THE EFFECT OF COLD-ROLLING ON THE MODULUS OF ELASTICITY OF BRASS

by

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INTRODUCTION

Very little investigation has been made in America on the effect of cold-work on the modulus of elasticity of metals. As late as the year 1924 doubt was indicated by eminent metallurgists as to whether cold-working caused change in the modulus at all.[1] However, these metallurgists, through X-ray diffraction diagrams, were acquainted with the fact that cold-working causes certain preferred crystal orientation with reference to the direction of deformation.[2] It has been discovered, later, by working with single crystals, that the modulus of elasticity of a crystal varies with the direction in which it is loaded.[3] Thus in annealed metal, with equiaxed grains, we may expect an identical modulus in all directions. And if cold-work is done on the metal, we may expect a raising of the modulus of elasticity in a certain direction and a lowering in another.

A relatively large amount of investigation has been made abroad, but, until recently, it has been of a random nature and conflicting results have been reported for work done with non-ferrous metals.[4] Results of the most thorough investigation made to date were published in 1930.[5] This investigation was made on

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1 Jeffries and Archer, "The Science of Metals", (1924) page 197.
2 Ibid. pages 128 and 206-207.
3 Kawai, Tadashi, "The Effect of Cold-working on Young's Modulus of Elasticity", Science Reports, Tohoku Imperial University, Vol. 19, May 1930, page 231.
4 Ibid. pages 210, 211.
5 Ibid. pages 209-234.

the change in the modulus of elasticity of both ferrous and non-ferrous metals for the two forms of cold-working, known as stretching, and drawing.

The present investigation was made with the purpose of adding data for a third form of cold-working, rolling.

ACKNOWLEDGMENT

The Author is indebted to the Fulton Sylphon Company of Knoxville, Tennessee for providing the problem and the means for solving it. All work was done in the Company's Experimental Laboratory and considerable aid was received from the Engineering Department during the investigation.

PREVIOUS KNOWLEDGE OF THE EFFECT OF COLD-WORKING ON THE MODULUS OF ELASTICITY

Kawai[1] found that cold-work done by drawing, and stretching, always caused a decrease in the modulus of elasticity of ferrous metals. For the non-ferrous metals, copper, aluminum, and nickel, he found that the modulus decreased with increasing cold-work only for small amounts of working (from 0 to 5 or 10% reduction of area); for larger reductions the modulus rose and finally exceeded the modulus of the annealed metal by a considerable amount. He ascribed the difference in the effect on the ferrous and the non-ferrous metals to the difference in space lattice; iron having a body-centered cubic lattice and the non-ferrous metals a face-centered cubic lattice. The change in the modulus with cold-working was explained as being the result of two opposing forces; internal stress which tends to lower the modulus, and crystal rotation which tends to raise the modulus. In the ferrous metals, the effect of crystal rotation is relatively small and the change is dominated by the amount of internal stress caused by cold-working, thus the modulus is lowered in all cases. However, in non-ferrous metals with face-centered cubic lattice, the crystal orientation factor is the larger with large degrees of cold-work, and the modulus begins to rise with increased cold-work after a short fall for

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1 Kawai, Tadashi, "The Effect of Cold-working on Young's Modulus of Elasticity", Science Reports, Tohoku Imperial University, Vol. 19, May 1930, pages 209-234.

small degrees of working when internal stress is the controlling factor. His theories are supported by the investigations of others, to which he makes reference.

THE DIRECT OBJECT OF THE WORK

The direct object of this work was to determine values for the modulus of elasticity in brass sheets which had been cold-rolled to an approximately 0.008 inch thickness from various thicknesses of annealed sheet, the moduli obtained to be used in calculating the stresses in fatigue specimens placed in an endurance machine of the constant deformation type.

Specimens were taken from the sheets in the direction to rolling (called longitudinal specimens herein-after) and also in the direction of the roll axes, or perpendicular to the direction of rolling (called transverse specimens herein-after). Transverse specimens were chiefly studied, as they were thought to simulate most closely the cold-worked condition to which the endurance data obtained was to be applied in practice.

METHODS CONSIDERED FOR DETERMINING THE MODULUS

The extreme thinness of the sheet (approximately 0.008 inch) presented difficulties that are not found in the ordinary modulus determinations made with bars near one-half inch in diameter. A method previously tried in the Fulton Sylphon Company's laboratory was to load a horizontally supported strip as a beam and to calculate the modulus from load-deflection readings and the dimensions of the specimen, using the proper beam formula. This method was discarded for two main reasons. First was the extreme accuracy with which the thickness measurement had to be made in order to prevent large error from this source alone. Since the thickness is raised to the third power in beam formulae an error of 0.0001 inch in an 0.008 inch thickness would cause an error of near 3.6% from the single source. A second fault was a lack of complete flatness in the specimen which caused a point of "snap action" in some cases. A third probable source of considerable error was due to stress concentration near supports and loading point.

Another method that has been employed with sheet metal specimens was to support the specimen at one end and determine its natural frequency as a vibrating reed.[1] The modulus could then be calculated from the frequency, metal density, and speci-

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[1] Beilby, G. T., "The Hard and Soft States in Metals" J. Inst. Metals, 1911, No. II, page 5.

men dimensions. This method was not used in the present investigation because of doubt as to the effect of localized stress at the support, the effect of the air density, and other minor considerations.

It was decided to determine the modulus in the conventional manner of loading a tension specimen of an 8 inch gage length, and measuring the elongation with an extensometer. This method presented several difficulties. The manner in which they were met will be dealt with in the description of the apparatus.

THE BRASS SHEET

All of the metal used was obtained from the American Brass Company. All sheets were of approximately 32 gage (Brown and Sharpe) thickness and 16 inch width.

Five sheets of 80:20 copper:zinc composition (herein-after called 80:20 brass) were received by the Fulton Sylphon Company about the year 1927, when a portion of each of them was used in tests. One sheet had been annealed at a temperature above that of recrystallization after its last cold-rolling operation. It is said to possess no cold-work and is referred to herein-after as 0# hard. A second sheet had been reduced from an annealed condition at 31 gage (B. and S.) thickness to 32 gage, with no final anneal. This sheet is said to be one number hard (1# hard) and has received cold-work by a reduction in thickness of approximately 11%. A third sheet , reduced to 32 gage from an annealed sheet of 30 gage, is said to be 2# hard and has received cold-working by a 21% reduction in thickness by rolling. In similar manner the fourth and fifth sheets were 3# hard and 4# hard, having had thickness reductions of 29% and 37% respectively.

Eight transverse tension specimens, of a form described later, were taken from each of the five sheets. Eight longitudinal specimens were taken from the 4# hard sheet and four longitudinal specimens from the annealed sheet. There was not sufficient length of sheet available to obtain longitudinal specimens from the 1, 2, and 3# hard sheet after taking the transverse specimens.

Sheets of 90:10 brass, 70:30 brass, and of deoxidized copper

were received in the summer of 1931. These were used only to determine the effect of the copper-zinc composition on the difference between the longitudinal and the transverse modulus of cold-rolled brass. Of these, only 4# hard sheets were used. Four specimens were taken from each of them in a longitudinal direction, and four in a tranverse direction.

THE APPARATUS AND PROCEDURE

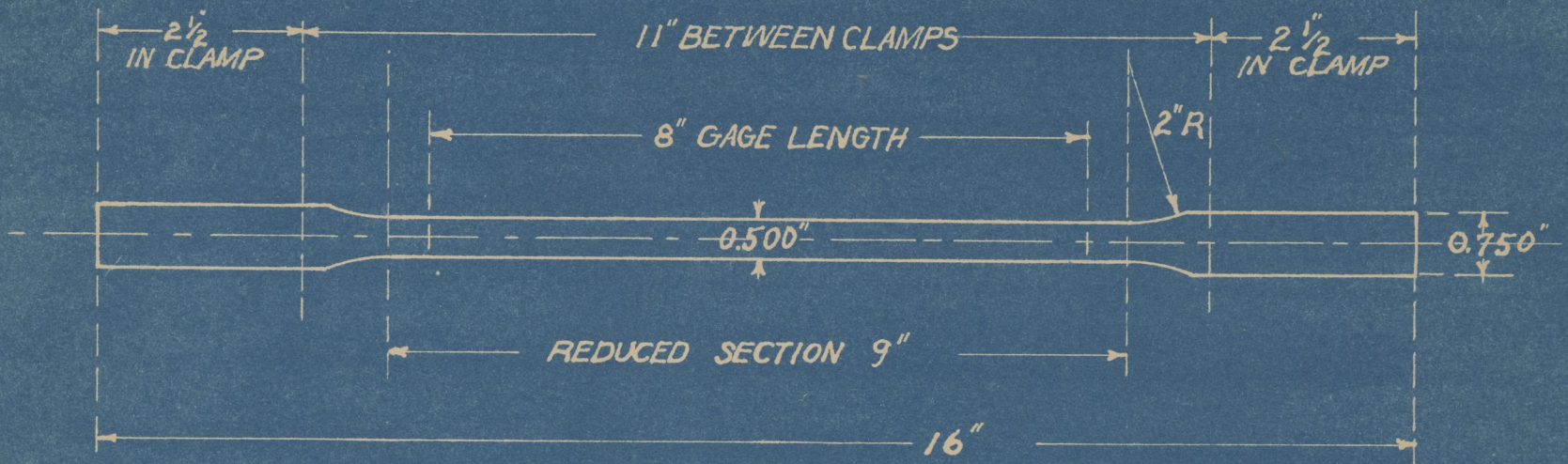
Since the procedure is closely tied to the apparatus and its peculiarities, description of each piece of apparatus is accompanied by explanation of its use in the work. It is thought that this arrangement will save space and, at the same time, promote clearness.

The Specimen and its Preparation

The shape of the tension specimen conforms to A. S. T. M.[1] recommendations, except for the gage length of eight inches, which is rather long for such thin sheet. This greater length was thought to be justified by the increased accuracy in determing unit elongation, and since the specimens were not to be broken in tension, or even stressed beyond their elastic limit. A detail drawing of the specimen is given in Fig. 1 (above). A side view of the template used in shaping it is shown in Fig 1 (below). The template was made of two lengths of steel bar one-half inch thick, milled to approximate shape, hardened, and then ground on the forming face. The one face of the template was used to form both sides of the specimen. (Another type, having two faces, was found to be unsatisfactory.) Pins O-O, Fig. 1, are fixed in one of the template halves and are a snug slip-fit in the other. They serve to hold the edges of the forming face in alignment, and to locate the specimen

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[1] R. L. Templin, "Effects of Size and Shape of Test Specimen on the Tensile Properties of Sheet Metals". Proceedings A. S. T. M. 1926 Part II page 379.



MODULUS SPECIMEN
(APPROX. 0.008" THICK)



TEMPLATE

FIGURE ONE

blank longitudinally. Loose pins P-P of ground drill rod serve to locate the blank transversely while the second edge is being formed. The first edge is shaped without the pins, P-P, the blank being placed as shown by the dashed rectangular outline in Fig. 1 (below). A hand cutting tool was made from a hardened steel bar by grinding one edge to make an angle of approximately 30 degrees with one of the flat faces, and attaching a wooden handle so that it might be used in the manner of a bearing scraper.

The first step in the preparation of the specimens was to cut rectangular blanks, 7/8 inch wide and 16 inches long from the brass sheets. Sharp power-shears were used for this purpose. Each blank was then clamped firmly between the template halves, with a vise (applied at the middle), and four C-clamps (two located on each side of the vise). The cutter was used to shave away all metal above the template face. Minute scratches left on the edge of the specimen were removed by hand with a fine carborundum stone after raising the specimen so that its edge was near 1/32 inch above the template face. Then the half-formed specimen was removed and inverted after inserting locating pins, P-P, in their holes. Clamps were applied again and the second edge shaped in the manner of the first.

After being shaped, the specimen was cleaned with alcohol. Ten light pencil marks were made at one-inch intervals along the 9 inch reduced section to aid in distributing the measuring points evenly along the gage length. Even though the thickness is raised only to the first power in the calculation of the

modulus, the extreme thinness of the specimen made this measurement require more than ordinary accuracy. The thickness was measured near each of the ten pencil marks with a Brown and Sharpe micrometer caliper No. 233 which has a screw with 50, instead of the usual 40, threads per inch, and a large barrel on which the smallest division represents one ten-thousandth of an inch. Individual thickness readings were made, and readily checked, to 0.00005 inch. Specimen width measurements were made with a Starrett Micrometer caliper No. 434, graduated in one-thousandths of an inch. The average of each set of ten readings was taken for calculating the area of the cross-section.

The gage marks for the micrometer microscope of the extensometer (see page 15) were made in the following manner. Black drawing ink was applied to two ½ inch lengths of the reduced section of the specimen with a distance of 8 inches between their centers. When the ink was dry, a ruling block with accurately ground parallel ends 8 inches apart was used to space fine parallel gage marks, or scratches, made by a sharp edged knife in the ink fields. Three sets of marks were made on each specimen to insure a sharp edge to which the movable cross hair of the extensometer might be worked. A light longitudinal line was made along the center of each specimen at each of the ink fields to aid in aligning extensometer and specimen. It was not necessary to space the gage marks with great accuracy as the extensometer could be used to determine the exact gage length. The chief purpose of the ruling bar

was to keep the image of the gage marks close together in the field and obviate unnecessary travel of the cross hair.

The Loading Device and Extensometer

Because of the small area in the specimen cross-section (0.004 to 0.005 sq. in.), which allowed a maximum load of only about 65 pounds, an ordinary form of tension testing machine could not be used. Because of the extreme thinness of the specimen, no conventional form of extensometer, or strain gage, could be satisfactorily supported on it. Figure 2 in a photograph of the loading device, extensometer, and accessories used in obtaining the stress-strain data. The loading device is built around a Buffalo platform scale (sensitive and accurate to 0.01 pound) with a machined cast iron plate (weighing 40 pounds) fastened on the platform. Four ten-pound cast iron weights are placed on the plate so that there is a total load on the platform of 80 pounds. The lower specimen grip is attached to the center of the plate. The upper grip is attached to a threaded rod passing vertically through a tapped hand wheel that rests on a ball thrust bearing that, in turn, rests on a horizontal bar supported by braced side bars screwed into a cast iron base plate.

Load is applied by setting the scale beam riders to balance the difference between 80 pounds and the load that is to be applied to the specimen, then slowly turning the hand wheel to raise the upper grip until the beam is balanced, as indicated by a pointer at its end.

Each specimen grip is connected to the rest of the machine

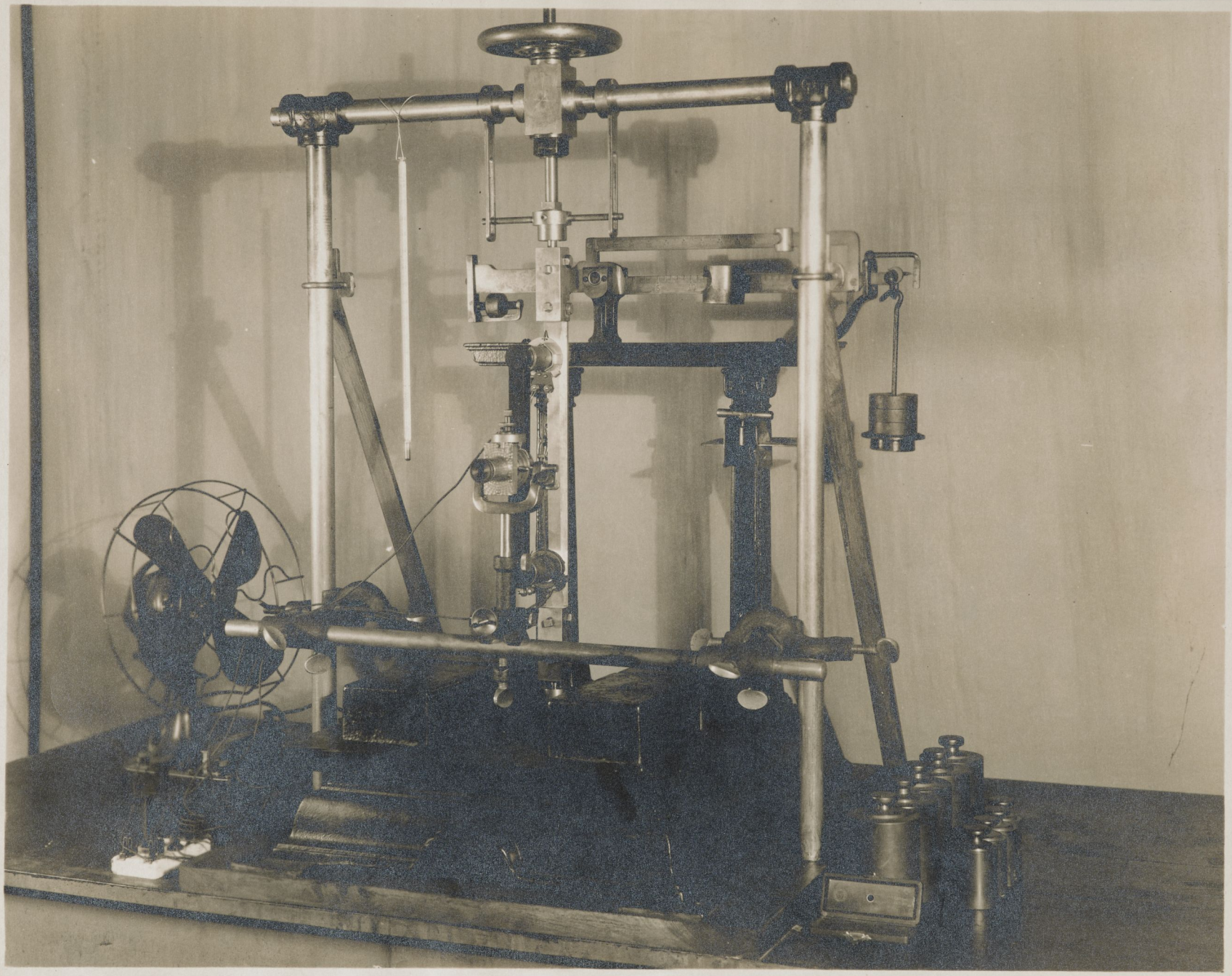


FIGURE 2

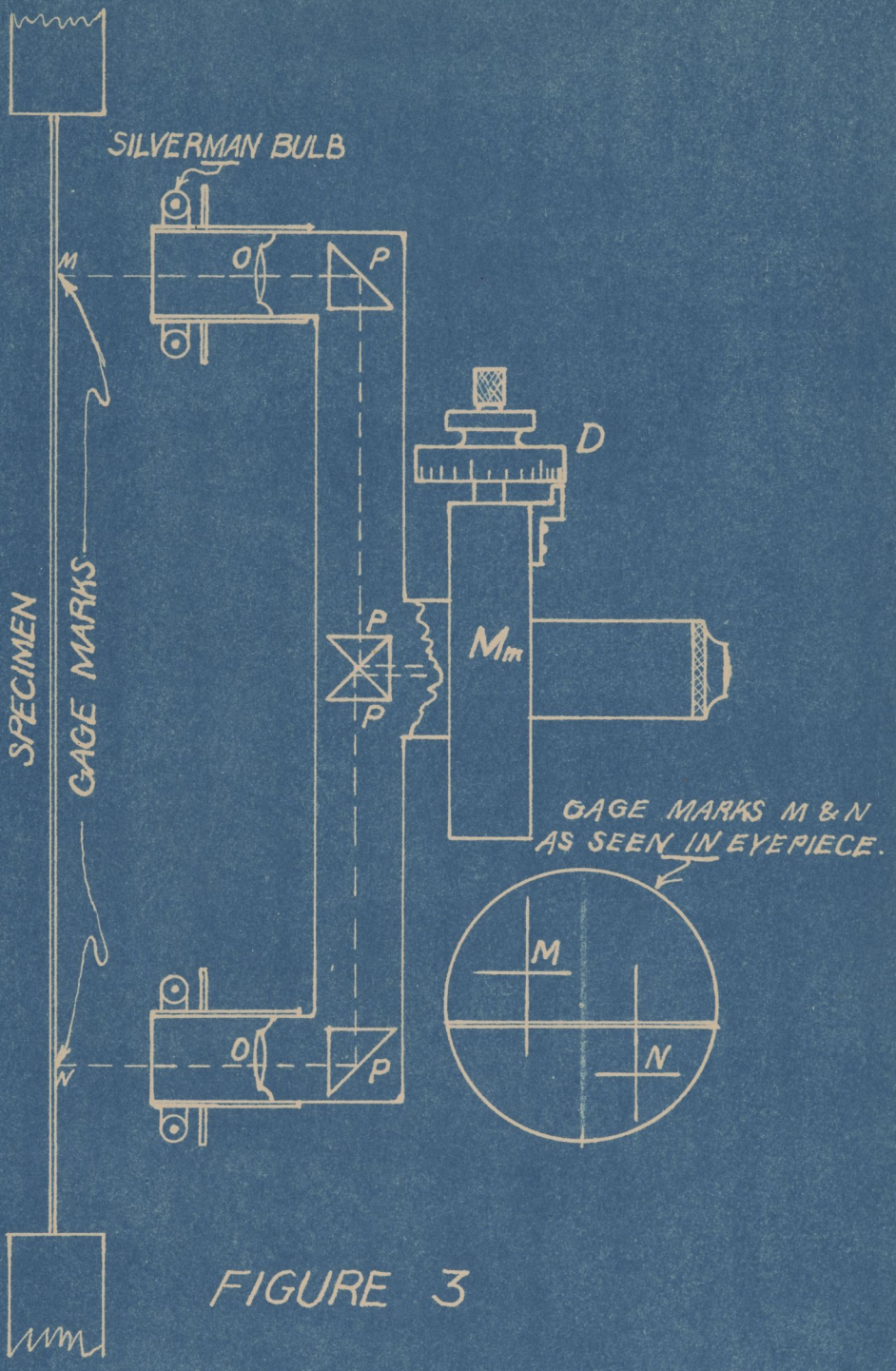

SILVERMAN BULB
M
O
P
D
SPECIMEN
GAGE MARKS
P
P
Mm
GAGE MARKS M & N
AS SEEN IN EYEPIECE.
M
N
N
O
P

FIGURE 3

through a small S. K. F, self-aligning ball bearing, loaded axially. The spherical surface of the outer race allows the grips to align themselves under load and give very nearly true axial loading.

To permit the thin specimens to be placed properly, and securely clamped in the swivelled grips, an aligning bar is used that fits into rectangular recesses in the rear of the grips and is held by thumbscrews. It is removed, of course, before applying load to the specimen. This bar is shown in location (behind the specimen) in Fig. 2.

The extensometer (shown in Fig. 2 supported in front of the specimen) was designed by Mr. W. L. Chandler of the Fulton Sylphon Company, and built by the Gaertner Company. It is optical, in the sense that there is no connection between the specimen and any part of the extensometer, except optically. Figure 3 is a diagram showing the internal arrangement. A single micrometer microscope, Mm, is used to gage the change in distance between two gage marks, M and N, approximately 8 inches apart on the specimen, but which appear close together in the single eyepiece. This is accomplished by using two microscope objectives, O-O, 8 inches apart, and prisms, P-P-P-P, to bring the two marks, M and N, to the field of the single eyepiece. The appearance of the marks, as seen through the eyepiece is shown in the circle (Fig. 3). The double cross-hair is moved, by the micrometer dial, D, from gage mark M to N. The difference in distance between M and N, with loading, is a measure of the elongation. The micrometer dial was calibrated by means of a stage micrometer which has a length of 2 millime-

ters accurately ruled in 20 divisions of 0.1 mm each. The stage micrometer is shown in Fig. 2 near the standard weights used for calibrating the platform scale. One division on the micrometer dial was found to represent 0.0000305 inches. Very little trouble was experienced in getting readings to check to one dial division.

Lighting of the gage marks is by two Silverman microscope illuminators. They are set out from the extensometer on metal extensions in order to provide brighter illumination and minimize any effect that their heat might have on the extensometer. The source of light in the Silverman illuminator is a small bulb of glass tubing, bent in circular form so that the ends almost meet, in the center of which is a circular metal filament. The bulb is supported in a holder which clamps around the microscope objective and allows light to be thrown on all sides of the object viewed. Correct voltage for the bulbs is obtained by the use of a resistance box (shown at the left of the loading device in Fig. 2). The switch shown in front of the resistance box was used to cut out either of the two lamps momentarily while making a reading when the gage marks interfered with each other in the eyepiece.

The temperature of the bulbs and their proximity to the specimen heated it enough to give an erratic elongation. This was stopped by placing a 10-inch G. E. fan, with a slow speed, to give light steady current of air accross the specimen and bulbs. The fan in Fig. 2 is shown resting on the table, but in actual use it was supported independently of the other appara-

tus in order that its vibrations might not affect the readings.

Several methods of providing illumination and making gage marks were tried before the method described was adopted. The first lighting was by direct sunlight with gage marks of fine scratches in the bright metal. But the sunlight was too irregular and not very satisfactory at best. One hundred watt incandescent bulbs in various arrangements were unsatisfactory. It was thought that good results might be obtained with sharp scratches made directly in the metal, so light from two metallographic illuminators, with ribbon filament bulbs was made to strike the scratches at sharp equal angles to make the marks appear dark in a light background. But, due to reflections, the scratch could not be given a sharp outline. Silverman illuminators were used with marks directly in the metal, i. e. with bright background. But, with illumination from all sides, the marks were poorly defined. An attempt to fill the scratches with ink was unsuccessful. It was then decided to try bright marks in a background of black India ink. This gave the best results by far.

The apparatus shown in Fig. 2 was placed in a thick walled, unventilated room that is used for storing experimental models, in order to obtain an even temperature, absence from outside vibrations and air currents, and also darkness, except for the gage mark illumination, while making extensometer readings.

In making "stress-strain" readings for the 80:20 brass sheet several different loads were applied to each specimen. An initial load of five pounds was used in all cases to straighten the thin specimens, and the distance between gage marks, with

this load, as measured by the extensometer, was taken as the gage length. Elongation readings were made with load increments of 5 pounds (corresponding stress increments being 1000 to 1200 pounds per square inch) on the annealed sheet. For the sheets having cold-work, the load increments were 10 pounds in most cases. The maximum load on the specimen was kept well below the elastic limit of the metal, as each specimen was to be used later in an endurance test.

For the 4# hard copper, and brass sheet of other than 80:20 composition, only two loads were applied, the initial, straightening load, of 5 pounds, and a second of 55 pounds. The elongation for these two loads was measured at least two times for each specimen, to give a check on the first reading. This method was used for three reasons. (1) Recent work by a special research committee of the A. S. M. E.[1] has shown that the modulus of elasticity of a given metal varies with the stress. (2) The apparatus used allowed relatively large error in elongation readings with small loads. (3) Comparative data only was desired to show the difference between longitudinal and transverse specimens, and the effect of the copper-zinc composition.

The method of calculating the modulus of elasticity for each manner of loading is shown in connection with the sample data sheets.

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[1] M. F. Sayre, "Elastic and Inelastic Behavior in Spring Materials" Trans. A. S. M. E., Vol. 53, no. 15, May-August, 1931, paper APM-53-8.

SOURCES OF ERROR

The 80:20 Brass.

The modulus of elasticity, $E = \text{unit stress} / \text{unit strain}$

$$= \frac{L}{tw} \Big/ \frac{e}{l} = \frac{Ll}{twe}$$

Where, L is the average of all loads in pounds.

l " " gage length in inches.

t " " thickness of strip in inches.

w " " width of strip in inches.

e " " average of all elongations in inches.

All factors of the above equation are seen to be of the first power. Possible error in each will be disoussed. The Buffalo scale used in measuring the load was found to be accurate to 0.01 lb. The average loads applied to the strips of various hardness and the possible error in percent is shown below.

Numbers Hard	Average Load - Lb.	Possible Error %
0	12.5	0.08
1	17.5	0.06
2	22.5	0.045
3	27.5	0.036
4	32.5	0.031

The weighing error is seen to be very small.

The gage length, l, is determined to within 0.001 inch by means of the extensometer. This may produce an error of only 0.012% which is negligible.

Thickness, t, is measured to 0.00005" (error equals plus or minus 0.000025). The possible error for a 0.0085" thick strip is 0.29%.

Width, w, is measured to 0.001" (plus or minus 0.0005"). For the 0.500 inch width used, this allows an error of 0.1%.

The average elongation, e, varies with the different hardnesses due to difference in elastic limit and modulus. Each of the two readings of the extensometer for each load is accurate to plus or minus 0.00003". This allows an inaccuracy of about 0.00006" in any one elongation measurement. The effect of this possible error is shown below for each of the hardnesses. The average elongation, e, is also affected by temperature change. The change in e, due to a variation of 0.5 degrees F. is 0.00004" (for 8" gage length and coefficient of expansion 0.000010 inches per inch per degree Fahrenheit). The possible errors in e due to extensometer reading and temperature change are as follows:

Numbers Hard B and S	Average e inches	Possible Error in e %		Total error in E %
		Extensometer	Temperature	
0	0.0015	4.0	2.6	7.1
1	0.0021	2.9	1.9	5.0
2	0.0027	2.2	1.5	3.9
3	0.0033	1.8	1.2	3.2
4	0.0039	1.5	1.0	2.7

The last column in the above tabulation shows the error that would occur in the value of the modulus if all individual errors were a maximum and were in a direction that caused all errors to be additive.

It should be noted that the 0.5 degree change of temperature is assumed. No attempt was made to correct for temperature change, as readings were made only when the temperature seemed to be fairly constant. However, it is highly probable that a

temperature variation of 0.5 degrees occurred during some of the determinations.

The Error with Specimens that were given only 5 and 55 lb. loads

As with the 80:20 brass, just discussed, the weighing error is negligible, and width and thickness errors are approximately 0.1% and 0.29% respectively. But the average elongation varied from 0.00534 inches to 0.00610 inches, allowing errors of from 1.0% to 1.1%. Thus we may expect a maximum error of only 1.4% to 1.5%, or not more than 3.0% maximum variation between specimens tested in this manner.

RESULTS

Figure 4 is a tabulation of the values obtained for the modulus of elasticity of all specimens of 80:20 brass. Figure 5 is a graph showing the variation of the modulus with the percentage reduction in thickness by cold-rolling. Average values from Fig. 4 were used in the plotting. The modulus of the transverse specimens is seen to fall with small reductions, reaching a minimum at a reduction near 10%, and then to rise with further reduction up to the greatest that was given, 37%.

As has been stated before, the sheets 1, 2, and 3# hard (of 80:20 brass) were not long enough to allow the taking of longitudinal specimens after the transverse specimens were taken. For this reason only two points are shown in Fig. 5 for longitudinal specimens, and it is impossible to draw the curve for longitudinal specimens. It may be noticed that the transverse specimens with 37% reduction have an average modulus (16,750,000 lb./sq. in.) that is approximately as much above the modulus of 16,000,000 lb./sq. in. for the annealed sheet with equiaxed grains as the average modulus (15,150,00 lb./sq. in.) for longitudinal specimens of the same reduction is below it. This suggests that the longitudinal modulus may drop with cold rolling to the same degree that the transverse modulus rises, for all reductions between 0 and 37%. If such is the case, the curve for longitudinal specimens is a reflection, in the horizontal line AB, of the curve for transverse specimens, as shown by the dashed line (Fig. 5). Crystal rotation will undoubtedly tend to produce this effect. There may be some doubt as to

Specimen number	Modulus of Elasticity, E, in lb. per sq. in.				
	0# Hard (00% Red.)	1# Hard (11% Red.)	2# Hard (21% Red.)	3# Hard (29% Red.)	4# Hard (37% Red.)
1-T	16,950,000	15,600,000	15,350,000	16,200,000	16,100,000
2-T	16,500,000	15,100,000	15,150,000	16,200,000	17,650,000
3-T	15,700,000	15,900,000	16,050,000	16,400,000	17,500,000
4-T	16,450,000	15,400,000	15,700,000	16,450,000	16,700,000
5-T	15,200,000	14,500,000	15,600,000	16,600,000	16,550,000
6-T	15,850,000	15,300,000	15,000,000	16,500,000	15,800,000
7-T	15,800,000	14,750,000	16,100,000	16,150,000	17,200,000
8-T	16,300,000	15,350,000	16,400,000	16,700,000	16,700,000
Average	16,000,000	15,200,000	15,650,000	16,400,000	16,750,000

1-L	16,100,000	1-L	15,150,000
2-L	16,350,000	2-L	14,800,000
3-L	15,500,000	3-L	14,900,000
4-L	16,650,000	4-L	15,350,000
5-L	- - - - - --	5-L	15,000,000
6-L	- - - - - --	6-L	15,050,000
7-L	- - - - - --	7-L	15,550,000
Average	16,150,000	Average	15,150,000

FIGURE 4

Tabulation of Values

for

80:20 Brass

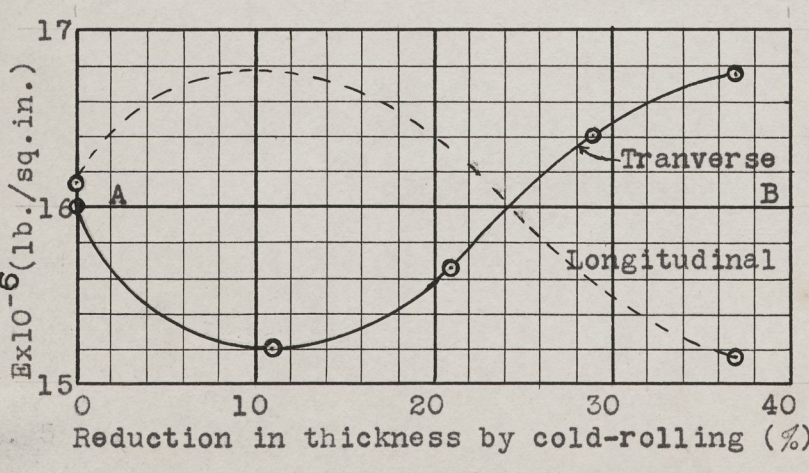


FIGURE 5

whether internal stress would cause a rise in one direction that is equal to the fall in a direction at right angles to it. The longitudinal modulus of annealed sheet as obtained by 4 specimens is slightly higher than the transverse modulus. But the difference is less than the maximum theoretical experimental error, and we may assume that the two moduli are substantially equal.

Figure 6 is a tabulation of the values obtained for the modulus of elasticity of all 4# hard specimens (both longitudinal and transverse) of all compositions used; namely, copper, 90:10 brass, 80:20 brass, and 70:30 brass. The last column of Fig. 6 shows that the moduli of the transverse specimens are greater by approximately 10%, than the moduli of the longitudinal specimens from the copper, 90:10 brass, and 80:20 brass sheet. But the 70:30 brass specimen moduli are hardly different at all, and the longitudinal modulus is slightly higher than the transverse if there is any difference. This result for 70:30 brass may be due to the drastic nature of the cold-work in the 37% reduction (60:40 brass with such a reduction could not be supplied by the American Brass Company).

Metal	Specimen number	Moduli (lb. per sq. in.) Longitudinal modulus	Transverse modulus	Increase in transverse modulus (%)
Copper	1	16,200,000	17,900,000	
"	2	16,050,000	17,900,000	
"	3	16,000,000	17,800,000	
"	4	16,100,000	17,900,000	
"	Average	16,100,000	17,900,000	11.2
90:10 Brass	1	14,700,000	16,250,000	
" "	2	14,500,000	16,100,000	
" "	3	14,800,000	16,300,000	
" "	4	14,750,000	16,300,000	
" "	Average	14,700,000	16,250,000	10.6
80:20 Brass	1	15,500,000	16,100,000	
" "	2	14,800,000	17,650,000	
" "	3	14,900,000	17,500,000	
" "	4	15,350,000	16,700,000	
" "	5	15,000,000	16,550,000	
" "	6	15,050,000	15,800,000	
" "	7	15,550,000	17,200,000	
" "	8	----------	16,700,000	
" "	Average	15,150,000	16,750,000	10.5
70:30 Brass	1	15,550,000	15,200,000	
" "	2	15,400,000	15,250,000	
" "	3	15,500,000	15,400,000	
" "	4	15,200,000	15,450,000	
" "	Average	15,410,000	15,325,000	-00.58

FIGURE 6 Tabulation showing individual and average moduli, and the effect of the copper-zinc composition on the difference between the "longitudinal" and the "transverse" modulus, of 32 gage brass sheet, 4# hard.

CONCLUSIONS

1. The modulus of elasticity of transverse specimens taken from thin brass sheet of 80:20 copper:zinc composition, decreases for small degrees of cold-working by rolling (up to 10% reduction in thickness) and then increases with higher reduction (at least to 37%, the highest used).

2. The modulus of elasticity of transverse specimens from annealed brass sheet (80:20 composition) is nearly, if not exactly equal to that of longitudinal specimens from the same sheet.

3. The modulus of elasticity of transverse specimens taken from sheets 4# hard (37% reduction in thickness by cold rolling) of deoxidized copper, 90:10 brass and 80:20 brass is approximately 10% higher than the modulus of longitudinal specimens taken from the same sheet.

4. There is some indication that the modulus of elasticity of longitudinal specimens taken from thin brass sheet of 80:20 copper: zinc composition increases for small degrees of cold working by rolling and then decreases with higher reductions. In other words, the effect seems to be directly opposite to that in transverse specimens. (See conclusion 1).

5. There is strong indication that an effect similar to that in 1. and 4. will be produced in deoxidized copper sheet and brass sheet of 90:10 copper: zinc composition.

6. The modulus of elasticity of transverse specimens taken from 70:30 brass sheet, 4# hard, is very nearly equal to that of longitudinal specimens from the same sheet.

SAMPLE DATA AND CALCULATIONS

For an 80:20 brass specimen with modulus determined by a series of loadings. Specimen number 4-T (3# hard).

Dimensions

Measuring point	1	2	3	4	5	6	7	8	9	10	Avg.
Width (in.x10^3)	503	503	504	505	505	505	505	505	504	504	504
Thickness(in.x10^5)	950	940	940	940	940	945	940	940	940	930	940

(Area of cross-section = 0.504 x 0.00940 = 0.00474 sq. in.)

Load-elongation Readings

Actual load(lb)	Extensometer readings (Divisions) Upper mark	Lower mark	Difference	Elongation referred to difference at 5 lb. as zero (div.)	Load(lb) referred to 5 lb. as zero
5	190	25	-165	000	00
15	182	52	-130	035	10
25	179	85	-094	071	20
5	179	14	-165	000	00
35	191	128	-063	102	30
45	180	147	-033	132	40
55	174	176	+002	167	50
5	167	2	-165	000	00
				Summation - 507 div.	150 lb.

Extensometer Constant = 0.0000305 (inches per division).

Summation of elongations = 0.0000305 x 507 = 0.01545 inches

Gage length 8.02 inches

$$\text{Modulus of elasticity, } E = \frac{Ll}{twe} = \frac{150 \times 8.02}{0.00940 \times 0.504 \times 0.01545}$$

$$= 16{,}450{,}000 \text{ lb. per sq. in.}$$

Sample data and calculations for the method used with the 4# hard specimens from sheets other than of 80:20 brass. The general procedure is the same except that only loads of 5 lb. and 55 lb. were given the specimen.

Specimen 1-L, of 90:10 brass, 4# hard

Dimensions

Measuring point	1	2	3	4	5	6	7	8	9	10	Avg.
Width (in.x10^3)	505	504	505	506	507	507	507	507	506	504	506
Thickness(in.x10^5)	925	925	922	923	922	925	925	915	915	915	921

(Area of cross-section = 0.506 x 0.00921 = 0.00466 sq. in.)

Load-elongation Readings

Actual load(lb)	Extensometer readings (Divisions) Upper mark	Lower mark	Difference	Elongation referred to difference at 5 lb. as zero (div.)	Load(lb) referred to 5 lb. as zero
5	274	91	-183	000	00
55	58	67	+009	192	50
5	288	105	-183	000	00
55	58	67	+009	192	50
				Summation - 384 div.	100 lb.

Extensometer constant = 0.0000305 (inches per division).

Summation of elongations = 0.0000305 x 384 = 0.01170 inches

Gage length 8.02 inches

Modulus of elasticity, $E = \frac{L1}{twe} = \frac{100 \times 8.02}{0.00921 \times 0.506 \times 0.01170}$

= 14,700,000 lb. per sq. in.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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