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EFFECT OF COLD DRAWING 
ON MECHANICAL PROPERTIES 
OF WELDED STEEL TUBING

BY

WINSTON E. BLACK

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URBANA

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THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS
EFFECT OF COLD DRAWING
ON MECHANICAL PROPERTIES
OF WELDED STEEL TUBING

BY

WINSTON E. BLACK
INSTRUCTOR IN THEORETICAL AND APPLIED MECHANICS

PUBLISHED BY THE UNIVERSITY OF ILLINOIS
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EFFECT OF COLD DRAWING ON MECHANICAL PROPERTIES OF WELDED STEEL TUBING

I. INTRODUCTION

1. Preliminary Statement.—A thin-walled hollow cylinder, here referred to as tubing, has many inherent advantages as a load-resisting or structural member because of the shape or distribution of material in the cross-section. In compression and bending, the tubular cross-section has the advantage of having the same relatively high moment of inertia about all axes of bending. In torsion, the circular tube is the most efficient structural shape. In tension, however, where the strength of the member depends only on the size (rather than the shape) of the cross-sectional area, it has no particular advantage. Although engineers have long been aware of the latent possibilities of tubing for structural members, the cost of production and the difficulty of obtaining economical and efficient connections between members have restricted its use. At present, however, increased attention is being given to the use of tubular members for structural purposes, especially where a large strength-weight ratio is desired. There is therefore a growing need for information concerning the mechanical properties of tubing, especially of cold-drawn welded steel tubing, which because of its strength and relatively low cost is finding extensive use in structural and machine parts.

In 1930 Whittemore, Adelson, and Seaquist carried out an extensive investigation of the physical properties of electrically welded steel tubing, but no attempt was made to evaluate the effect of cold working upon the properties of the material. The results of this investigation established the fact that the weld did not weaken the tubing structurally, and that the physical properties of the finished tube could be safely assumed to be the same as that of the base metal. Tubing of several commercial grades was tested.

2. Manufacture of Cold-Drawn Welded Steel Tubing.—In the manufacture of welded steel tubing, the material enters the mill in coils of flat strip stock which has been finished to a predetermined thickness and width. The strip is first passed through a set of forming rolls which gradually shape it into the form of a hollow cylinder containing a straight longitudinal slit. The butting edges along the slit are then pressed together and welded by one of several methods, namely, the electric resistance process, the atomic hydrogen arc proc—

*Numbers refer to the bibliography at the end of the bulletin.
ess, or the oxyacetylene process. For the smaller sizes of tubing, the electric resistance process is most common, and the tubing tested in the investigation herein reported was welded by this process.

It is becoming common practice to anneal or normalize the tubing following the forming and welding operation. The purpose of this treatment is twofold: first, it removes undesirable effects of heat treatment induced by the welding process (the metal is often cooled by a jet of liquid immediately after the weld is completed); and, second, it tends to standardize the properties of tubing of a given chemical composition by eliminating variations in the amount of cold working which may have been produced in the forming operation. These two factors are especially important if the tubing is to be subjected to further cold working by tapering, flanging, bending, or drawing.

The welded steel tubing is frequently cold drawn, following the normalizing treatment, by passing or pulling it through an exterior circular die whose diameter is smaller than the outside diameter of the tubing; usually no interior mandrel is used. Cold drawing of the tubing may be carried out for two reasons: first, special sizes of tubing which are not carried in stock by the manufacturer can be furnished more economically by drawing down a larger standard size than by setting up a mill to produce a single odd-size lot; second, cold drawing may be used to impart special mechanical properties to the tubing. The tubing is obviously deformed beyond the yield point, and therefore the strength and hardness are increased, and the ductility is correspondingly decreased.

3. Purpose and Scope of Investigation.—There seem to be no published data giving quantitatively the effect of cold drawing on the properties of welded steel tubing, and any attempt to impart special properties to tubing by this process seems to be done by trial and error. It is the purpose of this investigation to evaluate the changes that occur in the more common mechanical properties of electrically-welded S.A.E. 1010 steel tubing as a result of cold drawing the tubing. It is intended thereby not only to aid the manufacturer in producing tubing of known properties, but also to furnish information, for use in structural design, on the strength and ductility of low carbon (S.A.E. 1010) welded and cold-drawn steel tubing.

Experimental results of tension, compression, and hardness tests of samples of the S.A.E. 1010 welded steel tubing are presented herein. The tubing from which samples were taken, as originally
formed (welded and normalized), had an outside diameter of approximately one inch; the tubing had been subjected to various amounts of cold working by drawing through dies of different diameters. Tests were made both on the normalized tubing before being cold drawn and on the cold-drawn tubing. The structural behavior of members, machines, or structures made of the tubing is not discussed in this bulletin.

4. Acknowledgment.—A large portion of the material presented herein was originally presented as the thesis of Mr. H. R. Sandberg, a senior engineering student, whose careful work and intelligent grasp of the problem are hereby acknowledged. The investigation was carried out as a project of the Engineering Experiment Station under the administrative direction of Dean M. L. Enger, Director, and of Professor F. B. Seeley, head of the Department of Theoretical and Applied Mechanics. Acknowledgment is due to Professor Seeley, to Mr. H. S. Card, Director of Product Development, and to members of the Product Development Committee of the Formed Steel Tube Institute, for their interest and helpful advice in the initiation and conduct of the test program. Material for the tests was furnished by Clayton, Mark and Co., Evanston, Illinois, Michigan Steel Tube Products Co., Detroit, Mich., and Rome Manufacturing Co., Rome, N. Y.

II. Description of Specimens and Tests

5. Outline of Tests.—All samples of tubing were subjected to static tensile and compressive tests and to hardness tests. No repeated stress (fatigue) tests were made. The properties determined in each type of test may be listed as follows:

Tension—Yield point or yield strength,* ultimate strength, per cent elongation in both 2-in. and 8-in. gage lengths.

Compression—Yield point or yield strength,* maximum compressive strength.†

Hardness—Rockwell "B" hardness.

The testing program consisted of four series of tests. In each series were tested samples of tubing which, as originally formed, welded, and normalized, had the same outside diameter. Subsequent to normalizing, different samples of the tubing were cold drawn to different

*Defined in “Standard Definitions Relating to Methods of Testing,” A.S.T.M. Designation: E6-36 as “The stress at which a material exhibits a specified limiting permanent set,” and determined by the offset method as recommended using offsets of 0.02 per cent and 0.20 per cent.
†Defined as the maximum load per unit area resisted by a specimen before the specimen failed by wrinkling (specimens that failed by buckling were not considered, see Fig. 4).
diameters through dies whose diameters decreased by approximately \( \frac{1}{8} \text{-in. decrements. In Table 1 are listed the different samples of tubing according to the series and the nominal dimensions of the tubing before and after cold drawing. The only dimensions presented are those that are controlled in production.}

The tubing was produced by three different mills; series 1 and series 2 were produced by one mill, series 3 by a second mill, and series 4 by a third mill. It will be observed that in series 2, 3 and 4 the samples of tubing lettered A, E, J, and N represent the normalized tube which has undergone no cold drawing. No samples of the tubing in the original normalized state were obtained for series 1. It will be noted also that, in each series, tubing of two different wall thicknesses was tested, five different thicknesses being tested in all.

6. Details of Test Specimens. — The tubing was received from the mills in lengths of from ten to twenty feet. Two such lengths of a

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<th>Sample Designation</th>
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Table 2
AVERAGE DIMENSIONS OF TEST SPECIMENS

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<th>Outside Diameter</th>
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given size were used to obtain each of the samples listed in Table 1; these two lengths were selected at random from the tubing of the given size. The following test specimens were cut from each length of tubing:

3 tension specimens, 21 inches long;
4 to 9 compression specimens, 2, 3, and 4 inches long;
2 hardness specimens, 1 inch long.
All specimens were tested in the tubular form. No special treatment was given the tubing except that the ends of the compression specimens were machined perpendicular to the longitudinal axis of the tubing to insure an axial loading, and the hardness specimens were reamed or machined to remove the welding bead and to permit the supporting mandrel to fit the tube snugly. The external diameter and
the wall thickness of each specimen were measured to the nearest one-
thousandth of an inch.

In Table 2 are presented the nominal and the average measured
dimensions of the specimens in each sample of tubing. The average
dimensions of the cross-section of individual lengths of tubing varied
so little throughout the length that in general the cross-sectional area
could be assumed to be constant for specimens cut from the same
length of tubing. For tubing which had been formed and welded in
the same machine, but not cold drawn, the outside diameters of differ-
ent samples of tubes as received from the mill varied not more than
0.003 inch, and the wall thickness not more than 0.002 inch. The
outside diameter of cold-drawn tubing which had been drawn through
the same die was subject to a variation of only 0.001 inch. The wall
thickness of the cold-drawn tubing, however, varied somewhat more
than did the outside diameter, even for tubing that had received the
same nominal reduction of area in the drawing process. Such vari-
ations may have been caused by differences in drawing technique used
by different mills, or even by the same mill from time to time. A
further study of this variable is merited.

Despite the differences in wall thickness of the various tubes it
was found that the wall thickness of each tube remained very nearly
constant in the cold-drawing operation. The average increase in wall
thickness due to cold drawing was only about 5 per cent, the maxi-
mum increase being reached for a reduction of area of about 25 per
cent; further reduction decreased the wall thickness in some cases.

The percentage reductions of area listed in columns (6) and (7)
of Table 2 represent the changes in the nominal and actual cross-
sectional areas of the metal in the tube caused by the cold drawing.
Since in the drawing process the volume of metal in the tube remains
approximately constant, the actual reduction of area, in column (7),
bears a close relation to the percentage elongation of the tubing
produced by cold drawing, which is listed for two series of specimens
in column (8). This relation may be expressed approximately by the
following equation

\[(1 + e) (1 - R) = 1\]

wherein \(R\) = reduction of area, expressed as a decimal,

\(e\) = elongation, also expressed as a decimal.

It will be noted that the actual reduction of area is generally less
than the nominal, the nominal reduction in area being calculated on
the assumption that the wall thickness remains constant during cold drawing. Since the wall thickness actually increased slightly, the nominal reduction of area was therefore greater than that actually produced.

7. Testing Procedure.—The tension and compression tests were made in a 50 000-lb. Olsen testing machine equipped with pendulum dial load indicator and recorder. To prevent local failure of the tensile specimens at the grips of the testing machine, close fitting plugs were used as specified in ASTM Specifications E8-36; however, because of the bead on the inside of the tubing at the weld, it was necessary to cut shallow longitudinal grooves in the plugs to permit a close fit, especially for the tubing of greater wall thicknesses.

In order to determine the tensile yield strength of the cold-drawn tubing (which did not have a well-defined yield point), strain data were obtained by means of an extensometer with an 8-in. gage length. Up to and slightly beyond the yield strength, the load was applied
at a nominal rate of 0.1 inch per minute; from there on to rupture the head speed was increased to 1 inch per minute. After rupture, the elongation of every inch of an 8-in. gage length was measured.

Compression tests were made in a special compression rig, pictured in Fig. 1, which was designed to insure axial loading. On about one half of the compression specimens of each sample of cold-drawn tubing, stress–strain data were obtained using a compressometer having a 1-in. gage length. Since the slowest head speed of the testing machine proved to be too fast for accurate reading of the compressometer, the load was applied by hand while stress–strain observations were being made. Upon removal of the compressometer, the load was applied at a rate of 0.5 inch per minute until the maximum load was reached.

The hardness tests were made on a Rockwell hardness testing machine using the B scale (a 3⁄16-in. steel ball and a 100-kg. load). To provide a solid support for the material being tested, the specimen was placed on a mandrel, the ends of the mandrel resting in a cradle
made especially for this test as shown in Fig. 2. It will be recalled that hardness specimens were reamed slightly on the inside, the purpose being to insure a good bearing between the tube and mandrel immediately beneath the penetrating ball. Although the wall thickness of the thinner tubes was not as great as is usually considered to be desirable for satisfactory hardness readings, the "anvil effect" on the under side of the ball impression was very slight. At least six regularly spaced readings were obtained and averaged to give the hardness number of each specimen; hardness readings were not taken on or adjacent to the weld.

III. RESULTS OF TESTS

8. Types of Failure.—In the tension tests the normalized specimens, which had not been subjected to subsequent drawing, decreased in diameter and elongated considerably throughout their entire length, whereas in the cold-drawn tubing the elongation and reduction of diameter of the specimen was concentrated mainly near the fractured area. The general elongation of the specimens within the 8-in. gage length (disregarding the portion near the fractured area) varied from 0.01 to 0.05 in. per in. for the cold-drawn tubing, and from 0.20 to 0.30 in. per in. for the normalized tubing free from cold drawing.

A typical set of fractured tensile specimens is shown in Fig. 3. All specimens showed considerable necking down preceding rupture, and the fractured surfaces were for the most part inclined at an angle of about 45 deg. with the axis of the tube, indicating a shearing failure; some of the fractured sections had a saw-toothed appearance.

A typical set of compression specimens which were tested to failure is shown in Fig. 4; the types of failures may be classified as local wrinkling (A), buckling (B), and a combination of buckling
and wrinkling (C). In all cases the yield strength of the material was fully developed before any wrinkling or buckling took place. The maximum load or maximum strength, however, was affected by the type of failure, being somewhat lower for the specimens that buckled.

In a few compression tests of the cold-drawn tubing the weld split open at the outer edge of the wrinkles of specimens which failed by local wrinkling; this splitting action occurred only in tubing having the greater wall thicknesses and only in the final stages of the wrinkling type of failure. Such a failure is labelled D in Fig. 4. The location of the weld seemed to have no effect upon the manner of failure, except in the few cases in which the weld itself failed.

9. Test Data.—In Table 3 are presented the results of the tension, compression, and hardness tests. Each value listed is the average of the results of at least three tests, and in some cases of as many as nine tests.

Specimens of normalized tubing that had not been cold drawn possessed well-defined yield points in both tension and compression. The cold-drawn tubing, however, did not have a well-defined yield point, and hence the yield strength was determined. Both yield points and yield strengths are listed under the same headings in Table 3, the former being indicated by asterisks.

The yield strength corresponding to two values of offset are given, namely, a relatively small value (0.02 per cent) and a relatively large value (0.20 per cent), (see Fig. 5). In some applications, structural damage may possibly occur at a stress corresponding to as small an offset as 0.02 per cent but for most uses of this material in load-resisting members a value of 0.20 per cent offset would probably be a satisfactory criterion of structural damage. Unless otherwise speci-
### TABLE 3
RESULTS OF TESTS OF S.A.E. 1010 WELDED STEEL TUBING

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Per Cent Reduction of Area in Cold Drawing, Measured</th>
<th>Yield Strength</th>
<th>Tension</th>
<th>Ultimate Strength</th>
<th>Per Cent Elongation</th>
<th>Compression</th>
<th>Hardness Rockwell B</th>
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<td></td>
<td></td>
<td>0.02% Offset</td>
<td>0.20% Offset</td>
<td>in 8 in.</td>
<td>in 2 in.</td>
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*Yield Point.
fied, yield strength as used in the subsequent discussion is the value corresponding to an offset of 0.20 per cent.

The maximum compressive strength listed in each case is the average of the strengths of all the specimens of that sample which failed by local wrinkling. Since it was desired to eliminate the effect of length of specimen, maximum strengths of all specimens failing by buckling were disregarded. The maximum compressive strength may be defined as the maximum load per unit of original area that was developed before failure by local wrinkling took place.

The maximum compressive strength was affected somewhat by the ratio of the diameter of the tube to the wall thickness, particularly for the normalized tubing (free from cold work). For this tubing, the strength varied inversely with the \( D/t \) ratio; for the cold-drawn tubing, the effect was almost negligible.

In the tensile test the ultimate strengths of companion specimens varied only slightly, the maximum variation being 3 per cent. The corresponding maximum variation in the tensile yield strength was about 4 per cent. If only those compressive tests in which the specimens failed by local wrinkling are considered, the maximum variation in maximum compressive strengths of companion specimens was less than 3 per cent. The maximum variation in the compressive yield strength, considering all specimens of a given sample, was about 6 per cent. Similar variations in percentage elongation were likewise small.
In the Rockwell B hardness test, the maximum variation in the Rockwell B number was 6.0, although the variation in most cases was not greater than 3.

Companion specimens of tubing occasionally differed slightly in the roughness of the external surface; it is possible that the surface roughness is associated with a coarse grained structure, although this condition was not investigated. The specimens with the rougher surface generally gave strengths somewhat lower than those obtained from the smoother specimens.

IV. DISCUSSION OF RESULTS

10. Measure of Cold Working.—Two quantities have been commonly used as measures of the amount of cold working produced in operations such as rolling, forging, drawing, stretching, etc. These quantities are the reduction of cross-sectional area and the longitudinal elongation produced by the cold working. Since the volume of metal remains constant in cold drawing and in cold stretching, the reduction of area and the elongation are closely related to each other, and either should serve equally well as a measure of cold working. The percentage reduction of cross-sectional area of the metal in the tubing, however, lends itself more readily as a measure of the cold working produced by the cold drawing of welded steel tubing for the reason that the reduction of external diameter required (and hence the size of die needed) to produce a given amount of reduction of area of the metal in a tubing of a certain size may be readily determined if the change in wall thickness that occurs during cold drawing of the tubing is known. The measurements presented in Table 2 show that the wall thickness of tubing is affected but little by cold drawing, and may with little error be assumed to remain constant during cold drawing. Thus the amount of cold working may be controlled in production with no additional measurements or observations than those normally taken. The percentage elongation is not usually measured during the cold-drawing process, and there is no way of predicting in advance the treatment by which a given elongation might be obtained without first determining the reduction of area. Therefore, in the investigation herein reported, the amount of cold working will hereafter be expressed as the percentage reduction of cross-sectional area of the metal in the tubing caused by the cold drawing.

If it is assumed that the wall thickness of the tubing remains con-
stant during cold drawing, the cross-sectional area of the wall of the tube will be proportional to the mean diameter. The percentage reduction of area may then be expressed approximately as

\[ R = \frac{\pi D_m t - \pi d_m t}{\pi D_m t} \times 100 = \frac{D_m - d_m}{D_m} \times 100 \]

where \( R \) = percentage reduction of area of the metal in the tubing by cold drawing

\[ D_m = \text{mean diameter of tubing before cold drawing, inches} \]

\[ d_m = \text{mean diameter of tubing after cold drawing, inches} \]

\[ t = \text{wall thickness of tubing (assumed to be constant), inches} \]

The term "percentage reduction of area" as herein discussed is not to be confused with the percentage reduction of area commonly determined in a tension test from the original cross-sectional area and the area of the ruptured section. The latter quantity was not observed in the tests of the tubing, due to the difficulty of accurately measuring the wall thickness of the tubing at the fracture.

11. **Effect of Cold Drawing on Shape of Stress–Strain Diagram.**—Complete stress–strain data were obtained from at least one specimen
of each companion group of tension specimens for the purpose of constructing the entire stress–strain diagram. In Fig. 5 is shown a typical set of curves for the S.A.E. 1010 steel tubing originally formed and welded in one lot, indicating the effect of different amounts of cold drawing on the shape of the stress–strain diagram. The increase in tensile strength and the decrease in ductility (as measured by the total elongation of the specimen) due to the cold drawing are clearly illustrated by these diagrams.

The effect of cold drawing on the elastic properties and on the shape of the knee of the stress–strain diagram are qualitatively presented by the curves in Fig. 6. These curves were also obtained from a typical series of specimens originally formed and welded in one lot.
The tubing in the normalized state (free from effects of cold working) possessed a definite yield point in both tension and compression, whereas none existed either in tension or in compression for any of the cold-drawn material.

It will be noted that the slopes of the straight-line portions of the curves in Fig. 6 are all approximately the same. Although no values for modulus of elasticity have been presented in the data, it was found to be very close to 30 000 000 lb. per sq. in. for all specimens tested. In Fig. 6 the curves obtained from the compression tests begin to deviate appreciably from a straight line at lower stresses than do the curves obtained from the tension tests, but this was not true for all the series tested.

12. Effect of Cold Drawing on Mechanical Properties.—From the results given in Table 3 as obtained from test data, of which samples are shown in Figs. 5 and 6, it may be observed that cold drawing of the S.A.E. 1010 welded steel tubing increases the ultimate and yield strengths in both tension and compression, and increases the Rockwell B hardness, but decreases the ductility of the tubing. To illustrate
the manner in which these properties are affected by different amounts of cold drawing, the value of each property has been plotted against the amount of cold drawing as measured by the reduction of area of the metal in the tubing produced by the drawing.

In Figs. 7 and 8 are presented the relations between the tensile properties and the percentage reduction of area by cold drawing for all specimens tested. It will be noted that small amounts of drawing up to approximately 10 per cent, produced large changes in strength and ductility, but that additional amounts of drawing (up to at least 50 per cent) caused relatively smaller changes for the range beyond 10 per cent reduction of area. Beyond the initial rapid increase that occurred for reductions of area below 10 per cent, average curves through the data for the ultimate strength and the yield strength
approximated straight lines, although a slightly curved line would fit the data fully as well; in Fig. 8 the average value of the percentage elongation is represented by a curve, but a straight line would also fit the data almost as well for reductions of area greater than about 10 per cent.

The relations between the compressive strength properties and the amount of cold drawing, shown in Fig. 9, were very similar to those found for the tensile properties. In both tension and compression the amounts of cold drawing of the S.A.E. 1010 welded steel tubing up to 10 per cent reduction of area caused large increases in strength, whereas additional amounts caused the ultimate strengths and the yield strengths to vary according to a linear relationship which can be expressed by the general equation

\[ S = kS_a (1 + R) \]

in which

- \( S \) = the strength (tensile or compressive, ultimate or yield) in lb. per sq. in.
- \( k \) = a constant depending upon the material and type of test
- \( S_a \) = the strength (of the same type as \( S \)) of the normalized tubing free from cold drawing
- \( R \) = the reduction of area expressed as a decimal.

If average values are taken from the straight lines in Figs. 7 and 9, and average values for the strengths of normalized material are used, the values of \( k \) for the four of the properties determined are as follows:

- Ultimate tensile strength, \( k = 1.27 \)
- Maximum compressive strength, \( k = 1.33 \)
- Tensile yield strength (0.20 per cent offset), \( k = 1.67 \)
- Compressive yield strength (0.20 per cent offset), \( k = 1.45 \).

For amounts of cold drawing less than 10 per cent, the curves themselves provide the most reliable method for determining the properties of the tubing. The results of individual groups of specimens, all of which originated in the same forming and welding operation, did not
always follow closely the straight line given by the foregoing equations, but when the test results as a whole are considered, the scatter of the data is such that any attempt to obtain a relation more exact than the equation given is not justified.

It should be remembered, however, that these equations apply only to S.A.E. 1010 steel tubing for amounts of cold drawing between 10 per cent and 50 per cent as measured by the reduction of area of the material in the tubing. Templin\textsuperscript{6} has stated, however, that for several metals subjected to various types of cold working, the relationship between the ultimate tensile strength and the amount of cold working is linear for all amounts of cold working up to 50 per cent but that the strength of the material which was free from cold work was rather sensitive to the type of annealing or normalizing to which it was subjected. The normalizing processes used by two of the mills that supplied tubing for the tests reported herein were carried out as follows: One mill held the material at a temperature of 1650 deg. F. for 5 minutes, allowing it to cool in air; the other maintained a temperature of 1350 deg. F. for 20 minutes, and allowed the material to cool in a cooling chamber for 50 minutes (process annealing). The two treatments gave similar drawing properties to the steel, the material in each case being classified as “soft” for the S.A.E. 1010 steel according to mill standards established by the Formed Steel Tube Institute.

Of considerable interest from the design point of view is the

![Graph](Image)
margin of safety (reserve strength in the nature of accident insurance) indicated by the ratio of the yield strength to the ultimate strength of a metal used for static load-resisting purposes. This ratio, usually denoted as the yield-ratio, for ordinary hot-rolled medium-thick mild carbon steel commonly used for structural and machine members is usually about 0.6. The effect of cold drawing on this ratio for the welded steel tubing tested in both tension and compression is presented in Fig. 10; in determining the ratio, the yield strength is the stress corresponding to an offset of 0.20 per cent. For the normalized thin-walled tubing free from cold drawing the ratio is about 0.72 for both tension and compression, and, as seen in Fig. 10, it is increased by cold drawing. Beyond about 15 per cent cold drawing, however, the ratio becomes constant at about 0.95 in tension and about 0.8 in compression. Thus, in tension, at least, there is little additional strength available in cold-drawn tubing beyond the yield strength (0.20 per cent offset). The ductility of such cold-drawn tubing, as measured by the tensile elongation in an 8-in. gage length, varied from about 10 per cent down to 4 per cent, as the amount of cold drawing increased from about 10 per cent to 50 per cent (see Fig. 8).

The relation between the Rockwell B hardness of the tubing and the amount of cold drawing, shown in Fig. 11, was quite similar to that obtained for the strength properties. The first amounts of cold drawing produced a rapid increase in hardness, while further additions of cold work caused the hardness to increase at a slower but almost constant rate.
The primary purpose for making hardness tests in this investigation was to obtain the relation between hardness and tensile strength for the S.A.E. 1010 welded steel tubing. Such a graph is presented in Fig. 12. In the manufacture of this welded steel tubing the hardness test in conjunction with the graph in Fig. 12 offers a quick approximate method of determining the ultimate tensile strength of the cold-drawn tubing. As indicated on the graph, the average curve drawn through the data may be expressed by the equation

\[ T = \frac{4540}{146 - R_B} \]

in which \( T \) = the tensile ultimate strength in 1000 lb. per sq. in.

\( R_B \) = Rockwell B hardness number.

In using this equation, however, a testing procedure for determining the hardness number, similar to that described in Section 7 and illustrated in Fig. 2, should be followed. For convenience the Brinell numbers equivalent to the Rockwell B hardness numbers are also given in Fig. 11.

13. Variations in Data.—The rather wide scatter of the data, particularly noticeable in the graphs showing the relations between the amount of cold working and the tensile and compressive strengths, may be attributed to several causes. First, the samples of tubing were
obtained from three different mills, each of which had been directed
to form, weld, normalize, and draw the tubing in its own customary
fashion. The normalizing or annealing treatment may have a great
effect upon the strength of material intended to be free from cold
working, as previously pointed out by Templin. The two mills which
furnished information on the method of annealing used somewhat
different procedures. Another variable that may affect the properties
of the tubing is the speed of drawing; the higher speeds of passing
through the die are more likely to produce "over-drawing." Godfrey
has found in the cold drawing of wire, that "the greater the reduction
per draft, the higher will be the tensile strength for the same amount
of drawing." Since rigid control was not exerted over these factors in
the production of the steel tubing used in the investigation herein
reported, it is not surprising that the data exhibited considerable
scatter. This variation in data, however, serves to indicate the range
of values that may be expected when attempting to predict the static
strength and ductility of commercial cold-drawn welded steel tubing.

The specimens tested in series 3 and series 4 of the test pro-
gram (see Table 1) were identical except that they were produced by
two different mills. Thus, a comparison of the results obtained in these
two series of tests provides a good measure of the ability of two differ-
ent mills to produce like results. Such a comparison is shown in Figs.
7, 8, and 9 wherein the tensile and compressive properties of the
material from the different mills are plotted against the amount of
cold work, according to the series and the wall thickness of the tubing.
It may be observed that the strengths of the specimens in series 4
are uniformly higher than those in series 3; this is an indication that
the chief difference between the two lots of material lies either in the
carbon content of the steel or in the effect of the annealing process.
The effect of the cold drawing appears to be approximately the same.
There is comparatively little difference between the percentage elonga-
tion values of the samples from different mills, particularly if elonga-
tions are measured on 8-in. gage lengths.

14. Cold Drawing vs. Cold Stretching.—When the steel cylindrical
tubing is drawn through an exterior die having a diameter smaller
than the outer diameter of the tubing it is subjected to longitudinal
tensile stresses and to both radial and circumferential compressive
stresses. The magnitudes of these stresses are unknown, but such a
combination of stresses is accompanied by shearing stresses in the
material of the tube that are considerably higher relative to the longi-
tudinal tensile stress than is the maximum shearing stress in a bar
subjected to simple tension. It would be expected, therefore, that greater plastic deformations without fracture would occur in the cold-drawing process than are possible in the cold-stretching process as carried out in a simple tension test.

From Table 3 it may be observed that in the tension test an approximately uniform elongation in an 8-in. gage length for the normalized tubing (2A, 2E, 3J, etc.) was somewhat less than 32 per cent at rupture, since the 32 per cent includes the local deformation at the necked-down region; whereas, sample 2D, while being reduced in outside diameter from 1 in. to 5/8 in. by cold drawing, stretched uniformly 65 per cent (see Table 2) of the original length without rupturing. Furthermore, tension specimens of this same 5/8-in. tubing after thus being cold drawn, elongated approximately 4 per cent in a simple tension test before rupturing, thus indicating that a uniform elongation even greater than 65 per cent in the cold-drawing process would have been possible. This is borne out by the fact that specimens labeled 1D and 1H were reduced in outside diameter from 1 1/8 in. (instead of 1 in.) to 5/8 in. by cold drawing. Although no information was obtained on the elongation of this sample of tubing during the cold-drawing process, an elongation of over 90 per cent would have been necessary to produce the known reduction of cross-sectional area (assuming the volume of the metal to remain approximately constant). Since samples of this cold-drawn tubing also had an additional 4 per cent elongation in a simple tension test before rupturing, it appears safe to conclude that the welded steel tubing used in the tests could be elongated uniformly by cold drawing to 100 per cent of its original length without rupturing, which is several times greater than the maximum uniform elongation that could be produced in the same material by stretching in the tension test.

Although it is physically possible to produce elongations of such large magnitudes in a single pass, it is usually considered better practice to make two or more passes, according to conditions. In drawing the 1-in. tubing to the 5/8-in. diameter, the diameter was reduced to 3/4-in. in one draw, and then reduced without annealing to a 5/8-in. diameter in a second draw. The tubing may be "over-drawn" or actually ruptured by an attempt to effect too great a reduction in a single draft. Godfrey has reported that in the cold drawing of wire the optimum combination of strength, ductility, and toughness are achieved by a relatively low rate of drawing, i.e., a small percentage reduction of area per draft.

Several samples of the normalized tubing were overstrained in tension (stretched) by an amount calculated (on the basis of constant
volume) to produce about 10 per cent reduction of area of the material in the tubing uniformly throughout the stretched length. This material was then cut up into test specimens and tested in tension, compression, and hardness.

The effect of this type of cold working upon the shape of the stress–strain curve is quite different from that produced by cold drawing, as the diagrams in Fig. 6 show. The effect of cold stretching is to increase considerably the yield strength in tension, but to a much lesser extent in compression. Furthermore, a fairly well-defined yield point is retained in tension, but not in compression. On the other hand, cold drawing produced large increases in the yield strength both in tension and in compression. It may be observed in Fig. 6 that in tension the material cold drawn 11 per cent had a yield strength (for 0.20 per cent offset) only slightly greater than that of the cold-stretched materials, while in compression the yield strength of the drawn tubing was about 25 per cent greater.

The ductility of the cold-drawn tubing as measured by the percentage elongation in the tension test was slightly higher than that of the tubing cold worked the same amount by stretching, when the percentage elongation was measured on an 8-in. gage length, but somewhat lower when measured on a 2-in. gage length. The reason for this apparent contradiction is that most of the uniform elongation to be expected in a tension test had previously taken place in the cold-stretched material. The elongation measured in the tension test of the previously cold-stretched material corresponds to the elongation that is concentrated largely near the fracture, and that takes place during the latter stages of a tension test of hot-rolled or annealed steel.

V. SUMMARY AND CONCLUSIONS

15. Summary.—The effect of cold drawing upon the mechanical properties of S.A.E. 1010 welded steel tubing is summarized in Fig. 13, in which the percentage changes in the properties from the corresponding values for the normalized tubing free from cold drawing are plotted against the amount of cold working as measured by the percentage of reduction of area of the metal in the tubing caused by the cold drawing. The curves shown were obtained by replotting to the new scale the average curves drawn through the data in Figs. 7 to 10, inclusive. Thus, if the properties of the normalized S.A.E. 1010 welded steel tubing free from cold working are known or can be determined, the amount of cold drawing required to bring about a given increase
in strength or hardness and the concurrent decrease in ductility as measured by percentage elongation may be determined by use of this set of curves.

16. Conclusions.—The main conclusions drawn from this investigation may be stated as follows:

(1) The reduction of area of the metal in the tubing (as defined in Section 10) is a suitable measure of the amount of cold working produced by cold drawing. Furthermore, since the wall thickness of tubing remains approximately constant during cold drawing, the reduction of area may be roughly controlled by the change in outside diameter of the tubing, which is determined by the diameter of the final drawing die.

(2) Cold drawing of S.A.E. 1010 welded steel tubing increases the tensile ultimate and yield strengths, the compressive maximum and
yield strengths, and the Rockwell B hardness, but decreases the ductility of the tubing; the compressive maximum strength is defined as the maximum load per unit area that a specimen could resist before failure by local wrinkling (see specimens A in Fig. 4).

(3) The increases in the tensile and compressive yield strengths (0.20 per cent offset) of the S.A.E. 1010 welded steel tubing were of the same order of magnitude for equal amounts of cold drawing up to 50 per cent reduction of area, which was the maximum amount of cold drawing to which the tubing was subjected (see Figs. 6 and 13, and Table 3). This fact is important in the use of tubing for load-resisting members, and is in contrast with the effect of cold stretching, in which the compressive yield strength is increased considerably less than is the tensile yield strength (shown in Fig. 6 for one amount, namely, 10 per cent, of cold stretching).

(4) Amounts of cold drawing of the S.A.E. 1010 welded steel tubing up to about 10 per cent reduction of area produced relatively large increases in strength and hardness; whereas additional amounts of cold drawing up to at least 50 per cent reduction of area caused these properties to increase, but the increase was relatively less. For example, the tensile yield strength (0.20 per cent offset) is increased about 80 per cent by 10 per cent of cold drawing, and 150 per cent by 50 per cent of cold drawing (see Fig. 13); the corresponding increases in the tensile ultimate strength are 40 per cent and 90 per cent, respectively. For amounts of cold drawing above approximately 10 per cent reduction of area, the relation between the strength of the S.A.E. 1010 welded steel tubing and the amount of cold drawing may be expressed by the general straight line equation, 

\[ S = kS_a (1 + R), \]

where \( S \) is either the tensile or the compressive strength and either the ultimate or the yield strength, and \( S_a \) is the corresponding strength of the normalized tubing free from cold drawing (see Figs. 7 and 9).

(5) A fairly definite relation existed for the cold-drawn S.A.E. 1010 welded steel tubing between the ultimate tensile strength (which will here be denoted as \( T \) since \( S \) in the foregoing equation has several meanings) and the Rockwell B hardness number \( (R_B) \); namely, 

\[ T = \frac{4540}{146 - R_B} \] (see Fig. 12).

(6) The tensile yield strength of the normalized S.A.E. 1010 steel tubing free from cold working was about 0.70 of the ultimate tensile strength; for cold-drawn tubing in which the reduction of area of the metal in the tubing by cold drawing was greater than about 10 per
cent, the corresponding ratio was fairly constant at about 0.95 (see Fig. 10).

(7) The ductility of the S.A.E. 1010 steel tubing as measured by the percentage elongation in an 8-in. gage length in the tension test decreases rapidly with the amount of cold drawing up to about 10 per cent reduction in area, and decreases much less rapidly for further amounts of cold drawing (see Figs. 8 and 13). The decrease in ductility is about 70 per cent for 10 per cent of cold drawing, and about 90 per cent for 50 per cent of cold drawing.
### APPENDIX

#### BIBLIOGRAPHY

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