1941

The fatigue and bending properties of cold drawn steel wire, Trans. American Society of Metals, Vol. 29 (1941), p. 133, Reprint No. 52 (41-1)

H. J. Godfrey

Recommended Citation

Godfrey, H. J., "The fatigue and bending properties of cold drawn steel wire, Trans. American Society of Metals, Vol. 29 (1941), p. 133, Reprint No. 52 (41-1)" (1941). *Fritz Laboratory Reports.* Paper 1217.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1217

THE FATIGUE AND BENDING PROPERTIES OF COLD DRAWN STEEL WIRE

By H. J. Godfrey

Abstract

The paper presents the results of an investigation on the fatigue and bending properties of carbon steel wire. The special fatigue and bend testing machines developed for this study are described in this paper. The effect of wire drawing, decarburization and surface conditions on the fatigue properties have been investigated. The bend testing machine has been so designed that the severity of the bend test can be controlled in order to study the true bending properties of wire. Metallographic and X-ray studies of the internal structure of cold drawn wires are included in this paper.

INTRODUCTION

THIS investigation was primarily a study of the effect of cold working on the physical properties of steel wire. In this study the fatigue and bending properties as determined on especially designed testing machines have been emphasized.

Many investigators studying the wire rope problem feel that the most important stresses in a wire rope are those due to the repeated bending of the ropes when passing around sheaves and drums. This point of view has been challenged by others interested in this subject, since there are many factors other than actual stresses that help to determine the life of a wire rope. These factors include corrosion, abrasion, and localized compression forces on the surface of wire ropes and between the individual wires causing plastic flow to an extent which is generally not fully appreciated. However, the repeated bending stresses are important and a more complete knowledge of the fatigue properties of steel wire should lead to a *better* correlation between the manufacturing process of wire ropes with their service life.

The usual specifications for wire ropes include the tensile strength and the bending properties of the individual wires. Accord-

---

A paper presented before the Twenty-second Annual Convention of the American Society for Metals held in Cleveland, October 21 to 25, 1940. The author, H. J. Godfrey, is engineer of tests, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa. Manuscript received June 17, 1940.

ing to Bonzel (1),[1] the bend test is used in the mill to determine the malleability of wire. Bonzel states that under the present methods of bend testing it has been impossible to obtain an intelligent comparison between the results on a single wire in jaws of different radii of curvature. He also states that by varying the curvature of bending in accordance with some function of the wire diameter, it is impossible to get consistent results on wires in different stages of cold work. Many persons interested in the physical properties of rope wire give little credence to the bend test as it is now performed in the mill.

There are many factors affecting the bend test and since the conditions of testing have not been standardized there is little doubt as to the reason for the difficulty in interpreting the bend test results. In the design of the bend testing machine used in this investigation, as many unknowns as possible were eliminated.

The relationship between the bending and fatigue properties of steel wire is a debatable question. The bending of a wire around a small mandrel is very different than the conditions which exist in a fatigue test where the repeated bending stresses are in or slightly above the so-called elastic range of the material. However, in this study on the effect of wire drawing on the physical properties of steel, both the fatigue and bending properties show a definite change in their characteristics after a certain amount of cold working. It should be emphasized that the bend test cannot be substituted for the fatigue test. Prof. H. F. Moore stated in the 1939 A.S.T.M. Marburg Lecture (2) that no confidence should be placed in short time fatigue tests. In this instance the bend test is by no means a fatigue test and in no way may it be used to determine the actual fatigue properties of materials.

Von Ewald Buschmann (3) has attempted to determine the fatigue properties of materials by means of a bend testing machine similar to that described in this paper. The results of Buschmann's tests seem to be quite satisfactory for pure metals or alloys in the annealed condition in which the material is uniform throughout. However, this test would not be satisfactory for materials that are not uniform and whose fatigue properties are greatly affected by surface conditions.

Sachs and Sieglischmidt (4) report that as far as the effects of strength are concerned, the present information and tests show that

---

[1] The figures appearing in parentheses refer to the bibliography appended to this paper.

wires of a higher strength have a longer service life in spite of a correspondingly higher direct stress over the cross section. Since it has been found that for a given type of wire the fatigue limit stress increases in proportion to the tensile strength, it is quite logical that the endurance of a high strength wire rope operating around a given size sheave, will have a longer life than that of a lower strength rope around the same diameter sheave even though the actual direct stress in each case is a given percentage of the tensile strength of the wire. Sachs and Sieglischmidt also found that carbon steels had no direct relationship between the bend test and the strength properties as was found to be true for simple metals and other metallic alloys.

WIRE FATIGUE MACHINE

The two wire fatigue machines used in this study were designed and built at the Fritz Laboratory. The principle involved in the design of these machines is the same as that used in the Haigh-Robertson rotating wire fatigue machine which is now quite familiar to those interested in this subject. Changes were made, however, in several of the details which have simplified its construction without any loss in the required accuracy.

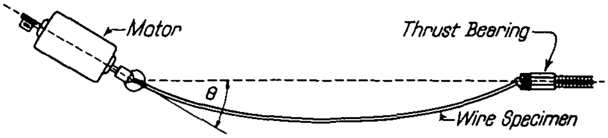

Fig. 1—Principle of Wire Fatigue Machine.

The difficulty encountered in the fatigue testing of wire is in stressing the wire specimen in such a manner that the test results are not affected by the gripping of the specimen. This difficulty is surmounted by stressing the wire specimen as a rotating wire strut, the ends of which are not fixed. Under this condition of loading the stresses vary from zero at the ends of the specimen to a maximum in the center of the column length. A diagrammatic view of the principle of the fatigue machine is shown in Fig. 1.

The stresses are computed by the well-known "Euler" column formula. The maximum stress at the center is equal to:

$$f = \frac{\pi^2}{360} \Theta \frac{d}{L} E$$

in which:

f = bending stress—pounds per square inch
Θ = inclination at the end of the wire—degrees
d = diameter of wire—inches
L = length of wire—inches
E = modulus of elasticity in tension—pounds per square inch.

The above formula is a close approximation and directly applicable when the angle of inclination is small. When the angle is greater than twenty degrees the curve of flexure changes perceptibly and a correction is necessary. However, for practically all fatigue tests made on steel wire the angle of inclination is less than twenty degrees.

A photograph of one of the wire fatigue machines is shown in Fig. 2. The machine consists of a base on which a motor is placed at one end and an adjustable tail stock at the other end. The wire specimen is held at one end by a chuck fitted to the shaft of the electric motor and by a thrust bearing at the other end. A special cap is fitted on the end of the wire which runs in the thrust bearing. In order to bend the wire to any desired angle of inclination an end thrust is applied by turning the tailstock. Simultaneously, the motor rotates the wire on its own axis, thus causing a complete reversal of the bending stress for each revolution.

The motor is placed in a swinging frame in such a position that the end of the chuck is exactly at the center of rotation of the frame. The counterweights on the swinging frame balance the weight of the motor. The angle of inclination is measured by a scale and vernier reading to 0.05 degrees, which for steel, corresponds to a stress of approximately 300 pounds per square inch for an L/d ratio of 150. When the specimen fractures, the swinging frame is thrown off balance and a mercury switch automatically stops the motor. The speed of testing used in these experiments was approximately 5000 revolutions per minute.

The stresses due to the dead weight of the specimen are not calculated as such, since the total stress is computed from the actual strains as measured by the angle of inclination. There is a small error caused by the fact that for a given stress at the center of the specimen the angle of inclination, due to the dead weight of the specimen, is not the same as that determined by the Euler formula. However, this difference is so small that it has no influence on the test results.

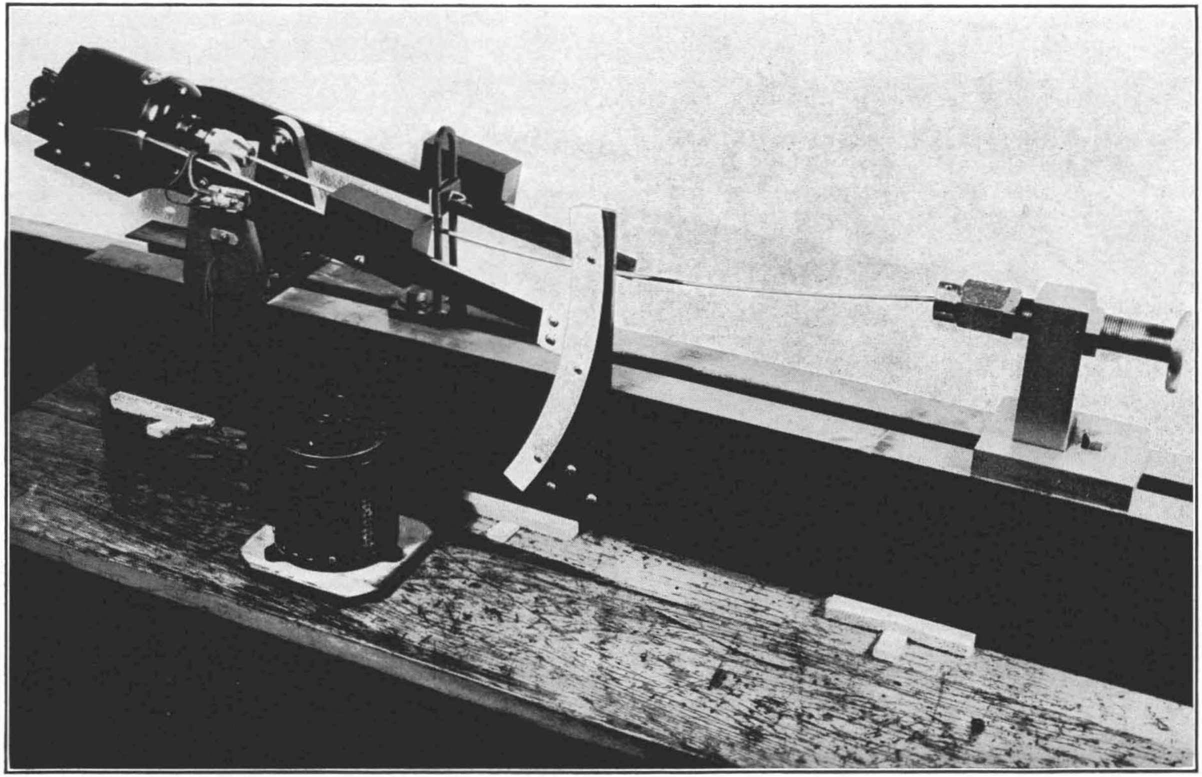

Fig. 2—Rotating Wire Strut Fatigue Machine.

WIRE BENDING MACHINE

The wire bending machine was designed and made in the Fritz Laboratory, and is shown diagrammatically in Fig. 3. A photograph of the bending machine is shown in Fig. 4. The wire is held in grips attached to the bending arm and weights are suspended at the lower end of the wire. The wire is then bent back and forth over the rollers by moving the bending arm through an angle of 180 degrees. These rollers are supported on bearings so that they are free to rotate during the bending operation. The rollers can be adjusted so that the clearance between them is slightly more than the diameter of the wire. The center of rotation of the bending arm is at a point 0.7R above the center of the rolls, where R = the radius of the rollers. In this position there is very little vertical movement of the wire during the bend test. For the various sizes of rollers used the bending arm may be adjusted to the proper elevation.

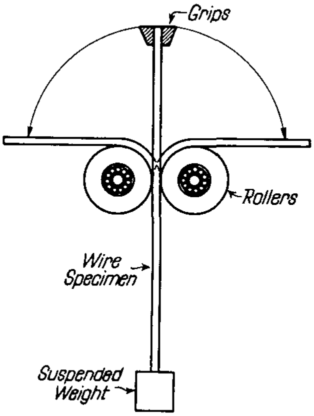

Fig. 3—Principle of Wire Bending Machine.

The bending machine is operated by hand and the speed of testing of fifty 180-degree bends per minute is controlled by a Metronome. The direct tensile stress in the wire specimen, due to the suspended weights, is equal to one per cent of the tensile strength of the wire. Three or four specimens were tested to failure for each roll size and the average number of bends were used to compare the bending properties of the various materials.

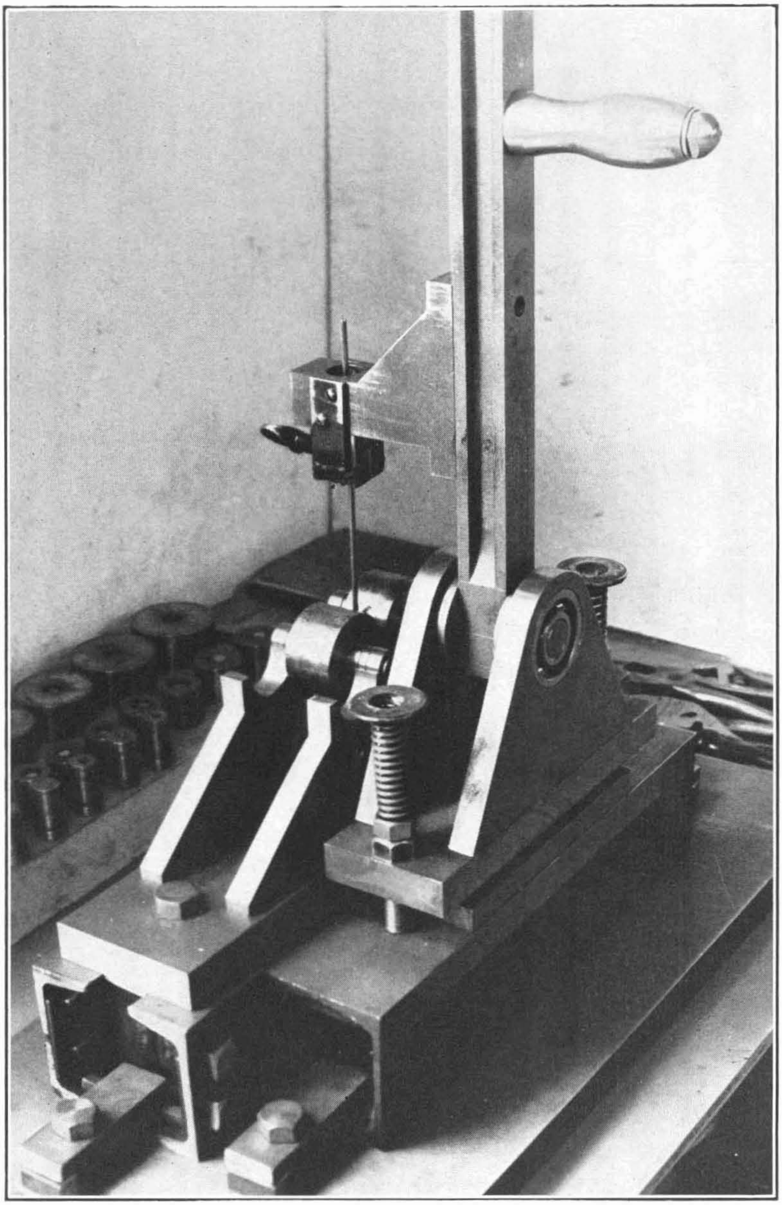

Fig. 4—Wire Bending Machine.

MATERIALS

The physical properties of the materials included in this investigation on the fatigue and bending properties of cold drawn steel wire

Table I
Tensile and Fatigue Properties of Cold Drawn Steel Wire

Carbon Content Per Cent	Diameter In.	Per Cent* Reduction	Per Cent* Elongation	Tensile Strength P.s.i.	Elong. in 10 In. Per Cent	Fatigue Limit P.s.i.	Fatigue Ratio Per Cent
0.05	0.215	0	0	45,900	24.0	......	....
0.05	0.134	61.2	157	75,500	4.4	36,000	47.6
0.05	0.112	73.0	269	84,000	3.2	39,300	46.8
0.05	0.062	91.7	1104	105,000	1.6	40,100	38.2
0.16	0.215	0	0	59,700	21.5	......	....
0.16	0.135	60.5	154	92,000	3.7	39,600	43.0
0.16	0.112	73.0	269	101,400	3.25	42,000	41.4
0.16	0.062	91.7	1104	128,000	1.15	43,400	33.9
0.39	0.205	0	0	101,500	9.0	......	....
0.39	0.136	56.0	127	135,000	4.6	47,000	34.8
0.39	0.113	69.6	229	148,000	4.3	55,800	37.7
0.39	0.062	91.0	994	208,000	1.6	60,400	29.0
0.58	0.139	0	0	144,500	9.5	45,200	31.2
0.58	0.106	41.9	72	171,500	6.1	55,800	32.5
0.58	0.081	65.9	195	195,000	5.6	63,500	32.5
0.58	0.061	80.6	418	227,000	2.9	64,500	28.4
0.90	0.147	0	0	212,000	7.5	68,200	32.2
0.90	0.124	28.8	41	222,000	6.8	72,500	32.6
0.90	0.102	51.9	108	239,000	5.9	79,000	33.0
0.90	0.085	66.6	199	258,500	4.4	83,600	32.4
0.90	0.077	72.6	264	272,000	3.8	90,000	33.1
			Polished Wire				
0.05	0.112	73.0	269	84,000	3.2	43,000	51.2
0.16	0.112	73.0	269	101,400	3.25	46,000	45.4
0.39	0.113	69.6	229	148,000	4.3	63,000	42.6
0.58	0.106	41.9	72	171,500	6.1	61,000	35.6
0.90	0.124	28.8	41	222,000	6.8	85,000	38.3

*By Wire Drawing.

are presented in Table I. This material was analyzed for its carbon and manganese content and the results are as follows:

Carbon Per Cent	Manganese Per Cent
0.05	0.11
0.16	0.49
0.39	0.75
0.58	0.60
0.90	0.35

The 0.05 and 0.16 per cent carbon wires were drawn from a hot-rolled green rod to the various wire sizes. The 0.39 per cent carbon material was drawn from a lead-patented rod and the high carbon material was drawn from wire which had been given an in-

termittent patenting. Although the exact temperatures of heat treatment were not available, it will suffice to say that the patenting process usually consists of quenching in lead to 900 to 950 degrees Fahr. (480 to 510 degrees Cent.) from above the critical temperature.

Table II
Tensile and Fatigue Properties of Decarburized Cold-Drawn Steel Wire

Material	Carbon Content Per Cent	Diameter Inches Net	Diameter Inches Gross	Per Cent* Reduction	Tensile Strength P.s.i.	Fatigue Limit P.s.i.	Fatigue Ratio Per Cent
Plain	0.73	0.095	......	50.5	202,000	46,000	22.8
	0.73	0.085	......	59.9	215,000	52,000	24.1
	0.73	0.074	......	70.0	228,000	54,000	23.6
	0.73	0.060	......	80.0	240,400	60,000	24.9
						Average	23.8
Electro-Galvanized Wire	0.73	0.1035	0.1065	48.1	185,000	47,000	25.4
	0.73	0.081	0.083	68.5	213,000	50,000	23.4
	0.73	0.070	0.072	76.4	236,000	54,000	22.9
	0.73	0.0585	0.060	83.5	243,000	58,000	23.9
						Average	23.9
Hot Galvanized Bridge Wire	....	0.190	0.194	....	235,000	48,000	20.4

*By Wire Drawing.
All Values Computed on the Net Diameter of Wire.

The material used in a supplementary study is presented in Table II. The chemical analysis of this wire is as follows:

	Carbon	Manganese	Phosphorus	Sulphur	Silicon
Bare Wire	0.73	0.65	0.028	0.025	0.19
Electro-Galvanized	0.73	0.56	0.026	0.025	0.18

The 0.73 per cent carbon material was lead-patented before drawing. The hot-galvanized wire included in Table II is cold-drawn bridge wire.

Discussion of Test Results

Metallographic Study—The metallographic examination of the material included in Table I was made to determine the structure of the rod before being drawn into wire and also to determine to what extent the surface of the material was decarburized. The photomicrographs of the 0.05, 0.16, 0.39, 0.58, and 0.90 per cent carbon material are presented in Fig. 5. The photomicrographs at one hundred magnification show that there is little or no decarburization on any of these materials. There were no further heat treatments on this material during the following stages of wire drawing.

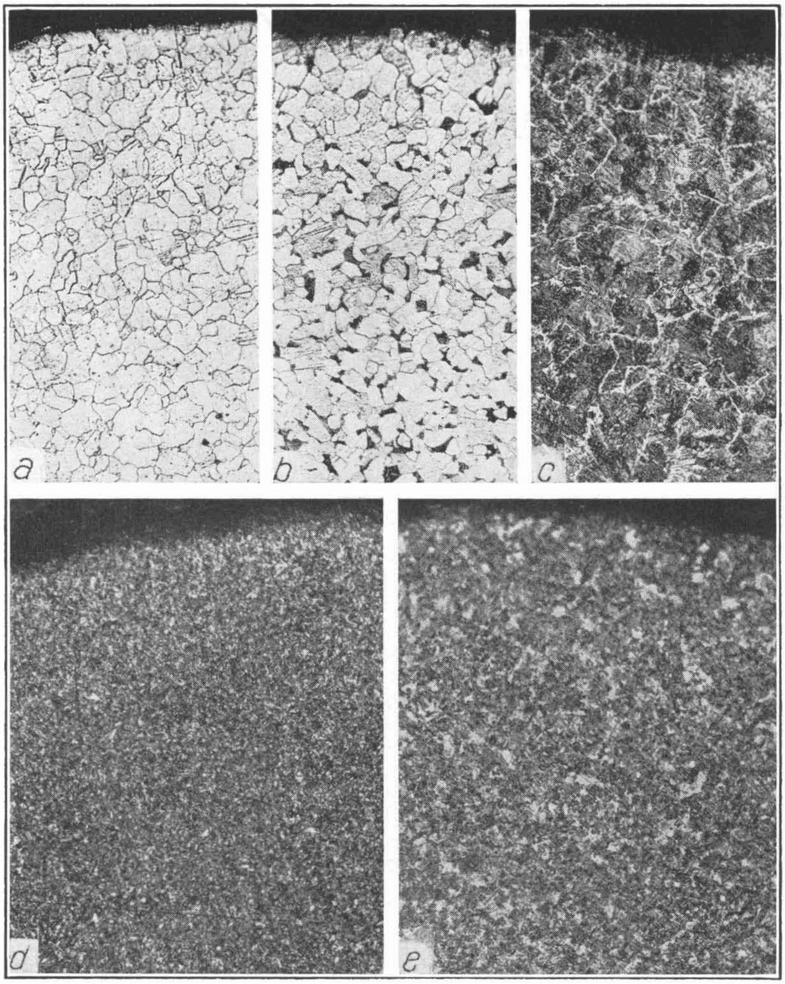

Fig. 5—Photomicrographs of Hot-Rolled and Patented Steel Rods. × 100. a.—0.05 Per Cent Carbon; b.—0.16 Per Cent Carbon; c.—0.39 Per Cent Carbon; d.—0.58 Per Cent Carbon; e.—0.90 Per Cent Carbon.

The 0.73 per cent carbon wire in Table II was included in this investigation in order to study the effect of decarburization on the fatigue properties of wire. The photomicrograph in Fig. 6 shows a distinct ring of decarburized material at the surface of the bare wire. Since the patented wire was not available for examination this photomicrograph was made from the 0.095-inch diameter wire drawn 50.5 per cent reduction. A study of the depth of decarburization was

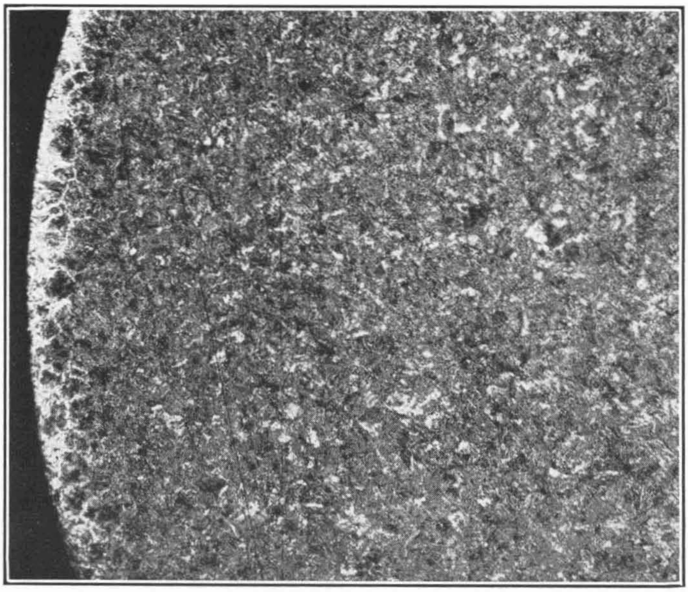

Fig. 6—Photomicrograph of Decarburized 0.73 Per Cent Carbon Steel Wire. × 100.

also made on the 0.73 per cent carbon electro-galvanized wire and the results were as follows:

Electro-Galvanized 0.73 Carbon Wire

Net Diameter Inches	Decarburization Inches Maximum	Decarburization Inches Minimum
0.1035	0.011	0.005
0.0810	0.010	0.006
0.0700	0.009	0.007
0.0585	0.008	0.004

It should be noted that the amount of decarburization was about the same for both the bare and electro-galvanized 0.73 per cent carbon wire.

A metallographic study of the cold drawn hot-galvanized bridge wire also showed a distinct layer of decarburized material beneath the hot galvanized coating.

Tensile Properties—In a study on the effect of cold working on the properties of steel an expression for the amount of cold work should be formulated. In the manufacture of steel wire the amount of cold working by wire drawing is usually expressed by the per cent reduction in area of the original rod or patented wire. This is expressed by the equation:

$$\text{Per cent Reduction} = 100 \text{ X } \frac{A_o - A_f}{A_o}$$

where A_o = original area

A_f = final area

Another means of expressing the amount of cold working is by the per cent elongation by wire drawing which is found as follows:

$$\text{Per cent Elongation} = 100 \text{ X } \frac{A_o - A_f}{A_f}$$

This expression shows the amount that the wire has been stretched or elongated by the wire drawing process. This value could reach infinity for a material with perfect ductility and often reaches as high as 3000 per cent. For example, an elongation of 1000 per cent means that the wire has been drawn eleven times its original length and is equal to 90.9 per cent reduction in the cross sectional area.

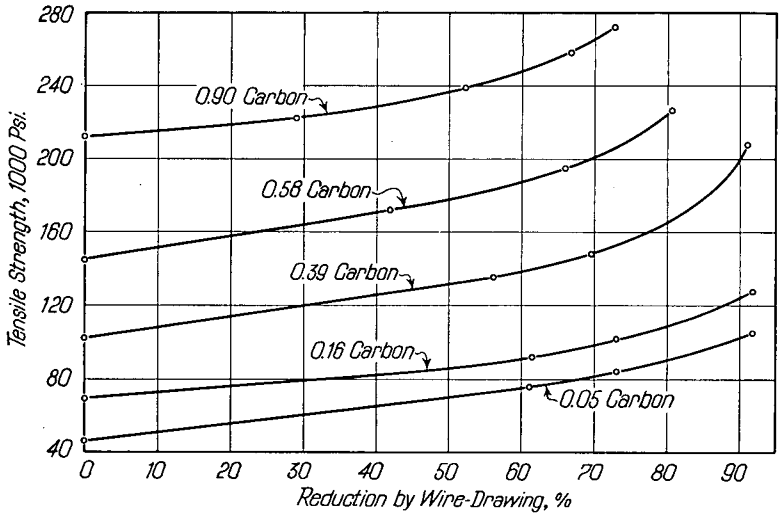

Fig. 7—Effect of Wire Drawing on Tensile Strength of Steel Wire.

The relation between the tensile strength of steel wire and the per cent reduction by wire drawing and per cent elongation by wire drawing is shown in Figs. 7 and 8. From these two figures it appears that the amount of cold working is more logically expressed by the percentage elongation since in this case, the tensile strength increases at a greater rate at the initial stages of wire drawing, where-as when related to the per cent reduction, the tensile strength increases at a more rapid rate during the final stages of wire drawing. However, since it is general practice to use the per cent reduction by wire drawing for comparative purposes, all other values in this report are compared on this basis.

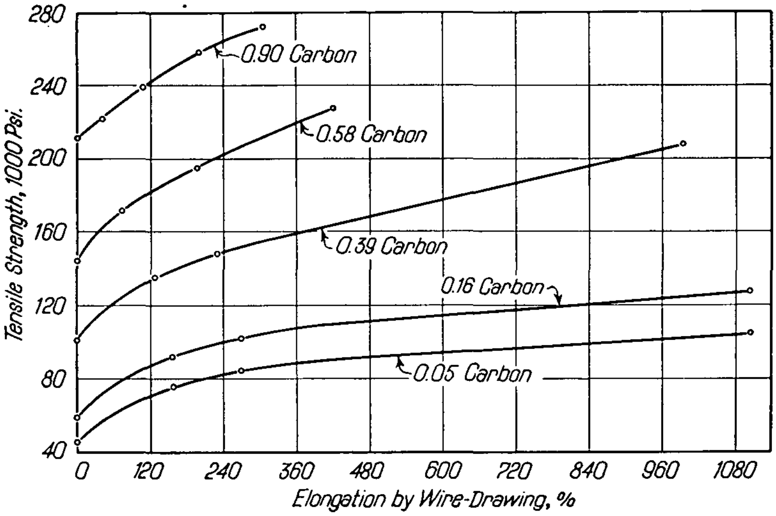

Fig. 8—Effect of Wire Drawing on Tensile Strength of Steel Wire.

Fatigue Properties—The fatigue properties for the wire free from decarburization are shown in Table I, along with the other physical properties as determined by the tensile test. This material was machine-straightened before any of the physical properties were determined. This straightening operation was performed so that a perfectly straight specimen could be used in the rotating wire strut fatigue machine. A number of tensile and fatigue tests were made on both machine and hand-straightened wire and it was found that the machine straightening process did not affect the test results to any appreciable amount.

The actual endurance curves for the carbon steels in Table I are presented in Figs. 9 to 13. These curves are presented mainly to show the effect of the carbon content on the characteristics of the fatigue curves. It should be noted that for stresses just above the fatigue limit the low carbon steels undergo a great many more cycles before fracturing than the high carbon steels. For example, a 0.05 per cent carbon wire fractured after nine million stress-cycles, where-

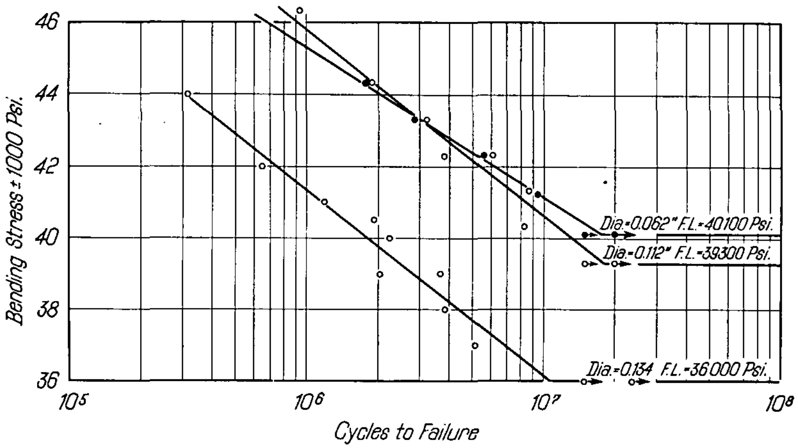

Fig. 9—Fatigue Test on 0.05 Per Cent Carbon Steel Wire.

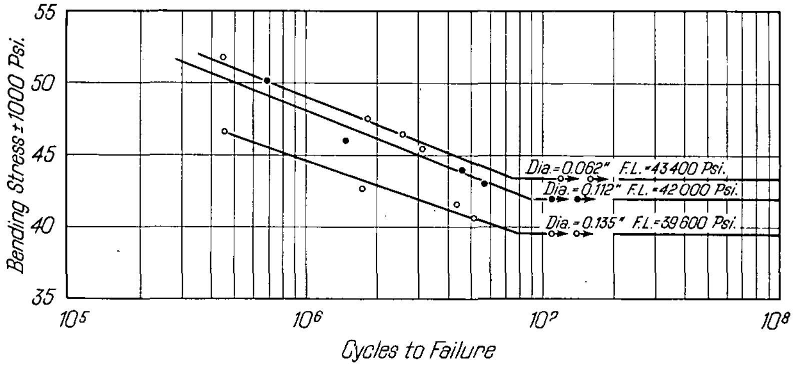

Fig. 10—Fatigue Test on 0.16 Per Cent Carbon Steel Wire.

as the maximum number of cycles before fracture for a 0.90 per cent carbon wire was slightly over one million cycles. The intermediate carbon steels ranged between these two limits. Gill and Goodacre (5) report that five million cycles were sufficient to indicate the fatigue limit of wire. Since their tests included only materials with a carbon content of over 0.36 per cent, their analysis was correct for the material investigated. However, the true fatigue limit for very low carbon steels should be determined from tests of over 10 million cycles in duration. Fractures in other metals such as aluminum take place after 100 million cycles of stress.

The effect of wire drawing on the fatigue properties of the material free from decarburization is presented in Fig. 14. These

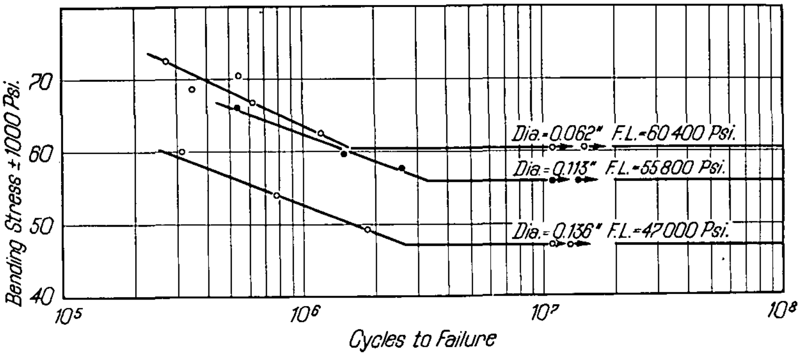

Fig. 11—Fatigue Test on 0.39 Per Cent Carbon Wire.

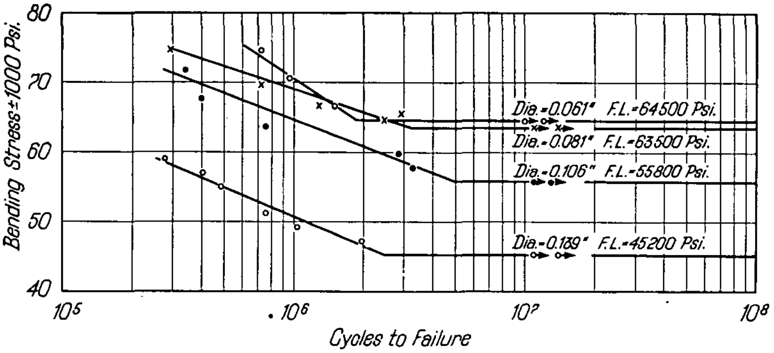

Fig. 12—Fatigue Test on 0.58 Per Cent Carbon Steel Wire.

curves show that the fatigue properties of steel wire increase with cold working, although the rate of increase is not always in proportion to the amount of wire drawing.

The relationship between the fatigue limit stress and the tensile strength of steel wire is of importance. The fatigue limits as compared to the tensile strength of the various carbon steels are shown in Fig. 15. On first sight it would appear that the fatigue limit is approximately a function of the tensile strength of the material regardless of the carbon content. However, when we note the ratio between the fatigue limit and the tensile strength as shown in the last column of Table I we find that this ratio (hereinafter termed the fatigue ratio) decreases with an increase in carbon content. This relationship is presented in Fig. 16. The solid line is an average for all the materials which have been wire drawn less than 75 per cent

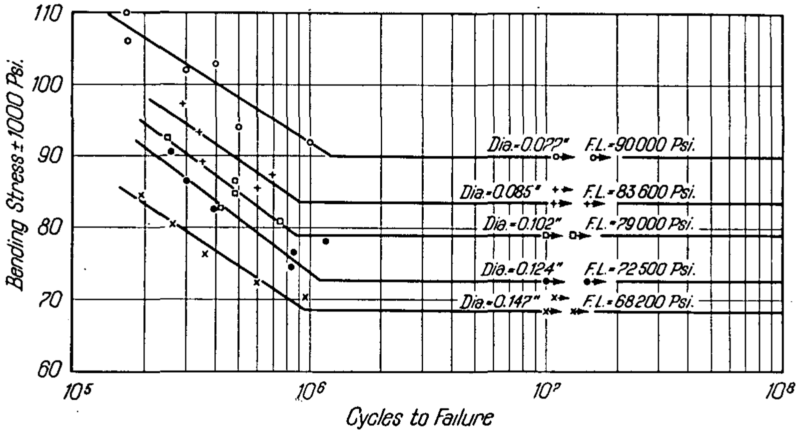

Fig. 13—Fatigue Test on 0.90 Per Cent Carbon Steel Wire.

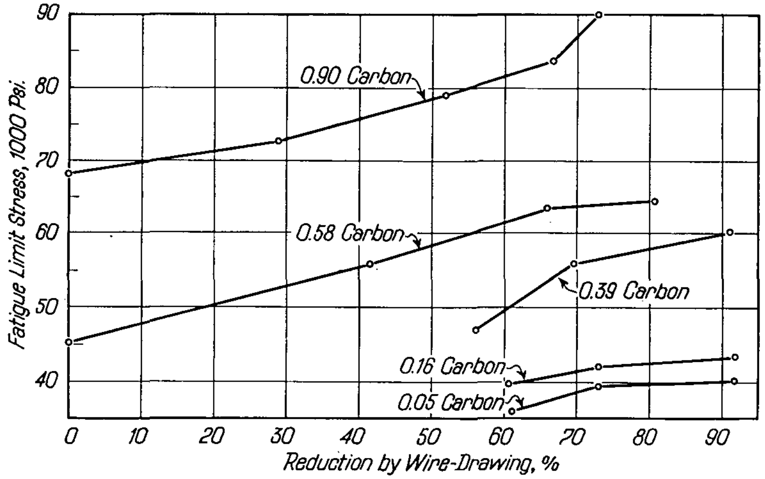

Fig. 14—Effect of Wire Drawing on Fatigue Limit Stress of Steel Wire.

reduction. The dashed line represents material drawn over 80 per cent reduction. It should be noted that the ratio between the fatigue limit and the tensile strength for the 0.90 per cent carbon wire is about the same value as for the 0.58 per cent carbon material. The reason for the lowering of the fatigue limit ratio with an increase in carbon content is one of conjecture. H. J. Gough (6) states that the fatigue limit can be correlated only to the ultimate tensile strength and that no adequate reason can, at present, be considered to account satisfactorily for the correlation observed and should be regarded only as affording a useful empirical and approximate rule.

The lowering of the fatigue limit ratio with an increase in carbon content may be due to surface conditions or to the inherent properties of the material. It is also noted that these materials of various carbon content showed a considerable drop in the fatigue ratio when cold-worked over 80 per cent reduction by wire drawing. These results are also included in Fig. 16, along with the amount of cold work. Gill and Goodacre (7) found in both decarburized wire and wire free from decarburization that the fatigue ratio was lowered when cold working was excessive. The 0.90 per cent carbon wire did not show any lowering of the fatigue ratio since it was only drawn to 72.6 per cent reduction.

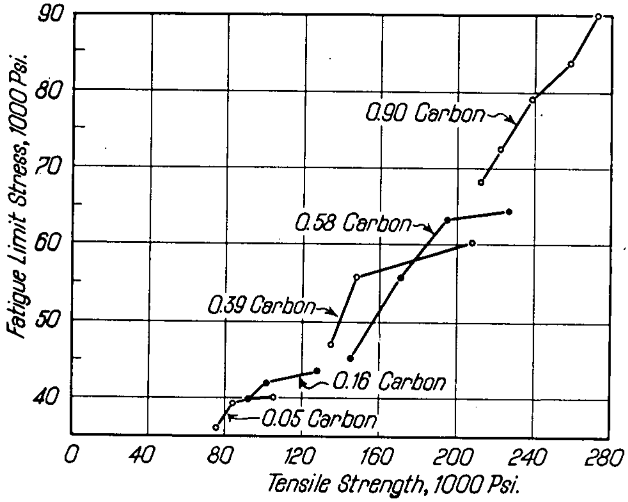

Fig. 15—Relation Between Fatigue and Tensile Strength of Steel Wire.

Fatigue tests were also made on wires of five different carbon contents polished to 000 emery and the results are shown in Table I. In every case the fatigue properties were improved by the polishing. However, the decrease in the fatigue ratio with an increase in the carbon content is still evident in the polished wires.

The hardness of the material cannot be related directly to the fatigue properties since the fatigue ratio remains practically constant for the 0.90 per cent carbon wire from the patented condition up to 72.6 per cent reduction. From this phenomenon it is apparent that the fatigue properties are dependent on some inherent characteristic other than hardness.

The physical properties of the decarburized wire were determined from hand-straightened specimens and are presented in Table II. The fatigue ratio of the bare wire averaged about 24 per cent which is considerably under the fatigue ratio of approximately 33 per cent for the 0.90 carbon and 0.58 carbon wire free from decarburization. The electro-galvanized material which had the same chemical composition as the bare wire had an average fatigue ratio of approximately 24 per cent which is the same value as that of the decarburized bare wire. The reason for this low fatigue limit is naturally explained by the decarburized surface of this material. Since the material at the surface is practically free from carbon, the fatigue limit is lowered to the extent of that of a low carbon steel. Once the fatigue crack starts in this material, it will progress throughout the higher carbon core since at the base of the fatigue crack the stresses are extremely high. The electro-galvanized wire had the same average fatigue ratio as the bare wire, indicating that the fatigue properties of this material are not affected by the electro-galvanized coating.

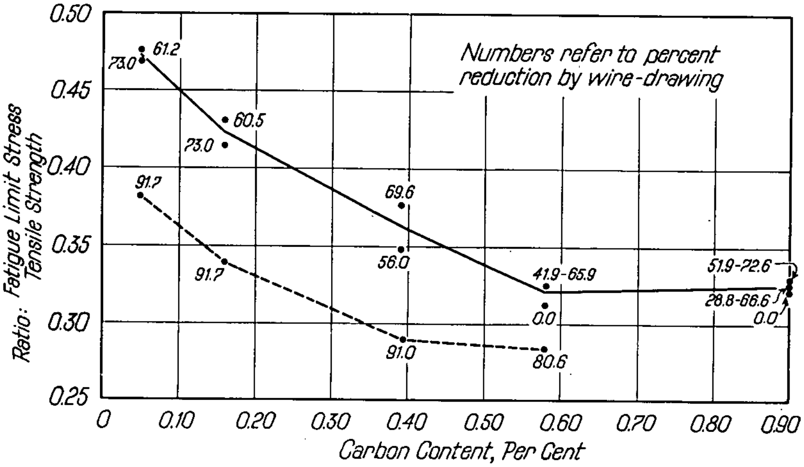

Fig. 16—Relation Between Fatigue Ratio and Carbon Content of Steel Wire.

For general interest we have included the results of fatigue tests on cold drawn hot-galvanized bridge wire. The fatigue limit stress for this material was found to be 48,000 pounds per square inch, which corresponds to a fatigue ratio of 20.4 per cent, based on the net diameter of the wire. Based on the gross diameter, the ratio would be 1 per cent higher. The extremely low fatigue ratio is probably due to both the effect of decarburization and the hot-galvanized coating.

The bending fatigue limit of heat treated galvanized bridge wire was found to be 50,000 pounds per square inch by Shelton and Swanger (8) or a fatigue ratio of 22 per cent. The fact that the fatigue stresses in suspension bridge cables are relatively low, probably account for the fact that cold drawn hot-galvanized bridge wire has proved to be a satisfactory material for this purpose. However, the fatigue properties of wire in the main cables of suspension bridges should be maintained at the highest possible level.

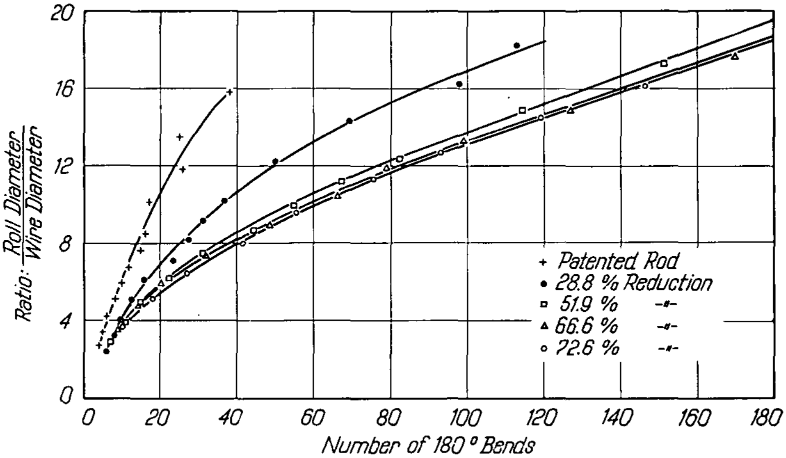

Fig. 17—Relation Between Roll Wire Ratio and Number of Bends for 0.90 Per Cent Carbon Wire.

Bending Properties—The wire bend test as carried out in this investigation was designed to study the effect of wire drawing on the bending properties of steel wire. The number of 180-degree bends that a wire can withstand before fracturing is used as the criterion for the relative bending properties. The severity of the bend test, as measured by the ratio of the roll diameter to the wire diameter, was also investigated. The ratio will hereinafter be termed the roll ratio.

The bend tests were made on the material included in Table I. This material was straightened by hand before testing. The results of the bend tests on the 0.90 per cent carbon wire are presented in

Fig. 17. The number of bends was found to be dependent upon the roll ratio and the amount of wire drawing. In the higher values of the roll ratio, the number of bends increased in proportion to the severity of the bend test. In this upper range a slight increase in the roll ratio will result in a relatively large increase in the number of bends. As the roll ratio approaches zero the bend curves converge and in this range it is not possible to differentiate between the bending properties of wire cold drawn to different amounts.

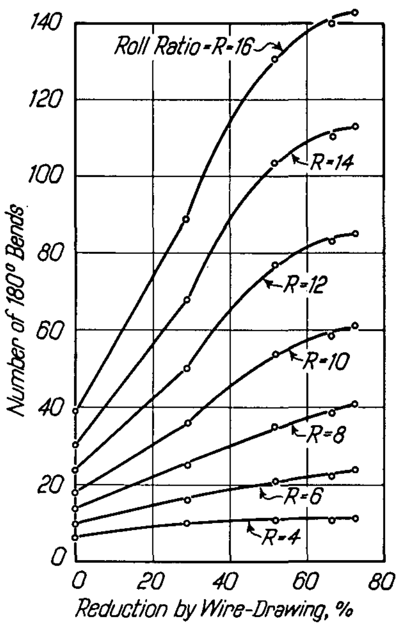

Fig. 18—Effect of Wire Drawing on the Bending Properties of 0.90 Per Cent Carbon Wire.

For the patented wire the number of bends for a given roll ratio was found to increase with wire drawing. This relationship is illustrated in Fig. 18 where the bend test results of the 0.90 per cent carbon wire are presented for a number of roll ratios. The 0.90 per cent carbon wire was cold drawn 72.6 per cent reduction and up to this amount of wire drawing the bending properties were improved.

Fig. 18 clearly indicates the effect of the severity of the bend test on the test results. For a roll ratio of 4 there is little difference in the number of 180-degree bends for the 0.90 per cent carbon wire drawn from zero to 72.6 per cent reduction. As the severity of the bend test is lessened by increasing the roll ratio a large difference in the bending properties of the wire is observed. It should be expected that the bending properties of wire should change with the amount of cold working by wire drawing. The flexibility of this bend test apparatus makes it possible to explore the bending properties of wire very much more completely than can be done by the conventional bend test apparatus.

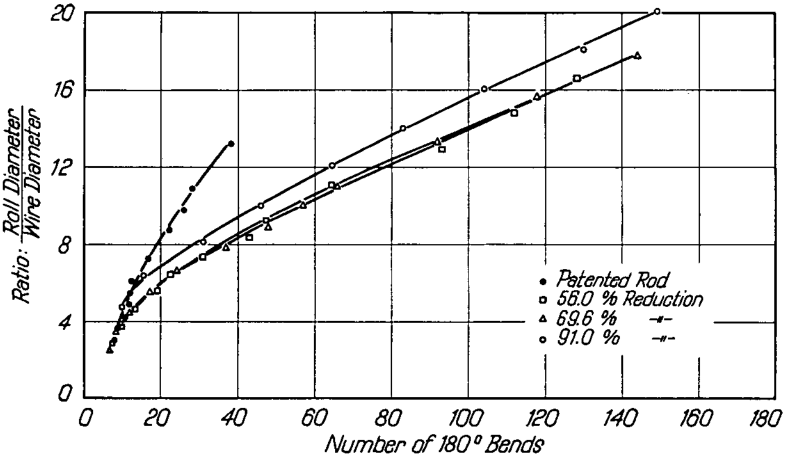

Fig. 19—Relation Between Roll Wire Ratio and Number of Bends for 0.39 Per Cent Carbon Wire.

The bending properties of the 0.39 per cent carbon wire are presented in Fig. 19. These curves have the same characteristics as those of the 0.90 per cent carbon wire except that when the material was severely cold drawn the number of bends, for a given roll ratio, decreased. The bending properties improved up to 69.6 per cent reduction but on further cold working to 91.0 per cent reduction the number of bends decreased. The effect of wire drawing on the 0.39 per cent carbon wire is illustrated in Fig. 20 and indicates that severe cold working by wire drawing injures the bending properties of wire. It also clearly demonstrates that the larger roll ratios are necessary to differentiate between the true bending properties of wire drawn to various percentages of reduction. Similar bend test results were obtained on the 0.58 carbon wire.

The results of the bend tests on the wire drawn from the hot rolled 0.16 carbon rod are presented in Fig. 21. There were only a

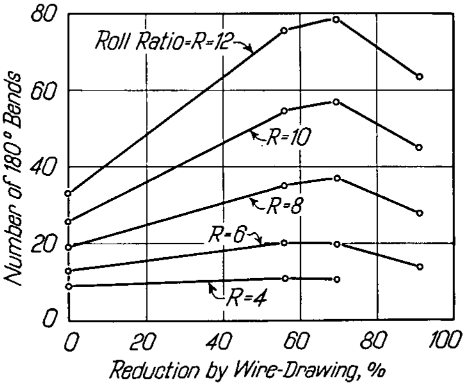

Fig. 20—Effect of Wire Drawing on the Bending Properties of 0.39 Per Cent Carbon Wire.

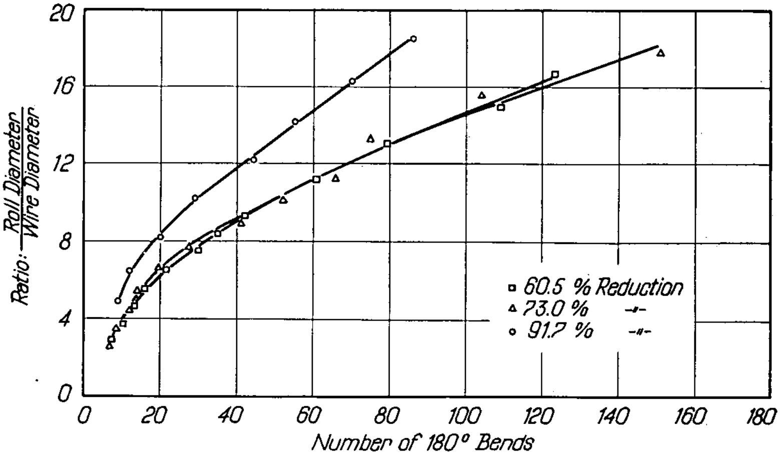

Fig. 21—Relation Between Roll Wire Ratio and Number of Bends for 0.16 Per Cent Carbon Wire.

few bend tests made on the hot-rolled rods since it was not possible to make a satisfactory test on this material. Bonzel (9) states that in patented wire the number of bends increases after the first few drafts and in the case of mild steel the number of bends decreases with wire drawing. The few bend tests made on the hot-rolled rods seem to confirm this statement. The bend test curves as presented in Fig. 21 have the same characteristic shape as those of the patented steel wire although none of the material tested was cold drawn less than 60 per cent reduction. This material shows a sharp decrease in the number of bends when cold drawn to 91.7 per cent reduction.

Fig. 22 shows the effect of wire drawing on the bending properties of the various materials tested. All of the bend curves with the exception of the 0.90 per cent carbon wire shows a distinct loss in the bending properties after severe cold drawing. The 0.90 per cent carbon wire was wire drawn 72.6 per cent, the 0.58 per cent carbon wire 80.6 per cent and all the other material over 0.90 per cent reduction. These tests show that the bending test can be used to differentiate between the true bending properties of wire, if the severity of the bend test is properly controlled.

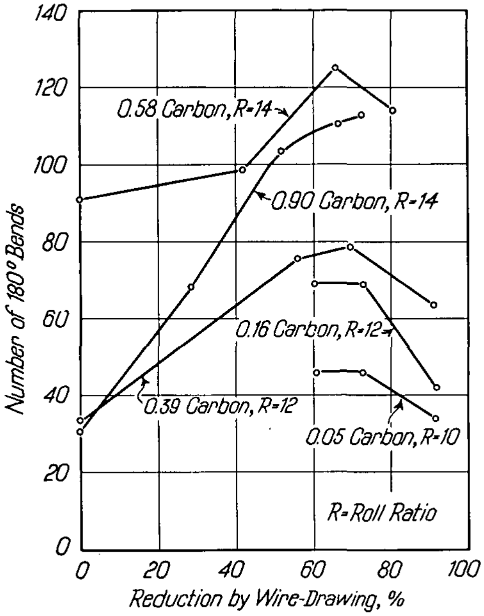

Fig. 22—Effect of Wire Drawing on the Bending Properties of Steel Wire.

General Discussion of Test Results

In this investigation the fatigue and bending properties of steel wire have been studied. The test results show that both the fatigue and bend tests as carried out in this investigation, can be used to study the effect of cold working on the physical properties of wire. The fatigue properties were found to increase in proportion to the tensile strength of the wire up to a critical amount of wire drawing,

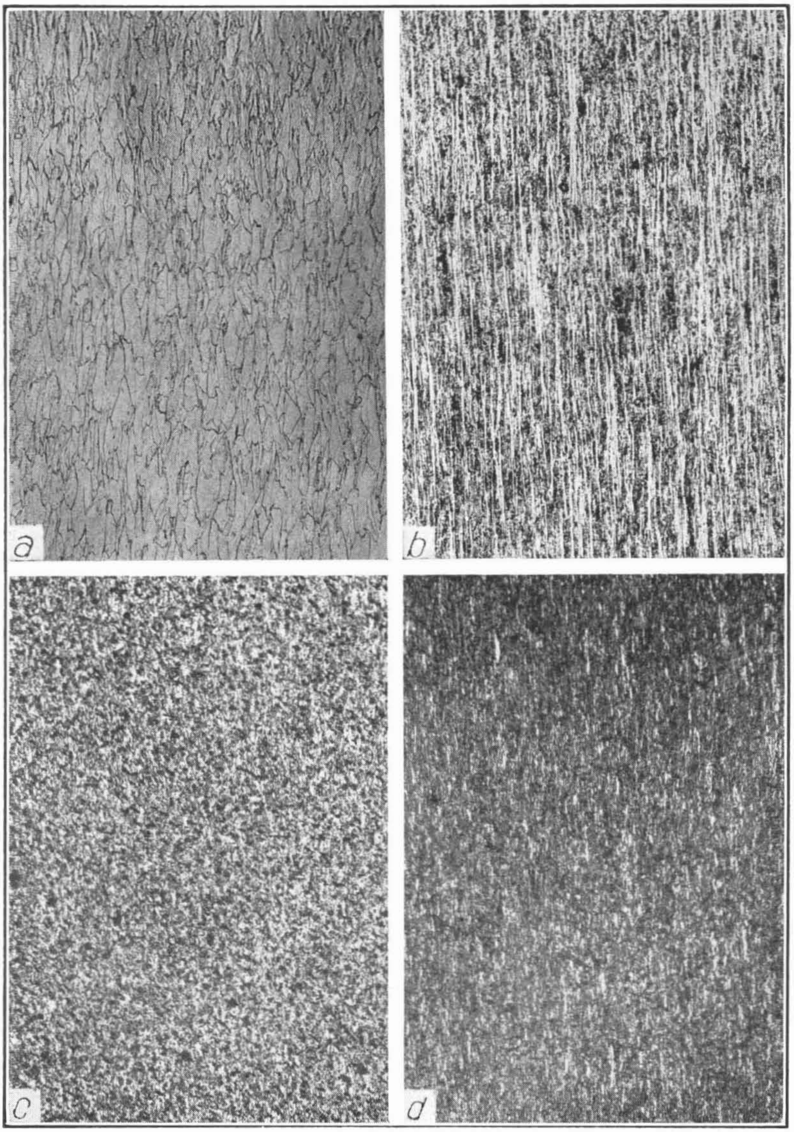

Fig. 23—Photomicrograph of Cold-Drawn 0.05 Carbon and 0.58 Carbon Steel Wire. × 100. a.—0.05 Per Cent Carbon. 61.2 Per Cent Reduction. b.—0.05 Per Cent Carbon. 91.7 Per Cent Reduction. c.—0.58 Per Cent Carbon. 41.9 Per Cent Reduction. d.—0.58 Per Cent Carbon. 80.6 Per Cent Reduction.

at which point both the fatigue and bending properties show a decided change.

A metallographic study of the cold drawn wire was made on the 0.05 and 0.58 per cent carbon wire and the photomicrographs are shown in Fig. 23. These illustrate the effect of cold drawing on the structure of steel wire. The extreme amount of fibering is clearly shown in the 0.05 per cent carbon wire drawn 91.7 per cent reduction. However, this metallographic examination does not indicate any decided change in the physical properties of the wire.

To investigate the problem more extensively, an examination of the internal structure of the wire was made with X-rays. By means of X-rays any change in the orientation of the grains in a polycrystalline material by wire drawing or other means of cold working can be identified. When a polycrystalline material is cold-worked the individual grains, which formerly were oriented at random, tend to orient themselves in a particular manner. In the case of wire drawing the deformation is always in the same manner so that the grains tend to orient in the same direction. As a result, the structure of the metal has a preferred orientation and the material can no longer be considered to be isotropic. The properties of wire in the longitudinal direction will thus be different from the properties in the transverse direction.

A monochromatic X-ray photograph made by reflecting the X-rays from the surface of the polycrystalline material will show a number of concentric rings of uniform density if the crystals are oriented at random. This is due to the reflection of the X-rays from the principal planes of the crystals. However, if the crystals are oriented so that a particular crystallographic direction lies in the axis of the wire, the material will no longer be isotropic and the Debye-Scherrer rings are broken up into patches corresponding to the preferred positions of the crystallites. The intensity of these patches is dependent upon the degree of preferred orientation.

Elam (10) reports that as a result of wire drawing the direction taken up by the crystals of a body-centered cubic lattice is such that the face diagonal of the cube, i.e., [110], lies parallel to the wire axis and that preferred orientation was more complete in the inside layers of a wire.

The X-ray photographs of the 0.05 per cent carbon wire drawn 73 per cent is shown in Fig. 24. Both the surface and the core of the wire were investigated. In order to reflect the X-rays from the core of the wire the outside of the wire was dissolved with acid. Both the surface and the core of this material show by the varying

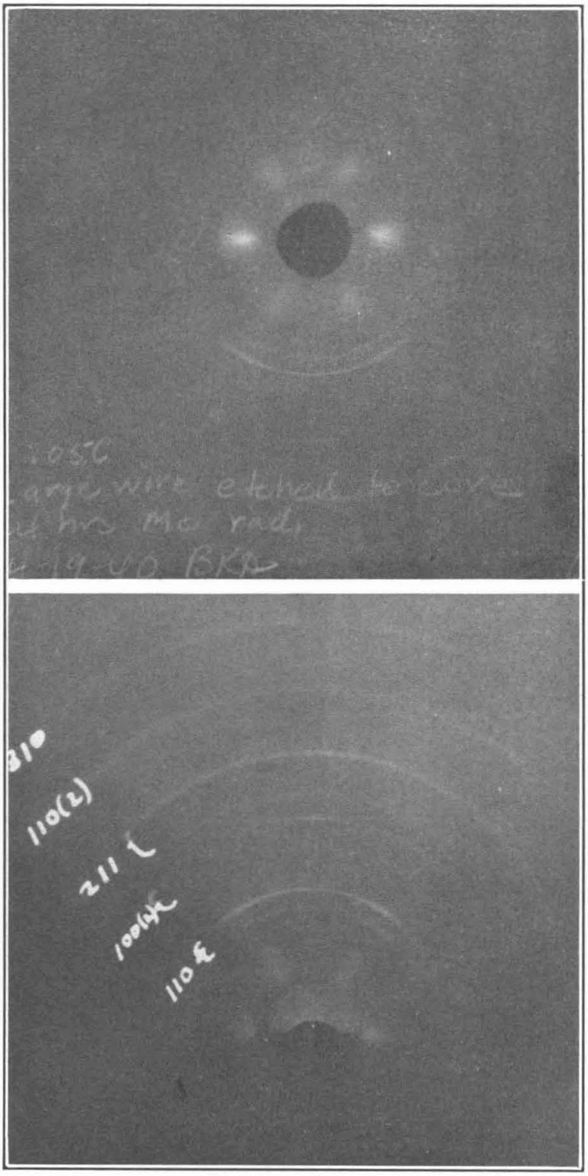

Fig. 24—X-Ray Diffraction Patterns of 0.05 Per Cent Carbon Wire Cold Drawn 73.0 Per Cent Reduction. Top—Core. Lower—Surface.

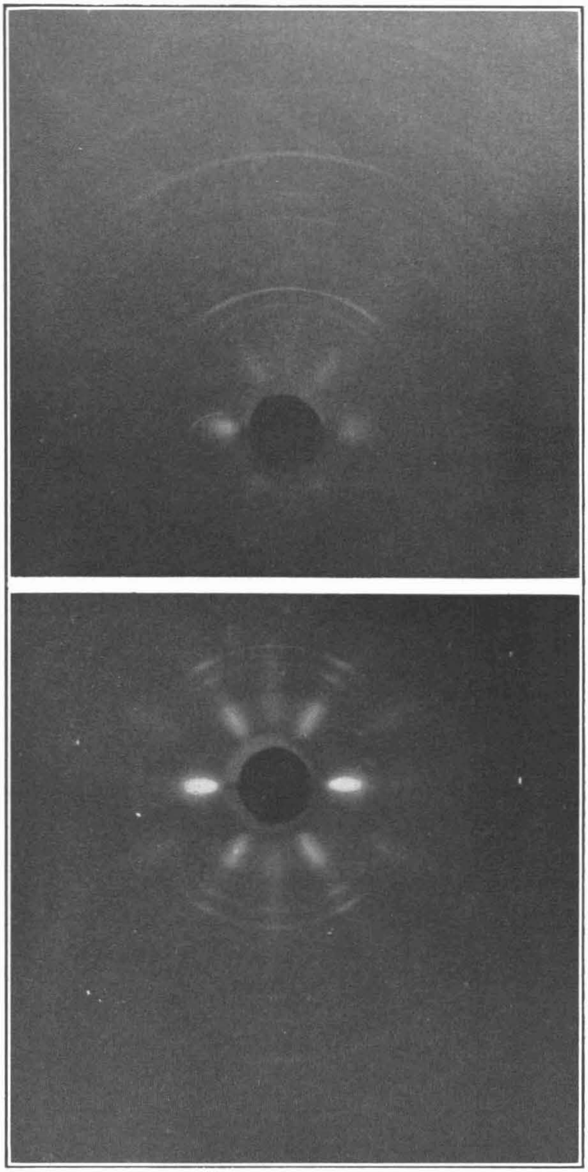

Fig. 25—X-Ray Diffraction Patterns of 0.05 Per Cent Carbon Wire Cold Drawn 91.7 Per Cent Reduction. Top—Surface. Lower— Core.

intensity of the rings that there is some indication of preferred orientation. The X-ray photographs of the 0.05 per cent carbon wire drawn 91.7 per cent reduction are shown in Fig. 25. The surface of this highly drawn material indicates some preferred orientation but the core of the wire indicates considerable preferred orientation.

A similar investigation of the 0.58 per cent carbon wire was made by means of X-rays. The results of the examination of the surface and core of the 0.58 per cent carbon material drawn 41.9 per cent reduction indicated a slight amount of preferred orientation. The reflection photographs of the 0.58 per cent carbon wire drawn 80.6 per cent reduction are shown in Fig. 26. The surface of the material indicates some preferred orientation while the core of the wire exhibits somewhat more preferred orientation than the surface.

Elam (11) reports that various investigators have found that the core of wires have the most perfect fiber-structure and that the tensile strength of the core was higher than that of the outer layers of hard drawn wire.

In extremely cold drawn wire we therefore have a condition in which the orientation of the wire is variable over the cross section. If the tensile strength of the core of highly drawn wire is greater than the outer layers the reason for the lowering of the fatigue ratio may be explained. The tensile strength is the average strength of the material over the entire cross section of the wire. The bending fatigue limit stress is largely influenced by the characteristics of the material at the surface of the wire since the maximum bending stresses occur at the surface. If the surface of the wire is not as strong as the core a drop in the fatigue ratio is therefore to be expected. This condition is similar to that in which the surface of the wire is decarburized.

A drop in the fatigue ratio does not necessarily mean that the wire has been actually damaged by wire drawing as far as fatigue is concerned, since no internal cracks or fissures were visible. As shown in Fig. 14 the fatigue limit stress increases with wire drawing up to 90 per cent reduction which is as far as this study has investigated. However, in the latter stages of cold working the fatigue limit stress does not increase in proportion to the tensile strength.

The bend test results as shown in Fig. 22 indicate that when wire has been severely cold drawn it is not able to withstand highly localized stresses which cause plastic deformation as well as wire

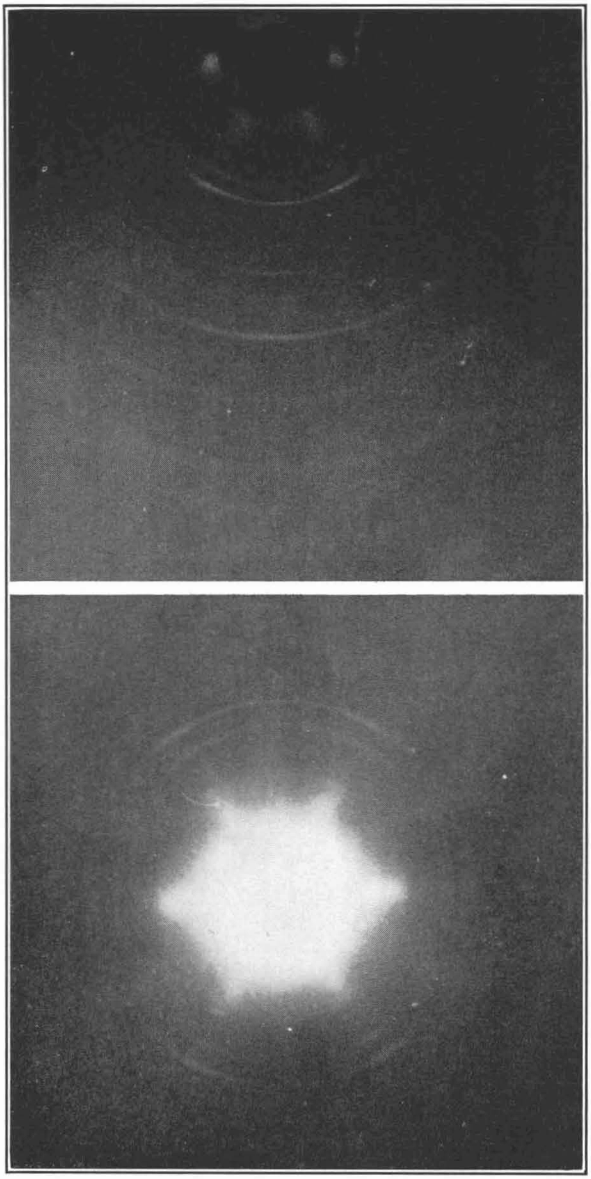

Fig. 26—X-Ray Diffraction Patterns of 0.58 Per Cent Carbon Wire Cold Drawn 80.6 Per Cent Reduction. Top—Surface. Lower—Core.

drawn to an intermediate amount of cold drawing. It is for this reason that the bend test as carried out in this investigation, might be used as an index to determine the amount of cold drawing most advisable for a given service. Wire should not be cold drawn to a maximum and then be expected to undergo plastic deformation in service without danger of an early breakdown. However, all features of a given problem should be given consideration because relatively heavy reductions might be most desirable in order to provide physical characteristics essential to satisfactory performance under special service conditions.

The work on the fatigue properties of steel wire is being continued at the Fritz Engineering Laboratory. The next investigation will include a study on the effect of the rate of drafting on the properties of steel wire.

CONCLUSIONS

1. The characteristics of the fatigue test results on steel wire are influenced by the carbon content of the material. The fatigue limit of a low carbon material should be determined by a fatigue test of at least 10,000,000 cycles in duration. For higher carbon materials, the length of the test may be considerably less.
2. Normal cold working by means of wire drawing increases the fatigue limit of steel wire in proportion to the tensile strength of the wire. However, after the cold working exceeds a critical amount, the ratio between the fatigue limit and the tensile strength decreases.
3. The ratio between the fatigue limit and the tensile strength decreases with an increase in carbon content, for materials free from decarburization.
4. Improving the surface of wire by polishing, increases the fatigue properties of wire.
5. Decarburization on the surface of cold drawn wire reduces the fatigue properties of wire. The depth of decarburization does not seem to have any effect on the fatigue ratio.
6. An electro-galvanized coating does not lower the fatigue ratio of a decarburized wire.
7. The bending fatigue properties of cold drawn hot-galvanized bridge wire may be approximately the same as a heat treated hot-galvanized bridge wire.
8. The bending properties of patented steel wire increase with

cold work up to a critical amount. Beyond this point the bending properties decrease.

9. The true bending properties of steel wire may be determined by controlling the severity of the bend test.

10. Both the bending fatigue test and bend test may be included in the several factors which should be considered in deciding upon the desired amount of cold drawing.

11. The effect of wire drawing on the internal structure of metallic crystals as shown by X-ray photographs is such that the individual crystals tend to orient themselves into one position. The amount of orientation is more apparent when cold working is excessive. The maximum amount of orientation takes place in the core of the wire.

ACKNOWLEDGMENT

The author wishes to express his appreciation to C. W. Meyers of the American Steel and Wire Company and to L. H. Winkler of the Bethlehem Steel Company for the material used in this investigation and for their suggestions and advice; to J. N. Kenyon of Columbia University for checking the accuracy of the wire fatigue machine used in this study and to B. K. Daubenspeck, Research Fellow in Chemistry at Lehigh University for the X-ray photographs included in this paper. To the Fritz Engineering Laboratory Staff which includes Professor Hale Sutherland, Director and Professor Bruce Johnston, Assistant Director, we express our sincere thanks for the co-operation received in carrying out this investigation. To Professor Inge Lyse, formerly in charge of the Fritz Engineering Laboratory and now at the Norges Tekniske Hoiskole, we express our sincere appreciation for making this investigation possible.

Bibliography

1. Maurice Bonzel, "Steel Wire," 1935, p. 212, Camelot Press.
2. H. F. Moore, "Stress, Strain and Structural Damage," *Proceedings*, American Society for Testing Materials, Vol. 39, Part II, 1939, p. 569.
3. Von Ewald, Buschmann, "Das Biege-Zug-Verfahren," *Zeit. für Metallkunde,* Vol. 26, N 12, December 1934.
4. G. Sachs and H. Sieglerschmidt, "Prüfung von Seildrähten durch Zug und Biegeversuche," *Mitteilungen der deutschen Materialprüfungsanstalten,* Sonderheft X 1930.
5. E. T. Gill and R. Goodacre, "Some Aspects of the Fatigue Properties of Patented Steel Wire," *Journal,* Iron and Steel Institute, Vol. CXXX, No. II, 1934, p. 323.

6. H. J. Gough, "The Fatigue of Metals," Ernest Benn Limited, London, 1926, p. 155.
7. E. T. Gill and R. Goodacre, Loc. Cit., p. 304.
8. S. M. Shelton and W. H. Swanger, "Fatigue Properties of Steel Wire," *Journal of Research,* National Bureau of Standards, Vol. 14, January 1935, p. 21.
9. Maurice Bonzel, Loc. Cit., p. 213.
10. C. F. Elam, "Distortion of Metal Crystals," Clarendon Press, Oxford, 1935, p. 56.
11. C. F. Elam, Loc. Cit., p. 128.

THE AUTHOR

H. J. GODFREY

HOWARD J. GODFREY has been engineer of tests at the Fritz Engineering Laboratory from 1937 to date. He received his B.S. in Civil Engineering at Tufts College, 1931; M.S. in Civil Engineering at Lehigh University, 1933. From 1934 to 1937 he was research engineer at John A. Roebling Sons Co.