SCHLINK & THOMPSON

A Study of the Internal Stresses in Cold-Rolled Shafting

Mechanical Engineering

B. S.

1912

A STUDY OF THE INTERNAL STRESSES

IN COLD-ROLLED SHAFTING

BY

FREDERICK JOHN SCHLINK
AND
HERBERT PERCY THOMPSON

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

MECHANICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1912

1912
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UNIVERSITY OF ILLINOIS

June 1, 1912 190

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Frederick John Schlink and Herbert Percy Thompson

ENTITLED A Study of the Internal Stresses in Cold Rolled Shafting

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Mechanical Engineering

H. F. Moore
Instructor in Charge

APPROVED: C. R. Richards

HEAD OF DEPARTMENT OF Mechanical Engineering.

A STUDY OF THE INTERNAL STRESSES IN COLD-ROLLED SHAFTING

Purpose of the Investigation-- This investigation was suggested by the phenomenon which has often been observed, of distortion of cold-rolled shafting, indicating the presence of initial stress. This defect of distortion is one familiar to every machinist and millwright, and in many cases prevents the use of this material for shafting where keyways must be cut or shoulders turned without impairing the straightness of the shaft. The presence of initial stress in a shaft may also have an effect on the strength of a shaft subjected to pure torsion, and presumably would affect its strength in cross-bending, especially under repeated or reversed stress such as occur in the fibers of belt-driven shafts. If an initial tensile stress is present in a shaft, the outer fibers can reasonably be expected to fail under a smaller stress than if the shaft were initially unstressed. The same result could be expected in the case of initial compressive stress. An investigation of initial stress might also lead to results of a qualitative nature regarding the magnitude of the distortion resulting from the cutting of keyways in the shaft, as well as the effect of different arrangements of keyways. It would also be of value to determine whether there is any essential difference in the matter of internal stress, both as to uniformity and magnitude, between cold-rolled and cold-drawn material.

Method of Investigation-- In general, the method used consisted in measuring, by means of a movable extensometer, the deformation produced in the shaft by the internal stress released by some machine operation. Computing from the unit deformation and an

assumed modulus of elasticity, the stresses released, and their sense, positive or negative, were determined.

On a piece of the shafting about a foot long, cut from the bars as received from the jobber, gauge points ten inches apart and uniformly spaced around the circumference, were marked off on the specimen by means of a standard marker. The points marked were drilled about an eighth of an inch into the shaft with a #54 twist drill (diameter 0.055"). After drilling, the holes were carefully finished so as to give a good seating surface for the extensometer points. The use of the extensometer and the method of figuring readings will be explained subsequently.

Lengths of shafting were obtained in two sizes, 1 3-16" and 1 5-16" diameter. Two different makes of cold-drawn and one make of cold-rolled shafting are represented in these tests. Duplicate pieces of each length were used in obtaining check data, and these were cut off opposite ends of the same bar.

Release of stress was determined for each size and make, in the case of turning off the outer surface, first to a depth of $\frac{1}{4}$" and then to a depth of $\frac{1}{2}$" .

Another series was run for each size and make, cutting a single standard keyway in each and determining stresses. Then a second keyway was cut on the opposite side of the shaft, and stresses again determined.

Extensometer tests in tension and compression were run to determine the difference of the properties of the materials under these two conditions of stress. The modulus of elasticity was determined in each case. These tests were run on the smaller size of shaft only, on account of the limited time available, and the capacity of the extensometer adapted to this use.

Apparatus Used -- Deformations were measured by means of the strain gauge. The strain gauge is a type of portable extensometer, adapted to easy application and removal. At the beginning of the investigation, the Berry strain gauge was used. This instrument is described in the Proceedings of the National Association of Cement Users, Volume VIII. Its readings may be estimated to 1-50000 of an inch but are subject to several variations due to (a) changes of temperature, (b) a certain sluggishness due to frictional and other resistances in the lever multiplication, and (c) differences in personal handling, both between the work of the same observer at different times, and that of different observers on the same day. Errors due to (a) can be obviated by the use of the standard bar, whose application will be explained later, except where these changes are rapid and irregular, in which case the proper correction is difficult and uncertain. On account of the fact that it was difficult to obtain an equable temperature, it was impracticable to isolate this cause of error in an instrument whose body is of a different material than the specimen under investigation, and it was decided to resort to the use of the Howard form of the micrometer strain gauge. This instrument has a steel body, and its changes of length due to temperature changes could reasonably be expected closely to keep pace with those of the steel specimen upon which readings are being taken. In practice, this is found to be sensibly true and the correction for temperature change during a series of readings was found to be negligible.

The Howard micrometer gauge as made by Brown and Sharpe is shown in its essential features in Figure 0. It consists of a micrometer head with contact tip A bearing against an anvil B

carried by the movable conical pointed leg C of the instrument. Thousandths of an inch may be read directly, and ten thousandths may be estimated. Contact was determined by the sense of touch. In this series of experiments, a ten inch gauge length was used. The standard bar was of machine steel with drilled holes at the ends of an accurately measured gauge length.

Any changes of length observed in the readings of this bar may be due to a change in length either of the standard bar or of the strain gauge itself. Of course, if the standard bar and the instrument change in length equally and simultaneously, no change of reading is observed. It was found by experiment that, so far as could be determined, all the change of reading observed was due to changes of temperature, as personal errors seemed to be negligible. It should be noted that the instrument was used in the position most favorable to accuracy of handling.

Observations of the standard bar were taken before and after each set of readings on each specimen. After a number of trials, it was found that no difference greater than 0.0001" between two consecutive readings of the standard bar were observed, and no corrections for cyclic error were considered necessary. After the bar was turned down, or a keyway cut, the corresponding reading of the standard was subtracted algebraically from the initial reading, and the result added to the reading of the length between gauge points on the specimen.

By the use of this method of correction, no further allowance need be made for changes in length of the specimen not due to release of stress, assuming, of course, that the standard bar, the strain gauge, and the specimen under observation pass through the same cycle of temperature variation during the taking

of the readings, an assumption which seems reasonable, and not inconsistent with results obtained on check specimens.

The tension and compression tests were made on the usual type of 100,000 pound Riehle testing machine. Wedge grips were used for the tension tests, and in the compression tests, a ball and socket was employed to apply the load.

The deformations were measured with a Ewing extensometer over a gauge length of $1\frac{1}{4}$". The smallest scale reading represented an elongation of 1-125,000 inch. The stretch of the specimen moves a diamond scratch engraved on glass across the field of a high-power microscope, carrying in its lens system a scale. This instrument is rather easily manipulated after focusing is completed, and is of course sensitive to very slight deformations.

Data of Tests-- Table I shows typical data of one complete determination of stresses.

Figures 1 to 12 show graphically the results of tests plotted to radial coördinates.

Figure 1 represents the release of stress for cold-rolled shafting of 1 15-16" diameter, reduced by turning off to 1 11-16"and 1 7-16" diameter. It will be noted that all the stresses indicated are compressive, and that the release of stress during the second turning-off was greater than that during the first. Time was insufficient to allow investigation of the exact relation of the depth of turning to release of stress, but from the results at hand, it is thought that the longitudinal compression extends to a considerable depth. The presence of initial compression in the outer layers of the shaft implies an equal tensile stress in

the interior or core of the bar. This longitudinal compression in the external fibers is without doubt accompanied by a lateral compression during drawing or rolling, extending possibly to the center of the bar. Its effect on the properties of the material is at present unknown.

Figure 2, Curve A shows the distribution of stress in a cold-drawn bar of the same diameter. It will be noted that, in this case, the initial stresses are all positive, that is, tension. The approximately circular shape of the diagram and its concentricity with the zero circle are indications of the uniformity of the distribution.

Curve B of the same figure shows the distribution for the same material but with an original diameter of 1 3-16". It will be noted that the diagram is still of about the same shape, but is shifted bodily to the left, giving compression at one point and tension at three others. This, in the opinion of the writers, is an indication of a bending moment, caused possibly in the straightening process. All shafting, is in general, straightened before being shipped, as the process of rolling or drawing leaves the shaft considerably out of true. The effect as shown in the curve is what one would reasonably expect as a result of this bending.

In Figure 3, we have a similar stress diagram for a different make of cold-drawn shafting, of 1 15-16" diameter. In this, all the stresses are negative, but show a shifting from the center similar to the previous case, possibly for the same reason. It was observed, however, that in no case did the larger shafting tested show a reversal of stress as did the smaller size. This is probably due to the fact that, in the larger sizes, the load in

the straightening press was not heavy enough to reverse the stress. It may be that the heavier shafting comes out straighter than the smaller sizes and hence requires less bending.

In Figure 5, the two curves are for the same size of shaft, 1 3-16, reduced $\frac{1}{4}$" in diameter. They are seen to be sensibly similar curves, both giving some rather unusually high values of compressive stress.

Figure 4 shows two curves obtained for machine steel bars $1\frac{1}{4}$" in diameter. In this case, it appears that nearly all the internal stress present is due to bending, as the algebraic sum of the stresses for diametrically opposite points is not far from zero.

Figure 7 shows the distribution of stress in cold-rolled shafting with single keyway. Both of these specimens were 1 15-16" in diameter, each with a single keyway $\frac{1}{2}$" wide by $\frac{1}{4}$" deep. It will be noted that on the side of the shaft on which the keyway is cut, there is a condiderable release of compression accompanied by a setting up of tension in the opposite side. The points at right angles to this axis seem to show little change of stress, and such change as is indicated may possibly be accounted for as the action of a bending moment.

Figure 8 shows the distribution of stress in the case of two cold-drawn, and one cold-rolled shaft of 1 3-16" diameter. In each of these there was a single keyway 5-16" wide by 5-32" deep. These curves, it will be noticed, show considerable divergence, especially in the case of the cold-rolled bar, for which the maximum release of compression is found to appear on the side opposite the keyway, the release on the keyway side being compar-

atively low. In fact, the check specimen for this piece showed tension on the keyway side, with low compression on the opposite surface, as is illustrated in Figure 11. This peculiarity is especially apparent in the cold-rolled shafting, which, seems, in general to show a great variation in its surface condition, especially in the smaller sizes.

Figures 9 and 10 show stress distribution for specimens of cold- drawn shafting 1 15-16" in diameter with a single keyway $\frac{1}{2}$" wide by $\frac{1}{4}$" deep. It is to be noticed that in figure 9, the curve shows a flattening towards a transverse axis of the bar through the keyway, while in figure 10 the flattening is towards an axis at right angles to that passing through the keyway. This again is probably to be explained by the presence of a bending moment introduced in the straightening process, which, in one case happened to fall along the axis of the keyway and in the other case did not.

Figure 6 shows stress distribution for 1 15-16" shafts with two diametrically opposite keyways. The effect of the cutting of the second keyway seems to be to make the distribution of stress more uniform, as indicated by the reduced eccentricity of the curve.

Figure 12 shows for the 1 3-16" shafting the same effect of increasing uniformity of stress for two diametrically opposite keyways, over the single keyway. The same slight flattening due to the release of internal bending moments was noticeable in this case as heretofore.

<u>Results of Tests in Tension and Compression</u> .-- The tests in compression, as shown in the stress-strain diagrams, Fig.14

indicate a very low limit of proportionality for the cold-drawn specimens. Above about 34,000 lb. per sq. in. the curve shows a very noticeable divergence from a straight line. The curves show a very high modulus of elasticity in compression, especially for the cold-drawn material, while the modulus of elasticity in tension is somewhat lower than ordinarily given for steel, the cold-rolled again being lower. This high modulus of elasticity would require all the compressive stresses to be refigured on the basis of the new values, as a value of 30,000,000 lb. per sq. in. was assumed in the stress computation. The same is true of the tensile stresses, as the modulus in tension came lower than the assumed value. However, as the variation is so great, and sufficient tests were not run to determine the correct average values, the value E = 30,000,000 will be kept in all stress computations.

Conclusions and Applications-- Initial Stresses as high as 6000 to 7000 lb. per sq. in. with one stress of 14000 lb. per sq. in. were found to exist in the various samples tested. The largest stresses were all compressive, the maximum tension being probably not over 4000 lb. per sq. in. with the average considerably below this. These stresses were by no means uniform in the different specimens but showed a wide and unsystematic variation due to a number of factors present difficult to isolate and determine, viz: Bending moments set up in the straightening process, differences in the rolling pressure or reduction in the dies; in the cold-drawing process, the method of forcing through the dies, whether pushing or pulling.

The fact of the increase of strength in tension due to the cold-drawing process is well-known and has been verified by numerous investigators. This is probably to be accounted for by the condition of high tensile stress imposed upon the bar in drawing through the dies. This stress is no doubt considerably above the elastic limit, as an actual detrusion of the metal from the end of the bar is produced. At the time of drawing, the inner core and the outer skin are probably both in tension, the greater tension being induced in the interior part. After internal equilibrium has been established, the two portions shorten, but the interior core shortens the more, and compression is set up in the outer surface, accompanied by a certain residual tension within, in the aggregate equal to the compression. The effect of the high tensile stress from the drawing operation is undoubtedly to lower the elastic limit in compression, and this is borne out by the results of compression tests made by the writers. A phenominally high modulus of elasticity in compression was observed, ranging from 36,000,000 to 56,000,000 lb. per sq. in. This value should not be accepted without verification, possibly with another extensometer, and on the larger specimens.

As regards the cutting of keyways in cold-rolled and cold-drawn shafting, the evidence of these tests points strongly to an advantage in cutting symmetrical keyways, two or four in number, whenever feasible. The effect of the addition of a second keyway results in a very noticeable evening up of stress around the shaft, accompanied, of course, by a corresponding lessening of the distortion or warping action. Of course, when more than one keyway is used, there is introduced the danger that

one of the keyways may be called upon to resist more than its figured share of the twisting moment, but where reasonably careful machine work is available, this should not be of great moment.

As a result of the initial compression in the outer fibers, the strength of the shaft subject to bending moment will be somewhat less than is ordinarily figured, as the fibers in compression will fail under lighter load, and in the case of repeated or alternating stresses, the effect of fatigue will be of more moment than for a material without internal stresses, on account of a lowered elastic resilience.

T A B L E I.

Sample Data For Determination of Initial

Stress by the Strain Gauge.

Date: March 22, 1912.
Bar #1 Black. - Cold-Drawn
Diam. 1 15-16"
Observer- Schlink, Recorder- Thompson.
Strain Gauge- B. & S. Micrometer.
Standard Bar.- U.I.

Hole No.	Stan.	1	2	3	4	Stan.
Average of Reading	.2053	.2065	.2098	.2029	.2125	.2054

After turning off $\frac{1}{2}$" on diameter.

Uncorr'd Aver.	.2052	.2054	.2091	.2019	.2105	.2052
Correction	+.0001	+.0001	+.0001	+.0001	+.0001	+.0001
Corrected Aver.	.2053	.2055	.2092	.2020	.2106	.2053
Corrected Diff.	-.0000	-.0010	-.0006	-.0009	-0019	.0001
Stress Release $= \frac{eE}{L}$		-.3000	-.1800	-.2700	-.5700	

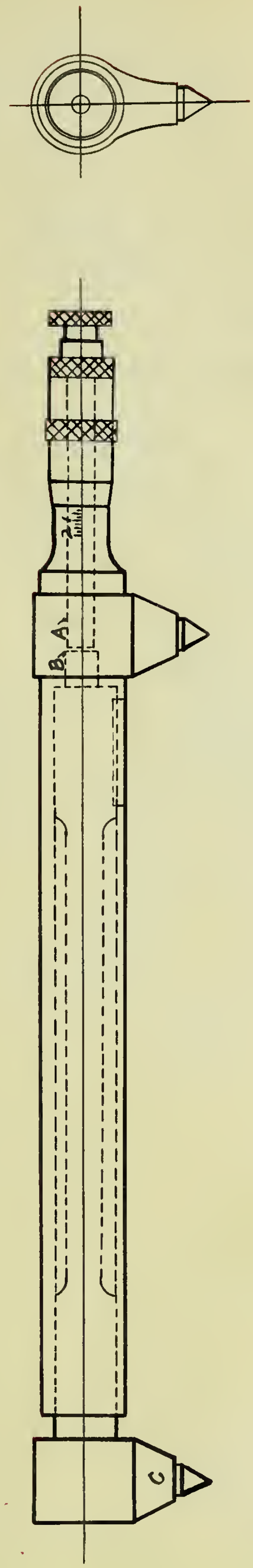
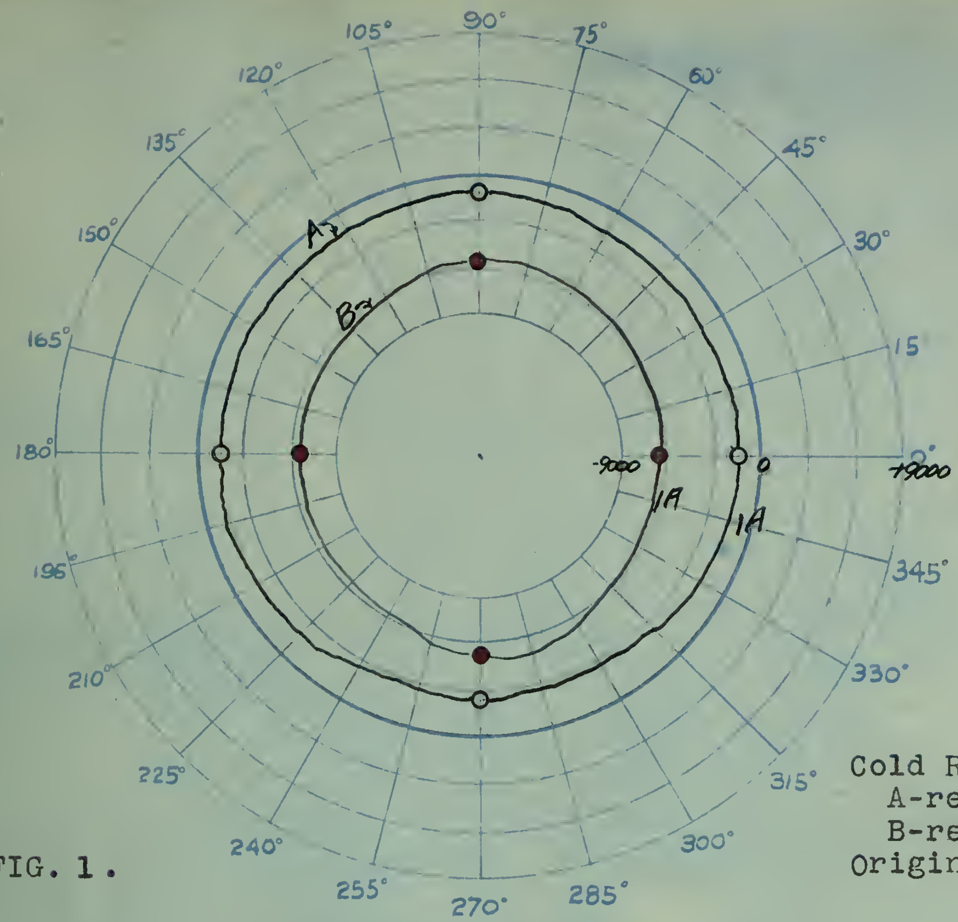


FIG. O.

Note on the Use of the Curves.

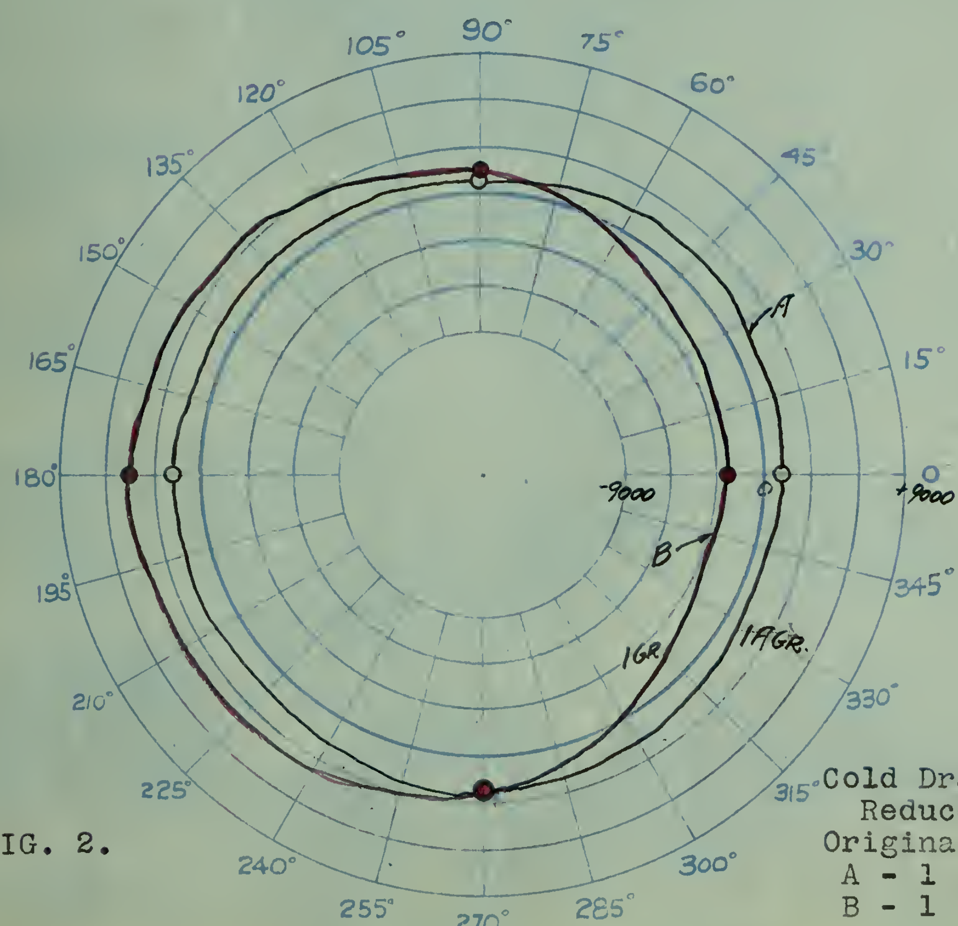
The following diagrams are plotted in radial coördinates. The heavy circle is the zero circle from which stresses are laid off. The radial lines are located at intervals of 15° and serve to locate the gauge line on the shaft relative to an arbitrary gauge line located at 0°. The scale of stresses is 3000 lb. per sq. in. per radial division($\frac{1}{4}$"). The marks shown against each curve represent the specimen number and are used for identification.



Cold Rolled Shafting
A-reduced $\frac{1}{4}$"
B-reduced $\frac{1}{2}$"
Original diam. 1 15-16"

FIG. 1.

RADIAL DIAGRAMS OF STRESS.



Cold Drawn Shafting
Reduced $\frac{1}{4}$"
Original diameters
A - 1 15-16
B - 1 3-16

FIG. 2.

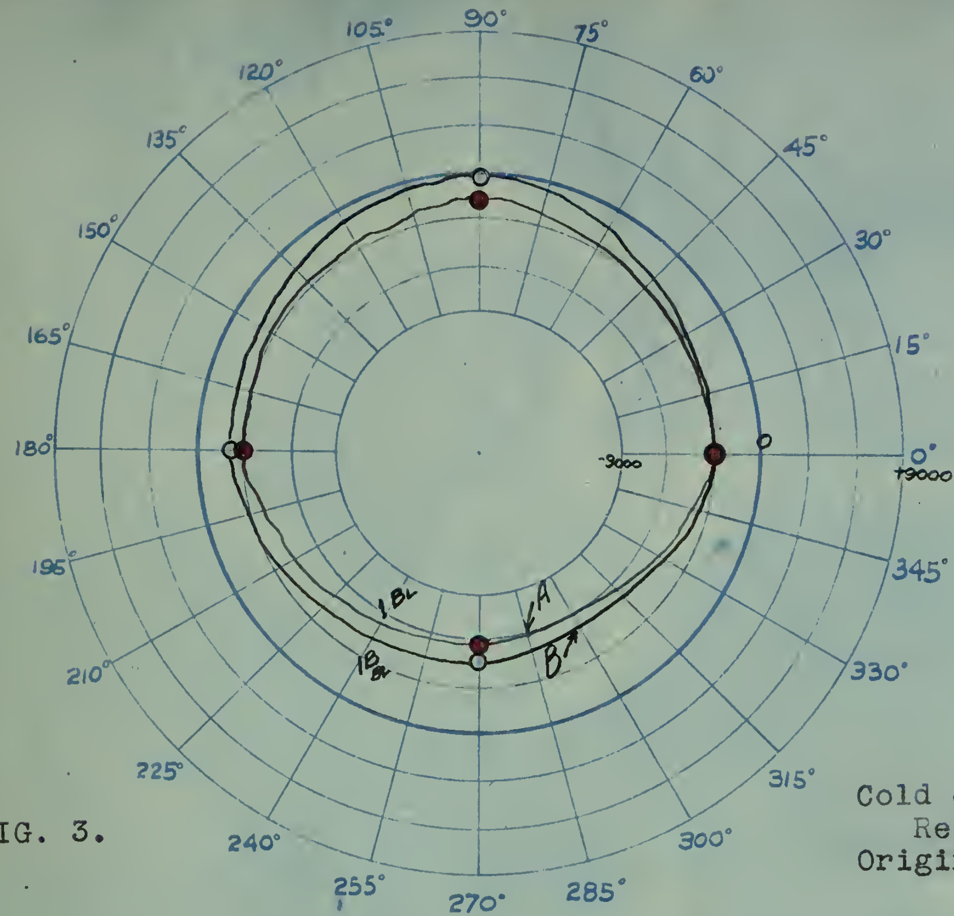


FIG. 3.

Cold drawn shafting
Reduced $\frac{1}{2}$ "
Original diam 1 15-16"

RADIAL DIAGRAMS OF STRESS

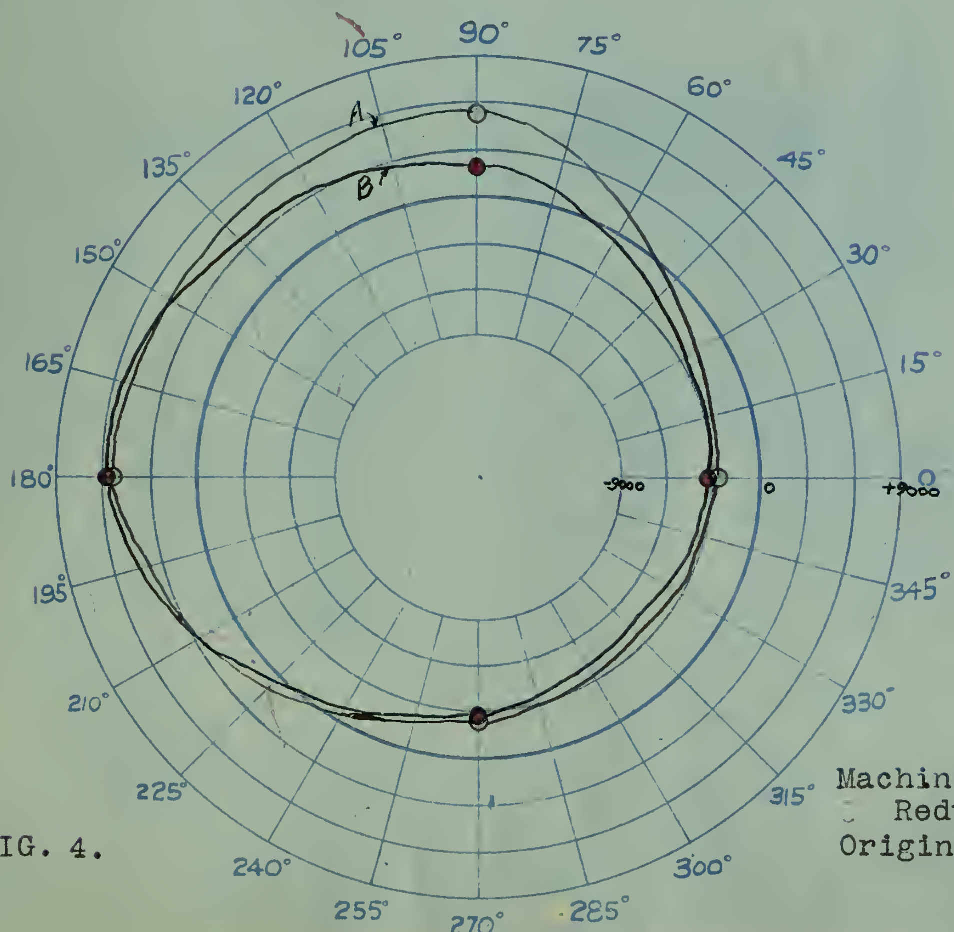
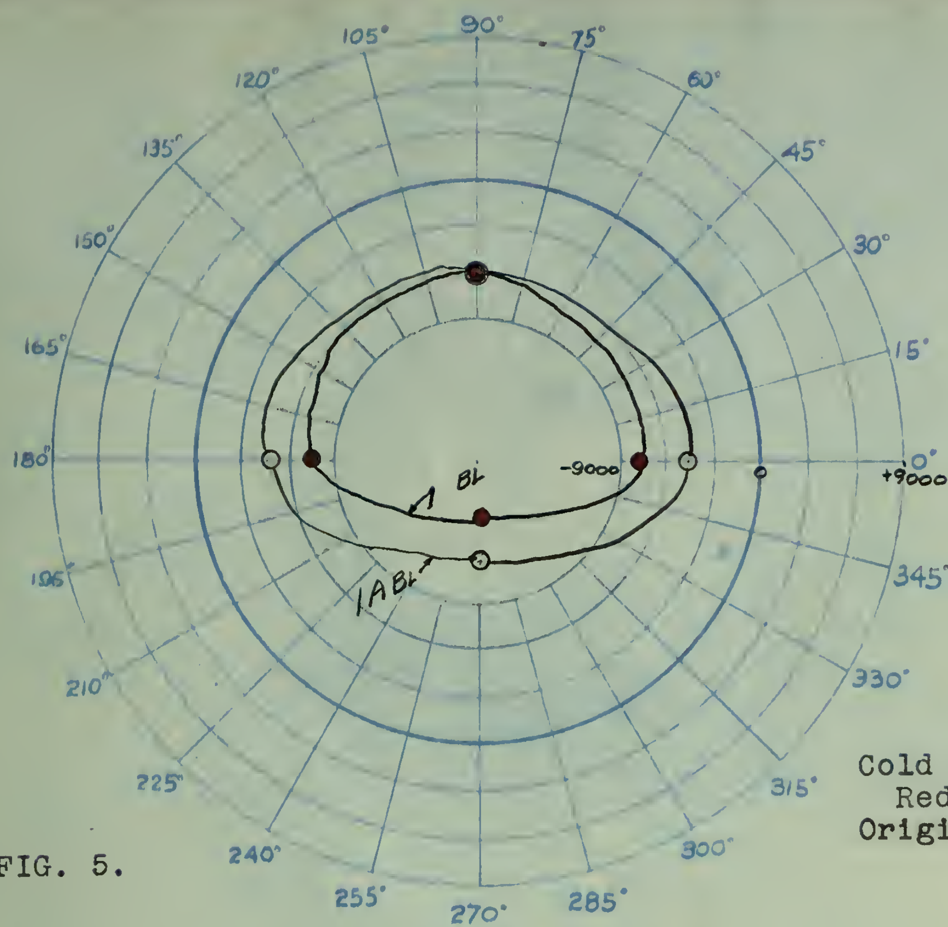


FIG. 4.

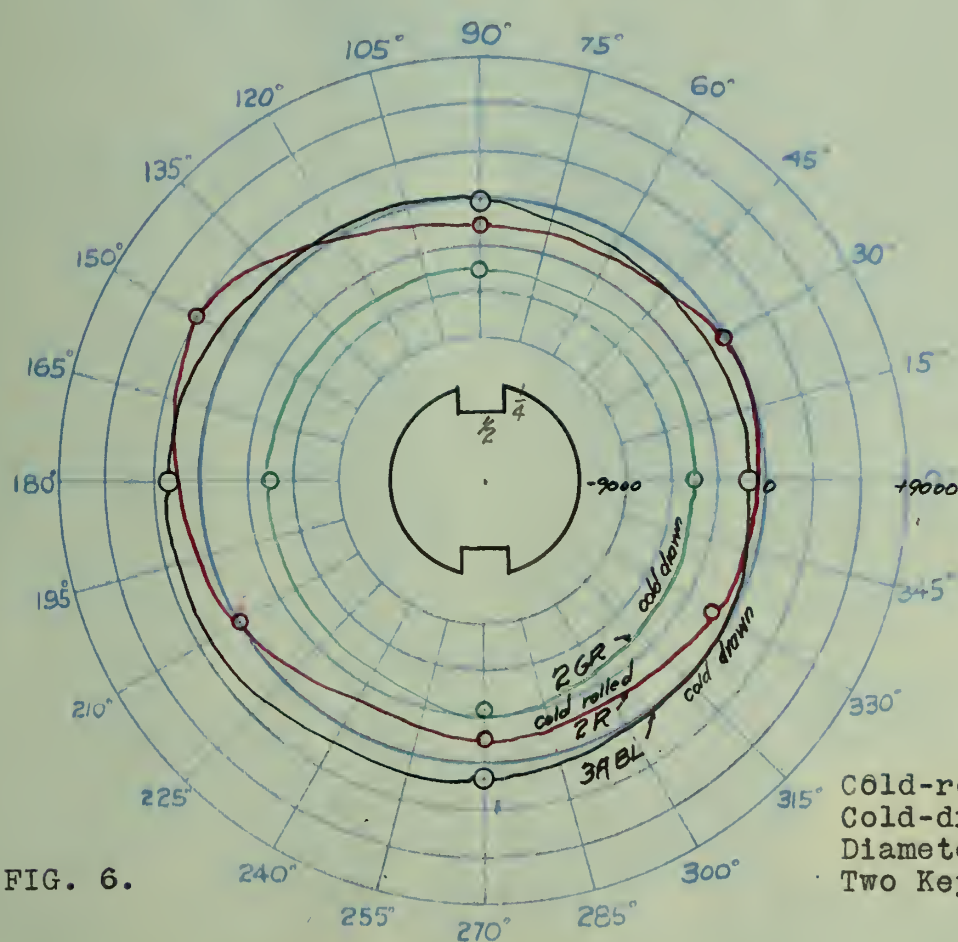
Machine steel bar.
Reduced $\frac{1}{4}$"
Original diam 1 $\frac{1}{4}$"



Cold Drawn Shafting
Reduced $\frac{1}{4}$"
Original diam. 1 3-16 "

FIG. 5.

RADIAL DIAGRAMS OF STRESS



Cold-rolled and
Cold-drawn shafting
Diameter 1 15-16"
Two Keyways $\frac{1}{2}$" x $\frac{1}{4}$"

FIG. 6.

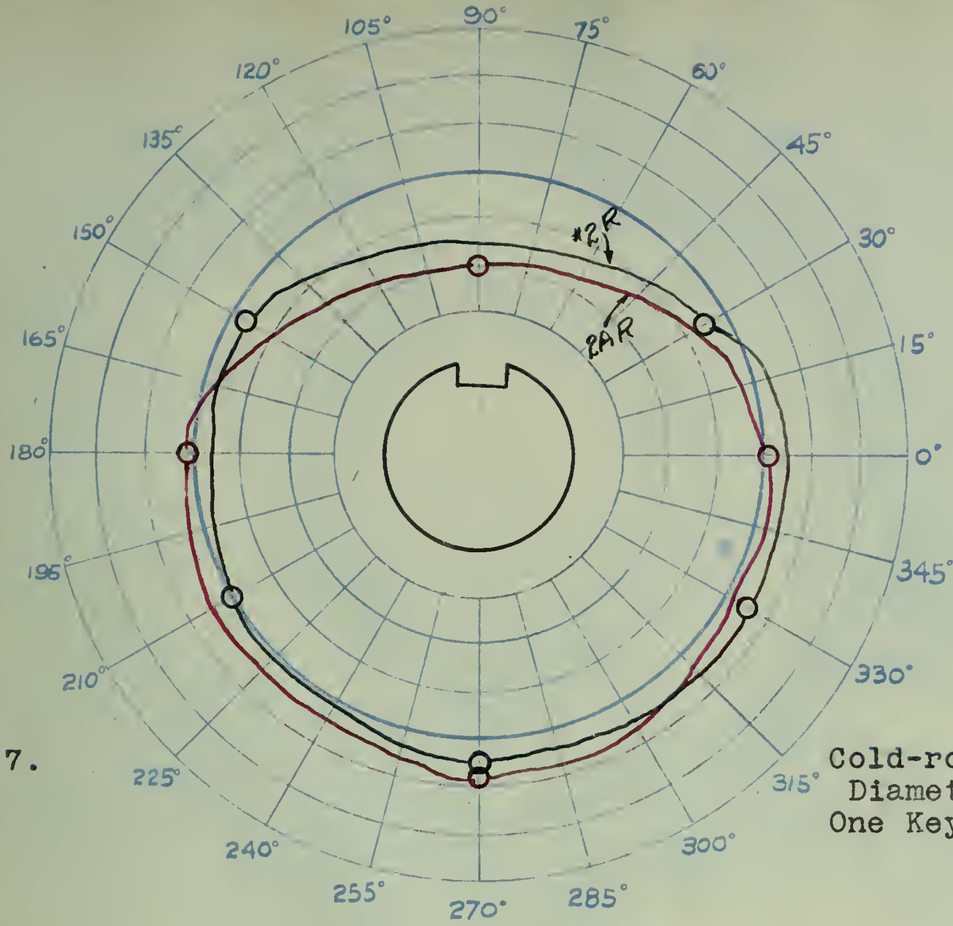


FIG. 7.

Cold-rolled shafting
Diameter 1 15-16"
One Keyway $\frac{1}{2}$" x $\frac{1}{4}$"

RADIAL DIAGRAMS OF STRESS

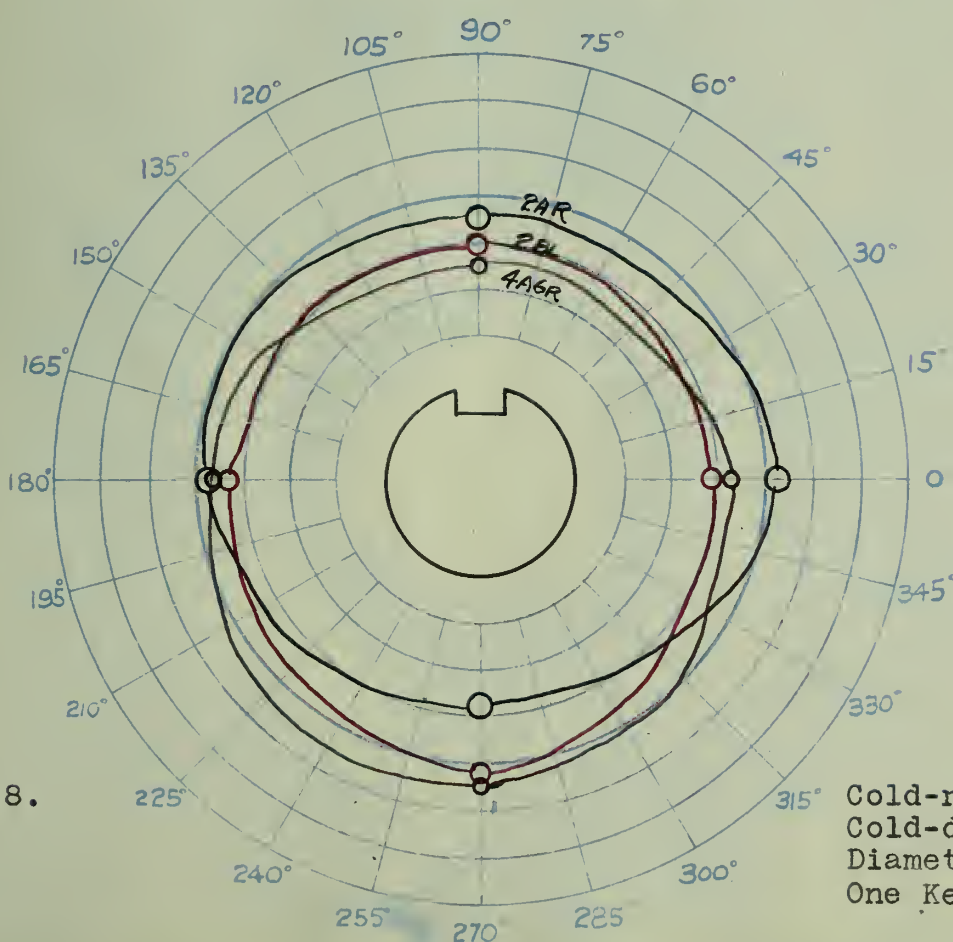


FIG. 8.

Cold-rolled and
Cold-drawn Shafting
Diameter 1 3-16"
One Keyway 5-16"x 5-32"

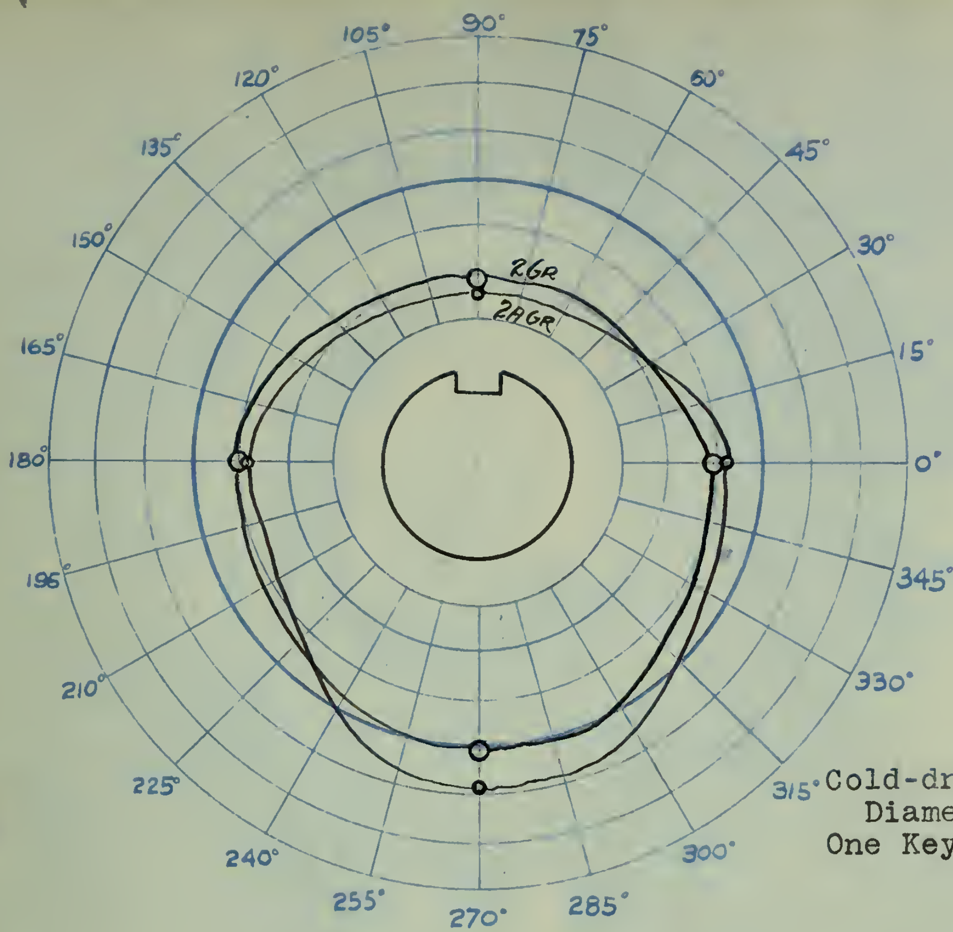


FIG. 9.

Cold-drawn Shafting
Diameter 1 15-16
One Keyway ½" x ¼"

RADIAL DIAGRAMS OF STRESS

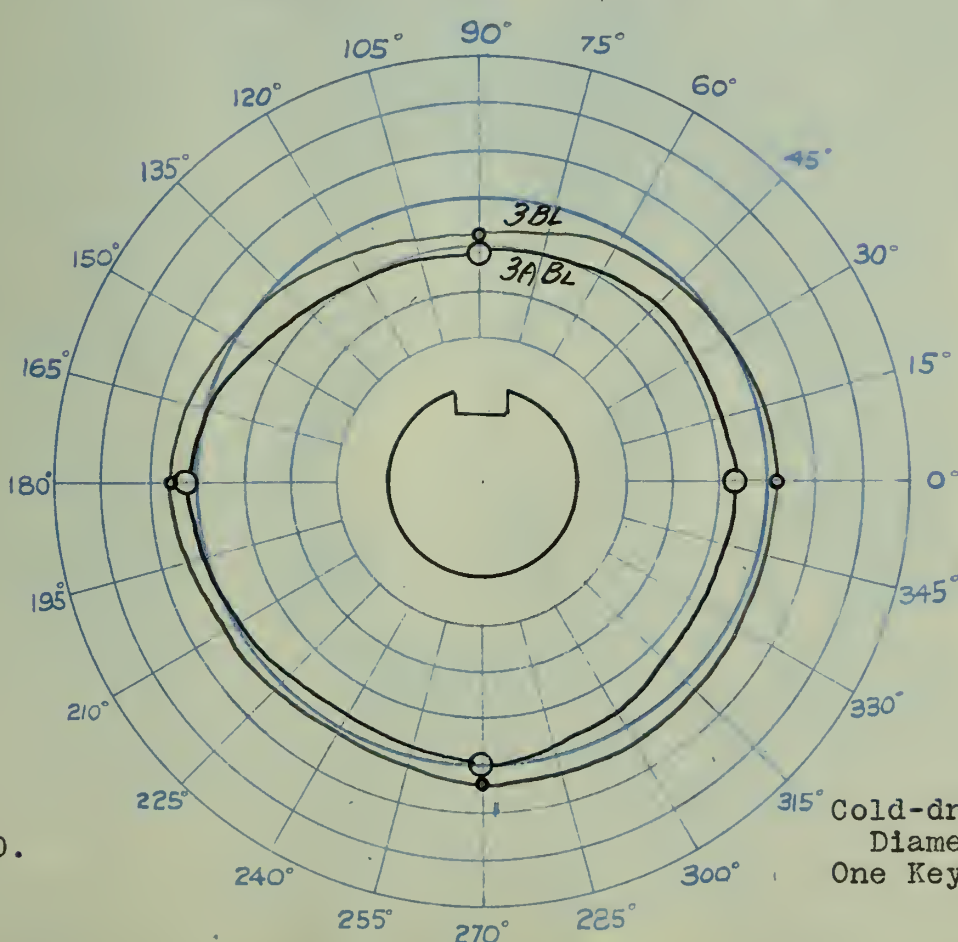


FIG. 10.

Cold-drawn Shafting
Diameter 1 15-16
One Keyway ½" x ¼"

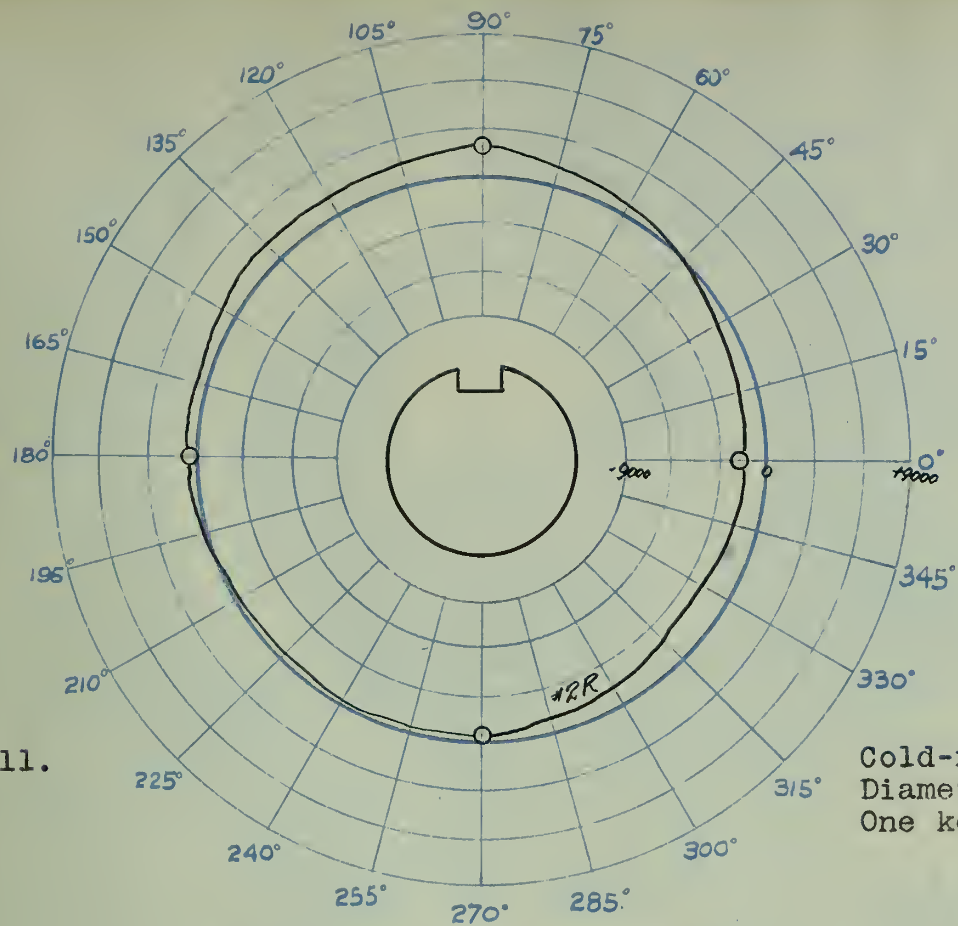


FIG. 11.

Cold-rolled Shafting
Diameter 1 3-16"
One keyway 5-16"x 5-32"

RADIAL DIAGRAMS OF STRESS

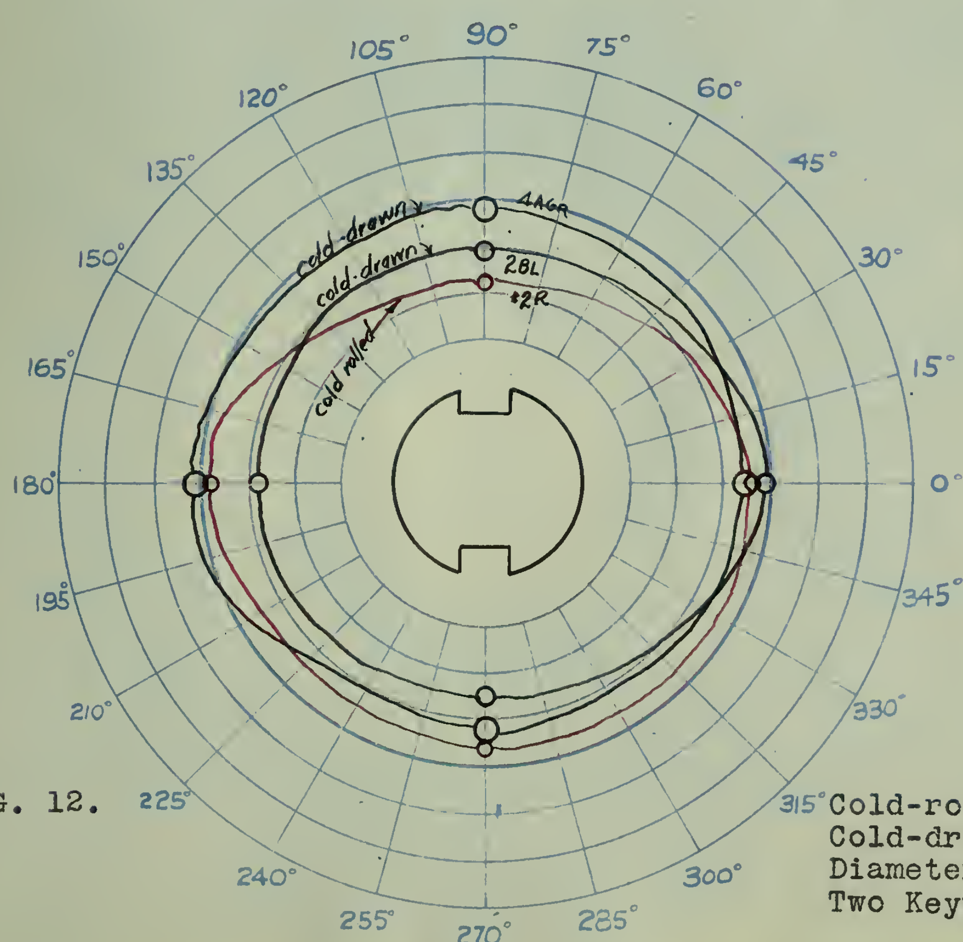
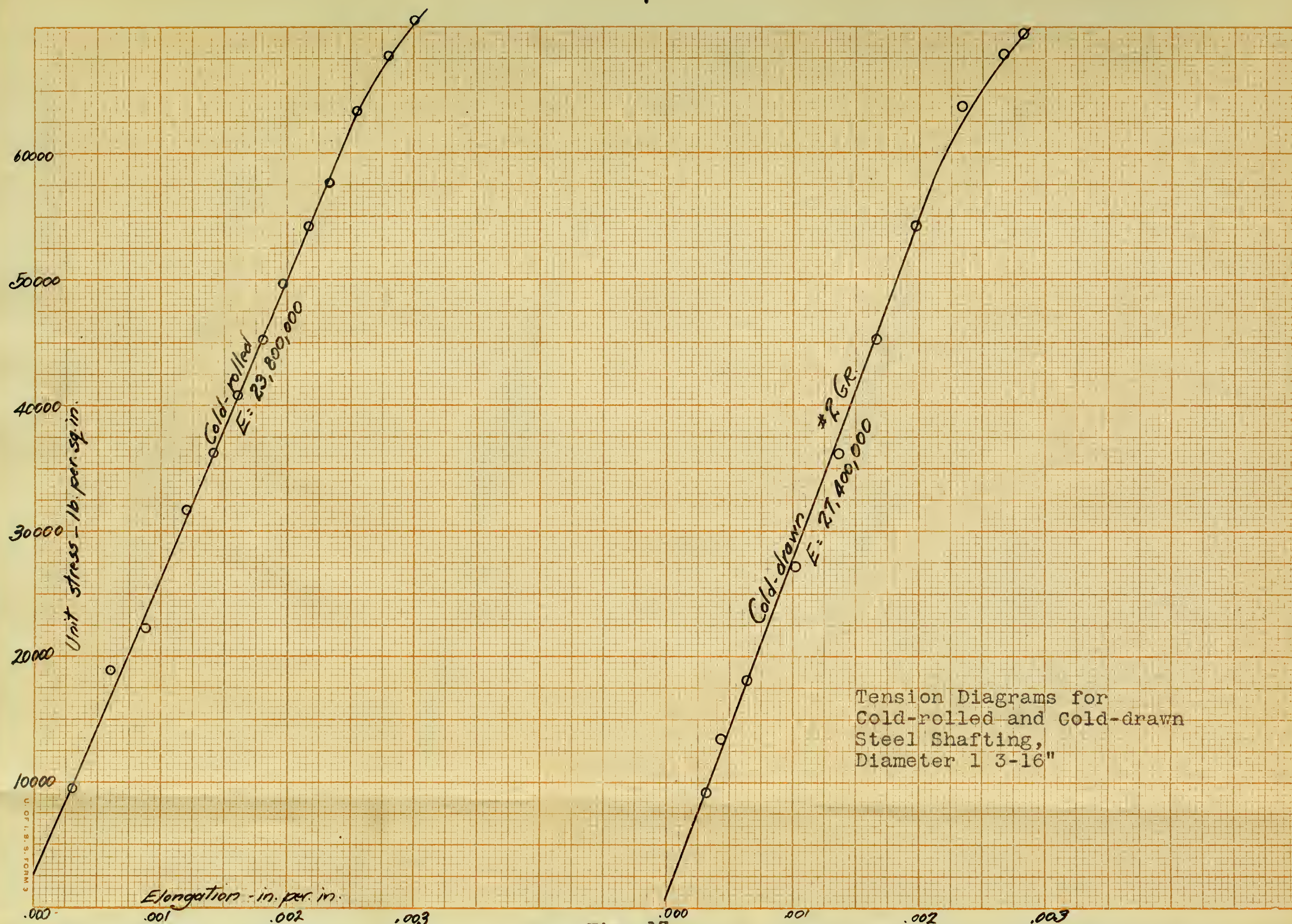


FIG. 12.

Cold-rolled and
Cold-drawn Shafting
Diameter 1 3-16"
Two Keyways 5-16"x 5-32"



Tension Diagrams for
Cold-rolled and Cold-drawn
Steel Shafting,
Diameter 1 3-16"

Fig. 13.

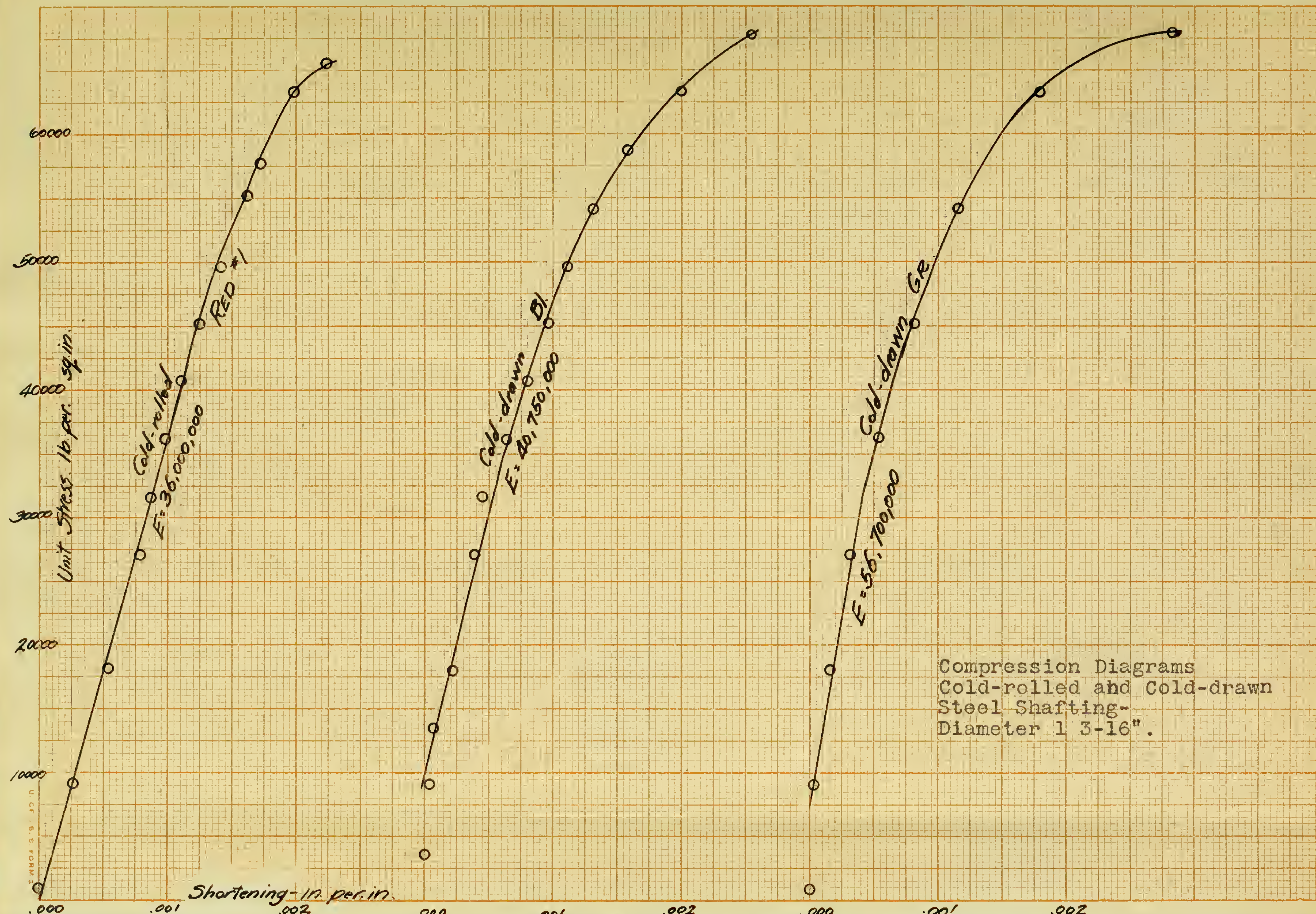

Compression Diagrams
Cold-rolled and Cold-drawn
Steel Shafting-
Diameter 1 3-16".
Unit Stress lb per sq.in.
60000
50000
40000
30000
20000
10000
Shortening-in per.in.
.000
.001
.002
Cold-rolled
E=36,000,000
RED #1
Cold-drawn
E=40,750,000
Bl
Cold-drawn Gr
E=56,700,000

Fig. 14.