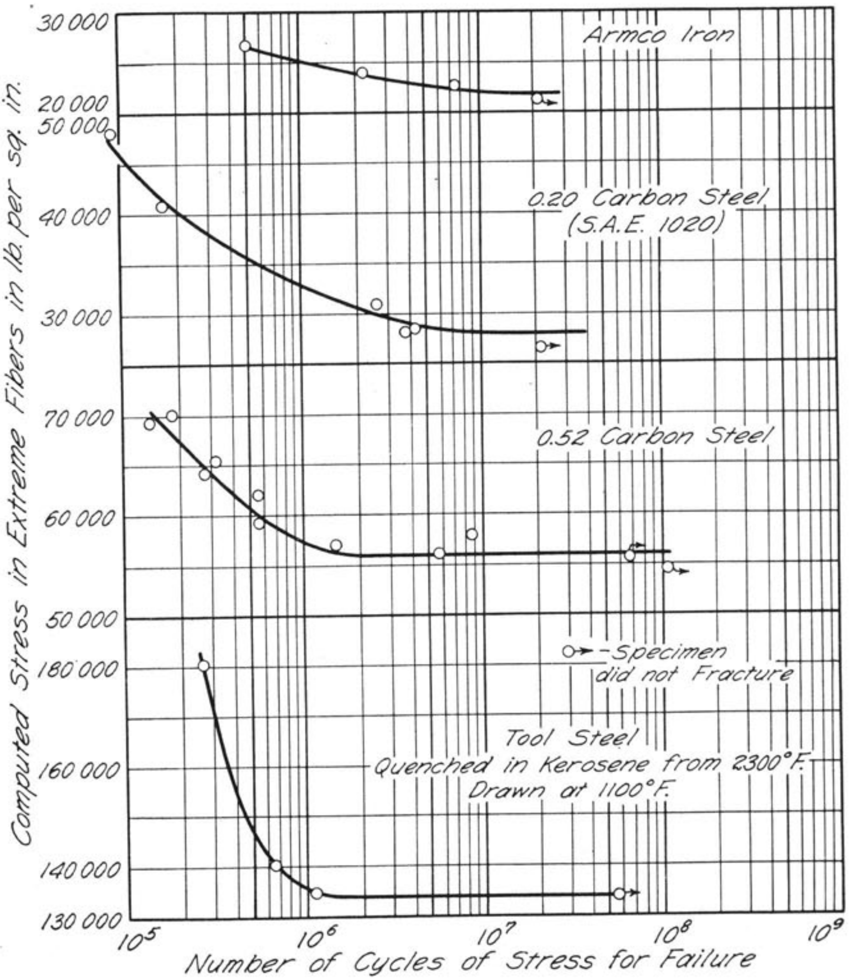

FIG. 12. *S-N* DIAGRAMS FOR LONG-TIME FATIGUE TESTS—FERROUS METALS

While further tests should be made before reaching a final decision as to the reliability of the Ikeda resistance test, especially tests of aluminum alloys, of cold-drawn metals, and of heat-treated alloy steels, yet the present tests do cover a considerable range of metals, both ferrous and non-ferrous, and do indicate that for this range of metals the Ikeda test does give results quite fairly close to those given by the ordinary long-time fatigue test.

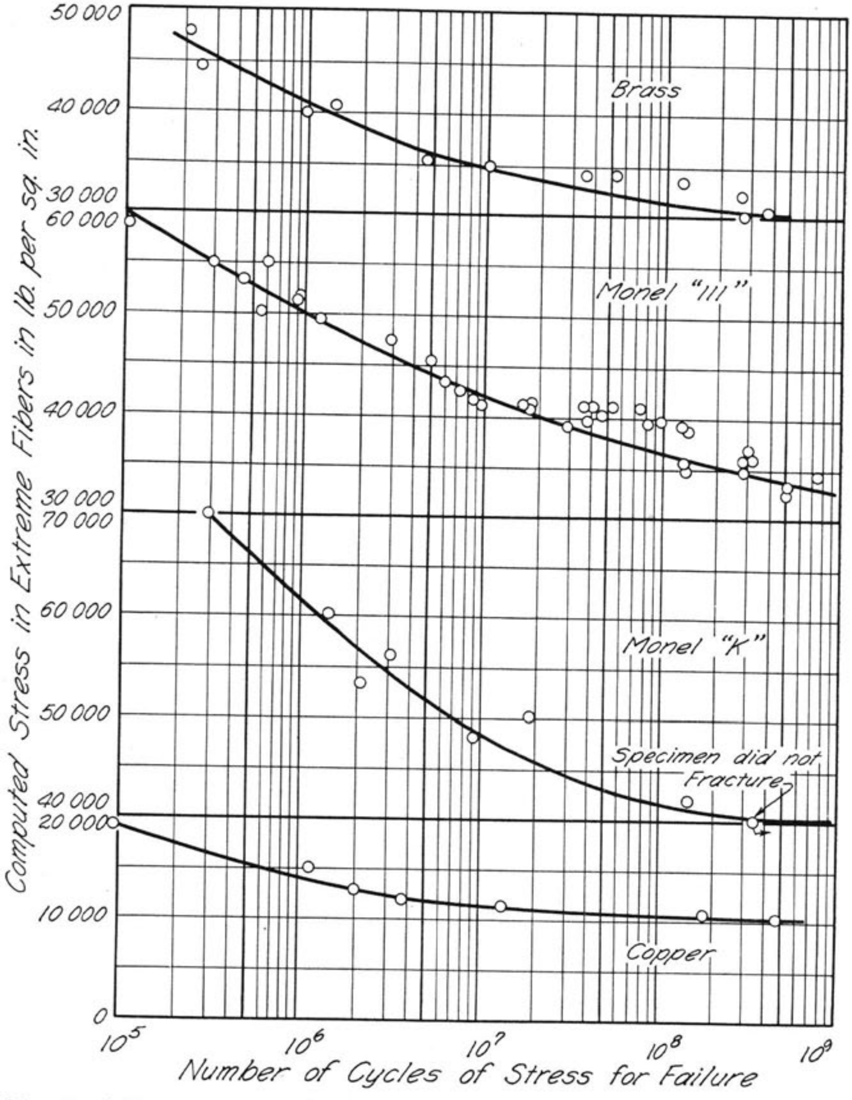

FIG. 13. S-N DIAGRAMS FOR LONG-TIME FATIGUE TESTS—NON-FERROUS METALS

14. *Mechanical Hysteresis under Repeated Stress.*—No well-defined relation has been established between mechanical hysteresis and the beginning of fatigue failure in a metal. Mechanical hysteresis does, however, appear to be the chief cause of the production of heat in a metal under repeated loading. Observations by Bauschinger, Bair-

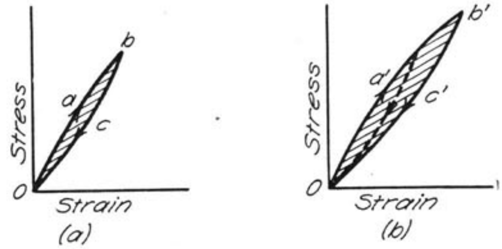

FIG. 14. ELASTIC HYSTERESIS LOOPS

stow, and others, have disclosed the fact that in a complete stress cycle from minimum load to maximum load and back to minimum again, a hysteresis loop is formed even for elastic materials, that is, materials that do not "set" upon the release of stress. Thus in Fig. 14 the stress-strain curve *bc* formed by the release of stress does not coincide with *ab* which is that formed when the specimen was stressed from *O* to point *b*. In an elastic material, however, there remains no permanent set upon release of the load, and the hysteresis loop forms a closed loop at point *O*. (For the sake of simplicity only one-half of the complete stress cycle is shown in Figs. 14 and 15, instead of the complete cycle from full tension to full compression.)

The size and extent of the hysteresis loop for the condition of elasticity is dependent upon (a) the character of the material, (b) the magnitude of stress, and (c) the previous history of the specimen, as follows:

(a) Materials with high elastic strength, as a rule, have smaller hysteresis effects. Certain non-ferrous metals exhibit marked hysteresis effects at low stresses.

(b) The area of the hysteresis loop is directly dependent on the range of stress, as can be seen from Fig. 14b, for both elastic and plastic materials. Certain metals, and especially a few in the non-ferrous group, exhibit some degree of permanent set even at stresses below the endurance limit under repeated stress. This factor must be accounted for in the establishment of a theory of fatigue failure.

(c) The previous history of the specimen, such as heat-treatment, cold-working, overstressing, etc., affects the constitution of a metal and its ability to recover from an applied stress, and hence the size and shape of the hysteresis loop.

When the metal passes from the stage of elasticity to one of plastic deformation the stress-strain curve begins to assume the shape shown

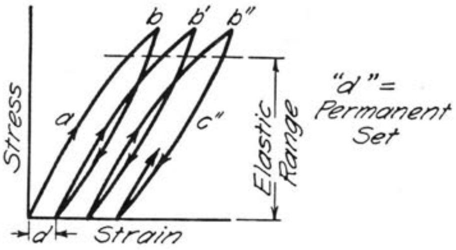

FIG. 15. HYSTERESIS LOOPS FOR SEMI-PLASTIC AND PLASTIC STRAIN

in Fig. 15, in which the curves for repeated-stress cycles are shown superimposed upon each other. At the end of the first cycle a small deformation *d*, or permanent set, has taken place, and when the stress is repeated the total set increases by additional amounts of *d*. Theoretically, if the stress were repeated a sufficient number of times it would be but a matter of time until the set has so increased that the breaking point would be reached. Actually, however, failure may or may not occur at this stress. Readjustments in structure may take place causing a diminishing set each time until finally the condition shown in Fig. 14a has been attained. The presence of adjustment slip-lines in micrographs of stressed specimens confirms the latter point of view.

We have then somewhat the following picture, from the strain viewpoint, of the behavior of a specimen subjected to cycles of repeated stress. In the first stage at very low stresses the hysteresis-loop formation is as indicated in Fig. 14a, a condition of elasticity (no permanent set). As the stress is slightly increased the hysteresis loop is increased in area (Fig. 14b), but the condition of elasticity or complete recovery is still maintained. As the repeated stress is still further increased a condition of semi-plasticity occurs in the second stage. As in Fig. 15 a small deformation *d* is produced at each stress cycle, but on account of the readjustments and orientations of the crystals, no further increase in set is produced. The area of the hysteresis loop is, however, larger than that in the first stage. In non-ferrous metals this stage may occur at fairly low stresses. As the stress is increased still more the third stage of disintegration sets in. The permanent set *d* after each cycle accumulates (Fig. 15) and the readjustment process can no longer strengthen the metal. Eventually the crack that is formed weakens the metal sufficiently to cause fatigue failure. In the case of some metals, such as monel and duralumin, the crack seems to form at stresses which do not cause hysteresis loops of appreciable size.

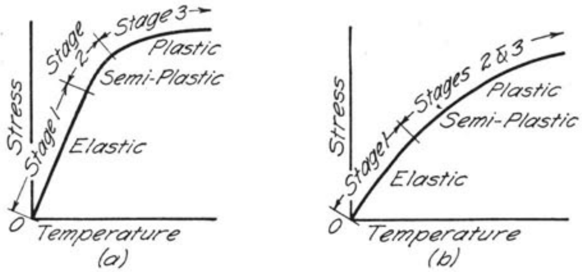

FIG. 16. STRESS-TEMPERATURE DIAGRAMS SHOWING STAGES OF HYSTERESIS

15. *Evolution of Heat under Repeated Stress.*—The area within a hysteresis loop is a representation of the net work which the specimen receives from each complete cycle of externally applied stress.* In the elastic range of stress, then, the heat evolved internally by the application of stress increases as the stress is increased (Fig. 14b). For most ferrous metals this heat evolution is approximately a linear function of the stress (Fig. 16a), although it need not necessarily be so. The curves for a few non-ferrous metals indicate that the relation between stress and heat, or temperature, is only approximately linear, and that at only very low stresses. The stress-temperature curves of such metals are slightly rounded even at low stresses (see Fig. 16b), also the transformation from the elastic state to the plastic state is less sharply marked than in the case of most annealed steels.

When the metal passes from the first stage of complete elasticity to the second state of semi-plasticity, the area of the hysteresis loop is increased more rapidly in proportion to the stress than before. The result is outwardly evidenced by a more rapid temperature increase. The approximately linear relation between stress and temperature is then displaced by a fairly rapid divergence of the curve. Finally, through a less marked transition, the third stage is reached, in which the temperature rises enormously with a small increase in stress.† In the rise-of-temperature method the attempt was made to correlate the endurance limit with the stress corresponding to the point of di-

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*Gough believes that the closed hysteresis loop has a definite width due to the presence of metastable atoms that are mechanically reversible but thermodynamically irreversible.
See Aeronautical Research Comm. Report No. 999, Nov., 1924 by H. J. Gough, D. Hanson, and S. J. Wright (London).

†Haigh classifies thermal effects due to any given load into primary, secondary, and tertiary effects. The primary stage is the adjustment stage, characterized usually by "heat bursts," the tertiary stage is one of rapid disintegration, and the secondary stage is regarded as a characteristic feature of fatigue. In the discussion here, the secondary stage is prominent in the elastic and semi-plastic stages, while the tertiary stage is dominant in the plastic regions.
See B. P. Haigh, "Hysteresis in Relation to Cohesion and Fatigue," Trans. of the Faraday Society, vol. XXIV, part 2, Feb., 1928.

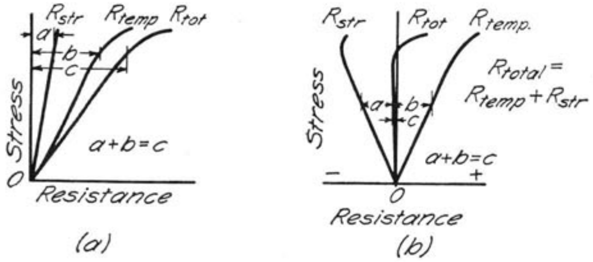

FIG. 17. TWO FORMS OF STRESS-RESISTANCE DIAGRAM

vergence of the stress-temperature curve from the linear relationship. The tests on ferrous metals appeared to indicate good coincidence between the two. For ferrous metals the curve for the first stage was practically linear, for stage two it was short, and for stage three it was unmistakable in its outward evidences. For non-ferrous materials, on the other hand, the coincidence between the endurance limit and the break in the curve was not so good. The transition stages between elastic and plastic conditions were less clearly defined, and it seemed probable that certain structural rearrangements were taking place at stages two and three.

16. *Change in Electrical Resistance under Repeated Stress.*—The method of measuring electrical resistance takes into account a factor which was neglected in the rise-of-temperature test. The electrical resistance of a metal is composed of two parts:

(1) that due to its absolute temperature, and
(2) that due to its structural arrangement.

For practically all metals a rise in temperature of the metal is accompanied by an increased resistance to a flow of electrical current. From the tests of resistance and temperature presented in this bulletin the following conclusions are made:

(a) For all the metals tested a rise in temperature of a metal is accompanied by an increase in its electrical resistance.

(b) For most ferrous metals and for many non-ferrous metals the break in the stress-resistance curve corresponds very closely to that in the stress-temperature curve. Apparently, then, the temperature effect is the larger factor for these metals, and the direct effect of structural change on resistance is comparatively small. (See Fig. 17a.)

(c) For certain non-ferrous metals, on the other hand, the effect of structural change must be considered, and not that of temperature alone. If we let the equation

$$R_{tot} = R_{temp} + R_{str}$$

represent the change in total resistance (R_{tot}), where R_{temp} is the increased resistance due to the temperature change, and R_{str} is the increased resistance due to structural change, then R_{str} for annealed ferrous metals is either negligible or a simple function of R_{temp}. For two non-ferrous metals studied, namely, monel and copper, R_{str} was not negligible and was negative in sign.

For instance, the stress-resistance curves for the two monel specimens and one copper specimen (Figs. 10 and 11) were negative in slope at the beginning, even though the temperature curve was positive in character. The *resultant* resistance curve may have a negative slope if R_{str} be greater than R_{temp}.

The negative slope thus obtained in these tests may not be a characteristic for the metals in general, but it brings to light a new phenomenon of fatigue failure. The decrease in resistance is comparatively small from O to c, but it does indicate that R_{str} must be greater than R_{temp} to overbalance its effect. This would indicate then that, up to a certain stress at least, a structural adjustment takes place such that the resistance to electrical flow is decreased. Whether this is due to the orientation of crystals, change of state, or formation of a closer bond between crystals cannot be stated at present.

A very interesting phenomenon was observed in the test on copper (see Fig. 11). In this test the slope of the resistance curve was negative at first, indicating that the resistance decreased as the stress increased. Possibly this may have been due to the release of internal strains within the metal. As the stress was increased beyond the critical range the slope became positive. In this test it must be noted that the metal was subjected to a stress well over the endurance limit.

When the same specimen was tested a little later under exactly the same conditions, except that of previous stressing, the slope of the resistance curve from beginning to end was positive in character (see Fig. 11, right-hand diagram). A possible explanation might be that any internal stress that may have existed in the specimen would have been destroyed by the first overloading, and hence any subsequent test would show no reduction in electrical resistance due to the release of internal strains.

Evidently in the tests of monel metal the conditions are not quite the same, since even for third and fourth tests on the same specimen the same decreasing resistance at the beginning of the test was observed. It is quite possible that metals subjected to working processes and metals having internal strains will give results of this nature. The action is well worthy of further investigation.

The action that was last discussed brings up the relative effects of surface hardening, case hardening, heat treatment, etc., on the shape of the resistance curve. From the small number of tests conducted no definite statment can be made as to whether this short-time resistance test will always give good correlation with the long-time endurance limit, although for the tests reported here the correlation seems fairly good. It is possible, for instance, that some metals may show such a drooping stress-resistance curve that a definite break in the curve will not be determinable.

17. *Desirable Lines for Further Study.*—The tests reported in this bulletin, the tests made by Suzuki (see Appendix), the tests made by Ikeda, and the success of the Sperry method of detecting incipient fissures in rails, give support to the statement that the Ikeda electrical resistance short-time test for endurance limit is a test having great promise of usefulness. In order to find out more about its uses and limitations the following subjects require further study:

(1) Tests of more metals, especially of aluminum alloys, cast iron, cold-drawn metals, and heat-treated alloy steels.

(2) Tests of the endurance limit of specimens with grooves, notches, threads, holes, poor surface finish, and other "stress raisers" to see whether the beginning of fatigue failure can be detected in such pieces by this short-time method.

(3) Tests of specimens under cycles of non-reversed stress, and under cycles of torsional (shearing) stress.

(4) Tests of case-carburized, nitrided, and heat-treated steel.

V. CONCLUSIONS

18. *Summary of Conclusions.*—The Ikeda electrical resistance method for determining endurance limit under repeated stress was investigated in connection with reversed-flexure fatigue tests of Armco iron, 0.20 carbon steel, 0.52 carbon steel, hardened tool steel, brass, monel metal, and copper. As a result of this investigation the following conclusions may be drawn:

(1) The results of these tests showed a fair coincidence between the endurance limit as determined by the Ikeda test and by

an ordinary long-time fatigue test. In general the Ikeda test gave results on the "safe" side, that is, the endurance limit determined by the Ikeda test was slightly less than that determined by a long-time test. The average deviation between the limit as determined by the two methods was 4.67 per cent, and the maximum, 9.4 per cent (disregarding results on 0.20 carbon steel, see p. 19).

(2) At the same time the rise-of-temperature test was made on the same metals. This test gave fair results for most of the metals, but signally failed in the test of one lot of monel metal, and for this case the Ikeda test gave good results.

(3) The tests gave evidence that the total change in the electrical resistance of a metal subjected to repeated stress depends on at least two factors: (a) change of resistance due to change in temperature, and (b) change of resistance due to structural rearrangements within the metal.

(4) For the ferrous metals tested the stress-resistance and the stress-temperature curves were of the same general character, and it appears probable that the temperature effect is the dominant one. For the monel metal specimens and one test of copper up to the endurance limit resistance *decreased* as stress increased, indicating that internal structural changes were more powerful in affecting resistance than heating effect.

APPENDIX

DIFFERENTIAL METHOD OF MEASURING CHANGES IN ELECTRICAL RESISTANCE DURING A FATIGUE TEST

The following is a description of an arrangement set up by Dr. M. Suzuki, Research Engineer with the Japanese Government Railways, at the University of Illinois in 1928 after the general scheme first proposed by Ikeda. Figure 18 shows the wiring diagram of the differential method. As noted on p. 8 Ikeda used a rotating-beam testing machine with contacts made between flanges on the specimen and mercury cups. Suzuki used the rotating-spring machine shown in Fig. 1 with contact wires soldered to the specimens.

It will be noted that the potential difference of the stressed specimen is compared with the constant potential drop across the unstressed auxiliary piece. The current through the two electrical circuits is maintained at a constant value by means of two separate battery circuits, and the difference in potential between the two circuits is measured on a deflection galvanometer. As the value of the

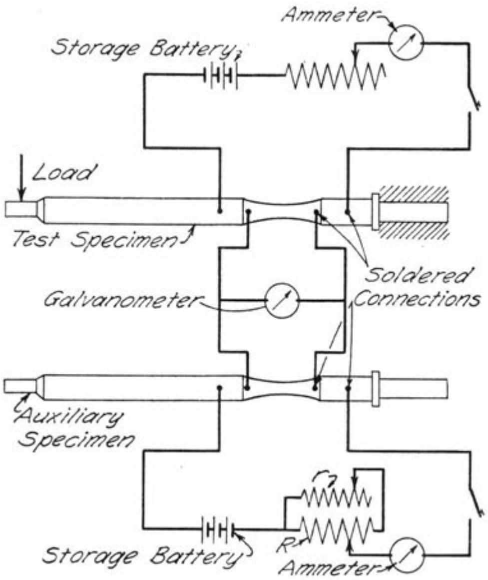

FIG. 18. WIRING DIAGRAM FOR IKEDA TESTS AS MODIFIED BY SUZUKI

repeated stress is increased in the test specimen its resistance changes and a larger galvanometer deflection is measured.

In order to be independent of the temperature changes of the laboratory, the two test pieces must be of the same material, or possess the same temperature coefficient of resistance. If some other constant resistance specimen be substituted for the auxiliary piece, then the change in laboratory temperature must be accounted for as in the potentiometer method described previously. A more complicated equipment is necessary for the differential method than for the potentiometer method, but the method will be found suitable where only a deflection galvanometer is available. It was found that the current strengths in the two circuits should be maintained at different values so as to have an initial deflection of the galvanometer at zero stress.

The results obtained for a 0.52 carbon steel and a monel metal specimen are shown in Fig. 19. The break in the stress-resistance curve for both tests is below the endurance limit as determined by ordinary long-time endurance tests. The 0.52 carbon steel specimen was later tested by the potentiometer method and its stress-resistance diagram is shown in Fig. 7. The endurance limit by the deflection method (Suzuki) was 52 000 lb. per sq. in., by the potentiometer

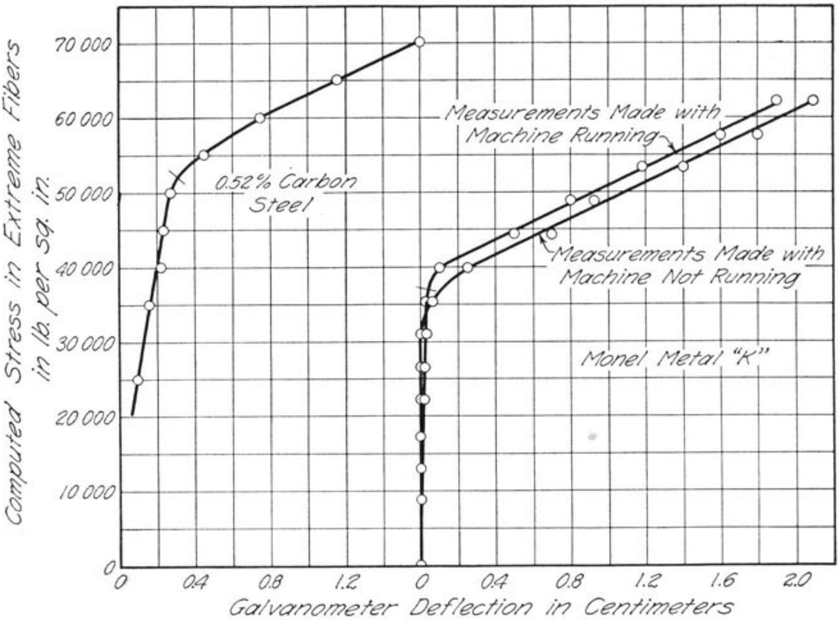

FIG. 19. GRAPH OF RESISTANCE TESTS BY SUZUKI

method (Konzo), 53 000 lb. per sq. in., and by long-time tests, 56 000 lb. per sq. in.

In the test of the monel metal by the deflection method (Suzuki) up to the endurance limit the resistance remained very nearly constant as the stress was increased; evidently the temperature effect and the effect of internal structural rearrangements very nearly neutralized each other. In this test readings of the galvanometer were taken while the machine was rotating, and also two minutes after the machine had been stopped to apply an increment of load. Figure 19 shows the two stress-resistance curves. Using the curve for readings taken with the machine running, the deflection method (Suzuki) gives an endurance limit of 37 000 lb. per sq. in. This specimen is the same metal as that listed in Table 4 as Monel metal "K", and the endurance limit by the potentiometer method (Konzo) is 39 000 lb. per sq. in., and by ordinary long-time fatigue tests, 40 000 lb. per sq. in.

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The Summer Session (eight weeks)

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