T-285

RELEASE OF INTERNAL STRESS IN BRASS TUBING [1]

By Robert J. Anderson and Everett G. Fahlman

ABSTRACT

The investigation discussed in this paper was carried out at the Pittsburgh experimental station of the Bureau of Mines in connection with related metallurgical studies on brass. However, since the nature of this phase of the work falls within the province of the Bureau of Standards, by special arrangement it is reported here rather than as a publication of the Bureau of Mines.

The effect of low-temperature heat treatment on the release of stress and on the physical properties of cold-worked leaded brass tubing of the nominal composition 66.33 : 33.17 : 0.5 copper-zinc-lead was studied. The object was to investigate the possibility of effecting stress release in cold-worked brass tubing by heating at moderate temperature without accompanying loss in hardness and strength. While considerable work has been done on stresses in other forms of wrought materials, actual measurement of the stresses present in tubes and of the effect of heat treatment in the release of such stresses was desirable. The strip method, described in Bureau of Standards Technologic Paper No. 257, was employed for the estimation of the internal stresses.

The effect of heating in the range 250 to 400° C. on the resultant hardness of the tubing and upon the release of stress thereby was studied, as was the effect of such treatment on the tensile properties of cold-worked brass sheet of the same composition as the tubing. It is shown that brass tubing which has been reduced in area by cold working in the range 17 to 56 per cent can be heated over a fairly wide time-temperature range without loss in hardness or tensile strength, but with substantially complete release of internal stress. From experiments on both ordinary commercial and specially drawn tubes it is shown that variations in mill practice during manufacture determine the heat-treatment characteristics of brass tubing as to hardness, internal stress, and physical properties on subsequent exposure to moderate temperatures. For the material worked with, heating for two to three hours at 325° C. was suitable.

CONTENTS

[1] Transmitted by the Director of the Bureau of Mines.

I. INTRODUCTION

This work was suggested by a user of tubes who experienced difficulty in certain manufacturing processes owing to warping of the tubes on maturing over a period of time at room temperature.

This user of tubes has materially diminished the warping by applying the treatment herein outlined.

A metal need not necessarily be harmfully internally stressed simply because it is deformed, but all cold-worked metals may be considered as internally stressed. The character and magnitude of the internal stresses in deformed metals and alloys have been discussed by Heyn.[2] He has shown that heating gradually relieves the stresses and that this effect becomes apparent at temperatures much below the temperature at which the effects of cold work are completely removed. Mathewson and Phillips [3] suggested that season cracking in severely worked brass due to stress, could be avoided by suitable heat treatment without loss of tensile strength. Hatfield and Thirkell [4] have measured the internal stresses in spun-brass cups and examined the effect of heat treatment thereon. They found that while the stress in the cups as spun was about 36,000 lbs./in.^{2} after heating for four hours at 450° C. it was of the order of 2,000 pounds. Moore and Beckinsale,[5] in experiments on spun cups of 70 : 30 brass, have found that internal stresses could be removed by heating within certain limits of temperature without important reduction in hardness. It was found that the minimum time in which injurious internal stress was removed by low-temperature heating ranged from 96 hours

[2] E. Heyn, Internal strains in cold-wrought metals and some troubles caused thereby, Jour. Inst. of Metals, 12, pp. 3-37; 1914.

[3] C. H. Mathewson and A. Phillips, Recrystallization of cold-worked alpha brass on annealing, Trans. Am. Inst. of Min. Engrs., 54, pp. 608-657; 1916.

[4] W. H. Hatfield and G. L. Thirkell, Season cracking, Jour. Inst. of Metals, 22, pp. 67-91; 1919.

[5] H. Moore and S. Beckinsale, The removal of internal stress in 70 : 30 brass by low-temperature annealing, Jour. Inst. of Metals, 23, pp. 225-235; 1920.

at 200° C. to 5 minutes at 325° C. Their criterion of removal of stress by heating was lack of cracking on treatment with mercurous nitrate.

In another paper, Moore and coworkers [6] have studied spun-brass cups for the presence of internal stress by cutting diametral strips and measuring the resultant springing out. They find that heating for 30 minutes at 370° C. wholly removes the stress and reduces the hardness a little. Moore and Beckinsale,[7] later examined the effect of heat treatment on 70 : 30 brass strips, cold-rolled from the fully annealed condition to 120, 160, and 200 Brinell hardness (1 mm diameter ball, 10 kg) maintained in a state of stress by external constraint in a holder. The amount of stress remaining after heat treatment in the range of temperature 200 to 325° C. was determined. In another paper Moore and Beckinsale [8] have discussed the question of internal stresses in brass condenser tubes and the rate of reduction of stress by low-temperature heat treatment. Their experiments were made on tubes highly stressed by drawing by the hollow-sinking method, and the rate of stress release was noted by observing the time required for cracking after treatment with mercurous nitrate solution. In the case of samples cut from the tubes as received, the material cracked within 40 seconds of immersion in the accelerating agent, while samples heated for 30 minutes and more at temperatures near 325° C. did not crack on treatment up to 28 days standing. These investigators have shown qualitatively that harmful stresses in condenser tubes can be substantially reduced by low-temperature heat treatment.

Vaudrey and Ballard [9] made an investigation on internal stresses in brass tubes. Qualitative experiments were carried out with both hollow-sunk tubes and tubes drawn with an internal mandrel, on the effect of stress release, as brought about by removing layers from the inside and outside of samples, on the time required for cracking in an accelerating agent. The experiments indicate that season cracking of tubing may be prevented by maintaining the equilibrium of stresses in the material.

Masing [10] has recently described experiments on the cracking of thin brass sheet with different percentages of reduction by cold working, and then further distorted to varying degrees by the Erichsen machine. The time in which cracking took place in mercu-

[6] H. Moore, S. Beckinsale, and C. E. Mallinson, The season cracking of brass and other copper alloys, Jour. Inst. of Metals, 25, pp. 35–125; 1921.

[7] H. Moore and S. Beckinsale, The prevention of season cracking in brass by the removal of internal stress. Trans. Faraday Soc., 17, pp. 162–192; 1921.

[8] H. Moore and S. Beckinsale, Further studies in season cracking and its prevention. Condenser tubes, Jour. Inst. of Metals, 27, pp. 149–170; 1922.

[9] R. H. N. Vaudrey and W. E. Ballard, Internal stresses in brass tubes, Trans. Faraday Soc., 17, pp. 52–57; 1921.

[10] Masing, G., Das Aufreissen von Messing durch innere Spannungen, Zeit. für metallkunde, 16, pp. 256–301; 1924.

rous nitrate was used as the criterion of internal stress in most of the work. With small reductions and distortions cracking (within three days) could be prevented by heating 30 minutes to around 200° C. or less. With greater amounts of cold work higher temperatures were required, but with still greater amounts of cold work, the temperature required decreased. The hardness and microstructure were not determined, nor was the percentage reduction brought about in making the various Erichsen impressions, and the work does not show whether internal stress was eliminated without bringing about recrystallization and loss of hardness. All specimens, however, showed practically entire release of internal stress after 30 to 60 minutes at 300° C. whether the criterion was failure to crack in three days in mercurous nitrate or heating strips held in a curved position by external restraint and determining their position after release.

Hardness was studied only in the case of three known cold reductions, 25, 40, and 60 per cent on a brass of 65.72 per cent Cu, 0.30 per cent Pb, 0.11 per cent Fe, balance zinc. With the first the hardness rose to a maximum on heating to 250° and did not decrease below its original value till above 325° C.; with the second the maximum hardness was at 225°, but at 275° it fell below its original value, and in the last it remained constant to 250° and then fell.

On combining these observations to apply them to the case of tubing it would appear that if the final cold reduction is around 25 per cent, internal stress might be released by heating to about 300° C. for 30 to 60 minutes without loss of hardness.

Information bearing on the subject under discussion is to be had also in papers by Price [11] and Allen,[12] and in the papers presented at a symposium on season cracking before the American Society for Testing Materials [13] in 1918 and at the recent symposium on the failure of metals under stress before the Faraday Society.[14]

II. MEASUREMENT OF INTERNAL STRESS

Various methods for measuring initial stress in a cold-worked metal object have for their basis the cutting, or removal of a portion, of the object by machining, with subsequent determination of dimensional changes and then the calculation of the stress. Measurement of internal stress may be made by different methods, depending upon the shape of the article to be tested and the nature of the stress.

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[11] W. B. Price, The prevention of season and corrosion cracking of brass artillery cases by special heat treatment, Proc. Am. Soc. for Test. Mats., 18, Part II, pp. 179–188; 1918.

[12] G. B. Allen, Service experience with condensers, Jour. Inst. of Metals, 24, pp. 285–293; 1920.

[13] Symposium, Topical discussion on season and corrosion cracking of brass, Proc. Am. Soc. for Test. Mats., 18, Part II, pp. 147–219; 1918.

[14] Symposium, The failure of metals under internal and prolonged stress, Trans. Faraday Soc., 17, pp. 1–215; 1921.

In some shapes the stress may be distributed very complexly, or there may be severe strain gradients, and in such cases it is practically impossible to arrive at even an approximate estimation of the stress. Hence, any method for the estimation of stress which involves cutting or machining with the measurement of movement or dimensional changes can not be regarded as precise.

However, it appears that cold-drawn tubing is under initial stress induced by the deformation, and that some method of cutting or machining will show movements or dimensional changes. Merica and Woodward[15] have described the various usual methods for measuring internal stress.

1. MATERIALS EMPLOYED

The tubing used for experimental work was that known in the brass trade as "leaded 2 to 1 mixture." The average chemical composition was as follows:

	Per cent
Copper	65. 67
Zinc	33. 94
Lead	. 30
Iron	. 06

The alloy is of the alpha type, consisting of a solid solution of zinc in copper plus free included lead.

The tubing was drawn according to the usual practice of American brass mills using an internal mandrel. The material was fully annealed at about 400° C. prior to the last draft, and then cold finished in one pass to size. Both stock and special tubing were used. Four lots, A, B, C, and D, of specially drawn tubing of the same composition as the stock material were prepared through the kindness of a brass maker.

TABLE 1.—*Manufacturing and hardness data relating to the tubing used in the experiments* [1]

Material	Original			Reduction in—		Brinell hardness [2]		Scleroscope hardness [3]	
	Outside diameter	Inside diameter	Wall thickness	Internal diameter	Area	Average	Range	Average	Range
	Inches	*Inches*	*Inch*	*Per cent*	*Per cent*				
Stock tubing	1. 219	1. 089	0. 065	9. 8	22. 4	142	132–148	45. 5	42–48
Lot A	1. 156	1. 028	. 064	4. 5	16. 8	124	121–125	39. 5	38–40
Lot B	1. 219	1. 079	. 070	9. 0	27. 2	141		51	
Lot B_1	1. 219	1. 079	. 070	9. 0	27. 2	140		50	
Lot C	1. 219	1. 061	. 079	7. 4	35. 4	149	148–151	50. 5	50–52
Lot C_1	1. 219	1. 061	. 079	7. 4	35. 4	147		52	
Lot D	1. 375	1. 166	. 104	15. 9	55. 9	176		64	

[1] All samples annealed at 400° C., then drawn cold to finished size; 1.094 inches outside diameter, 0.982 inch inside diameter, and 0.056 inch wall thickness.
[2] 1/16 inch ball, 25.2 kg; 30 sec., Le Grix lever type machine.
[3] Magnifier hammer.

[15] P. D. Merica and R. W. Woodward, Failure of Brass. 1. Microstructure and Initial Stresses in Wrought Brasses of the Type 60 per cent Copper and 40 per cent Zinc, B. S. Tech. Paper No. 82; 1917

There were prepared one batch of tubes in lot A, two batches each in lots B and C, and one batch in lot D. The second mentioned are referred to herein as lot B and B_1 and lot C and C_1. The treatment of the tubes in the two individual lots in the mill during manufacture was supposed to be identical. Experiments were made on the effect of heat on the resultant hardness in the case of lots A and C, and on the effect of heat on stress release for all the lots. A sufficient length of tubing in one piece was taken from each lot to insure uniformity so far as possible. Table 1 gives a summary of the manufacturing data for and hardness of the different lots of tubing.

Representative microstructures at 200 diameters of the different samples of tubing as received in the cold-worked condition are illustrated in Figure 1, which shows the effect of increasing amounts of cold reduction on the structure.

2. METHOD OF MAKING HARDNESS TESTS

Hardness tests were made on the samples of tubing with a small ball modified Brinell machine of the Le Grix type, described by Le Grix and Broniewski,[16] and used previously by Meneghini,[17] and others. This was of the lever type with a 5:1 ratio. All the determinations were made under the following conditions, unless otherwise stated: One-sixteenth inch diameter ball, 25.2 kg load, and 30 seconds duration of application. The average of four determinations was taken as the hardness. Determinations were also made with the Shore scleroscope, using the magnifier hammer.

3. METHOD OF EXPERIMENT

The various samples of tubing were examined for internal stress by observation of their performance under accelerating cracking tests and under machining tests of different kinds. In experiments to determine the effect of heat on the hardness of the materials small pieces about 1 inch square were cut from the cold-worked tubing and heated in an electric-resistance furnace at temperatures from 250 to 400° C. for different periods of time. In experiments on the effect of heat on stress release, pieces 3.25 inches long were cut from the lengths of tubing and similarly heat treated. Temperature control was maintained at ±2° C. Hardness determinations were made also on these samples, which were examined for stress release.

[16] G. Le Grix and W. Broniewski, Sur la dureté des alliages aluminum-argent, Rev. de Mét., 10, pp. 1058-1064; 1913.

[17] D. Meneghini, Structural changes in industrial brasses, Jour. Inst. of Metals, 14, pp. 154-159; 1915.

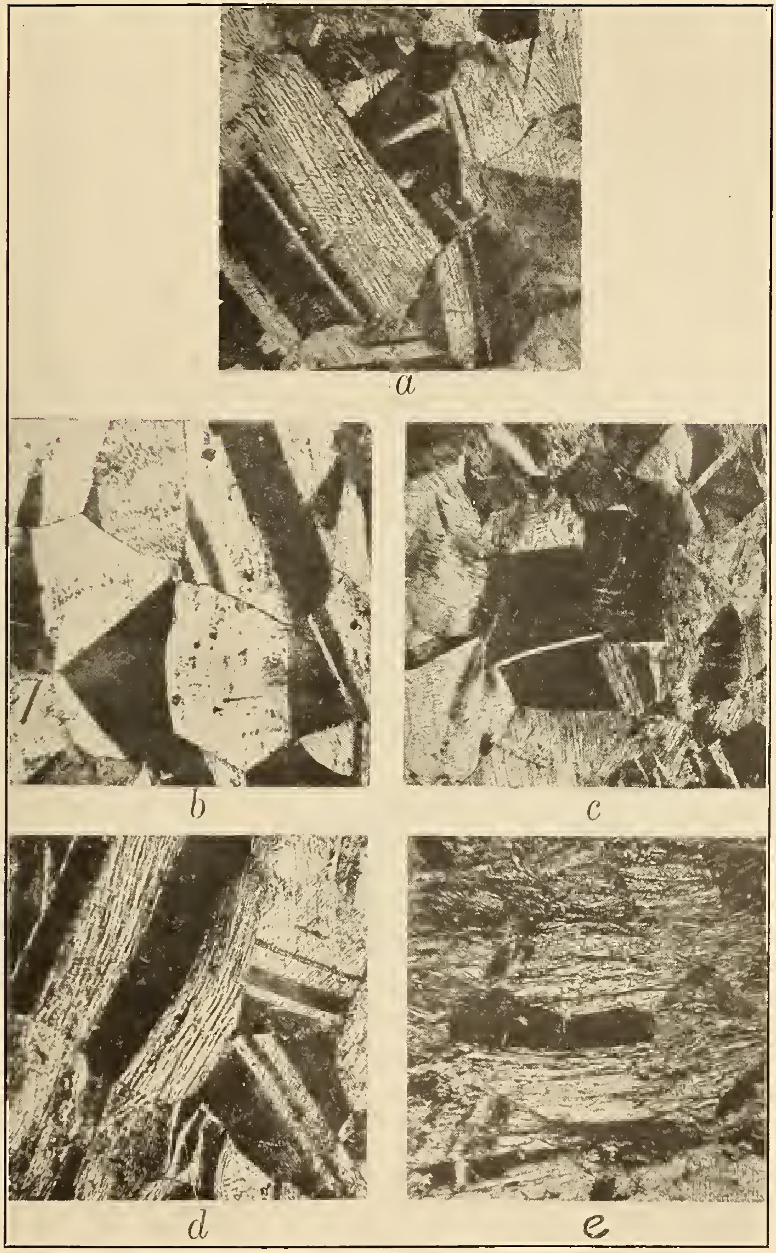

FIG. 1.—*Microstructure of cold-drawn tubing, as received.* × 200

Reduction in area in cold-drawing the tube:
a, stock tubing, 22.4 per cent
b, special tubing, 16.8 per cent
c, special tubing, 27.2 per cent
d, special tubing, 35.4 per cent
e, special tubing, 55.9 per cent
Etching reagent, ammonium hydroxide and hydrogen peroxide

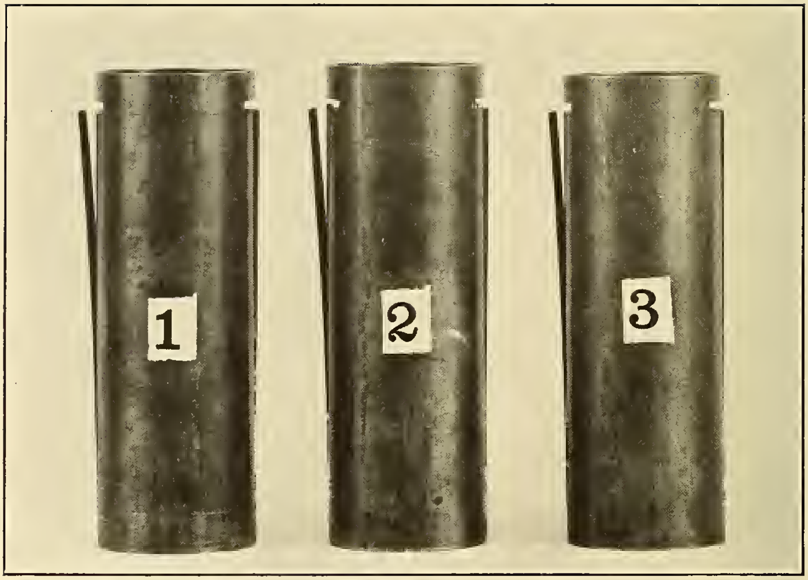

Fig. 2.—*Effect of heat treatment on internal stress in three tubes as shown by longitudinal cut strips*

(Actual size)

III. EXAMINATION FOR INTERNAL STRESS

The orthodox methods recommended for the qualitative detection of the presence of stress and for the quantitative estimation of stress in wrought metals were tried on many samples of the leaded brass tubing, but the results were nil. The usual methods appear applicable only to severely deformed manufactures or those in which the initial stress is high. In the case of the tubing under discussion, the actual amount of stress present was not large enough to be susceptible to detection by the usual methods, despite the fact that the material was known to be stressed because of its warping on maturing at room temperature. It has been pointed out by Merica and Woodward [18] that corrosion cracking does not take place when the surface layers of a wrought brass are under initial tensile stress amounting to less less than 25,000 lbs./in.[2] Wrought forms of brass in which the surface layers are under initial compressive stress do not crack. It will be shown later that the initial tensile stress of the surface layers of all the tubing examined was much less than 25,000 lbs./in.[2] Although a number of tests were made for the qualitative detection of stress by accelerating corroding agents and for the detection and estimation of stress in the tubing by machining, no stress could be found.

1. QUALITATIVE EXAMINATION FOR INTERNAL STRESS

Samples of the stock tubing (reduced in area 22.4 per cent by cold work) were treated with mercurous nitrate in the ordinary way. No cracks developed after standing for eight months. Samples of the specially drawn tubing (reduced in area 16.8, 27.2, 35.4, and 55.9 per cent by cold work) were similarly treated. No cracks developed after standing for 30 days. Samples of the stock tubing were exposed to ammonia and to an ammonia-saturated atmosphere, but no cracking resulted.

2. QUANTITATIVE EXAMINATION FOR INTERNAL STRESS

A few machining tests, according to the method of Heyn, were made in the hope of determining the amount of stress in the stock tubing. No length changes could be found on removing layers from either the inside or outside surface by turning in a lathe.

A modified form of the machining test suggested by Hatfield and Thirkell was applied, a piece of tubing being slit halfway around the circumference at several places, so as to test the entire circumference for internal stress. One end of each of the circumferential strips was then set free by cutting. No springing out or movement in any direction occurred. This indicated absence of circumferential stress.

[18] P. D. Merica and R. W. Woodward, Initial stress and corrosion cracking, Proc. Am. Soc. for Test Mats., 18, Part II, pp. 165–178; 1918.

3. STRIP METHOD

Failing in finding any visible evidence of internal stress in the various lots of tubing by the corroding and machining tests, a method[19] was devised for the qualitative demonstration of the presence of stress and for its quantititive estimation, called the "strip method." This is applicable to cold-drawn tubes in general, but it has not been tried on hollow-sunk material. In this method a strip 0.10 inch wide and 2.75 inches long is cut in a 3.25-inch length of tubing by slitting the tubing longitudinally and then cutting across one end of the strip. The freed strip then springs out a distance depending on the summation of the internal stresses in the strip and on the modulus of elasticity of the specimen. The equation for calculation of stress is:

$$S=\frac{t\,E\,i}{1^2}$$

when S is stress in pounds per square inch, t is the thickness of the strip in inches, E is the modulus of elasticity in pounds per square inch, i is the distance in inches which the end of the strip rises above the surface of the tubing, and 1 is the length of the strip in inches.

The derivation of the equation is fully discussed in B. S. Technologic Paper No. 257. Figure 2 shows on the left of each tube strips cut before heating, and on the right strips cut after a heating effecting considerable release of stress.

IV. EFFECT OF HEAT ON THE HARDNESS OF THE TUBING

Preliminary heat-treatment experiments at moderate temperatures were carried out on the stock tubing (reduction in area, 22.4 per cent) for the study of change in hardness. These tests showed that the material could be heated for any period up to 11 hours and at any temperature up to 300° C., with a maximum drop of 12 points Brinell and 4 points scleroscope. Substantial softening set in on heating at temperatures higher than 350° C. with fairly short exposures.

The results of the heat-treatment experiments on the special tubing (lots A and C), drawn with 16.8 and 35.4 per cent cold reduction in area are shown in the graphs of Figures 3 to 8, inclusive. The tubing may be heated at temperatures up to 325° C. and for moderately long times without great loss in hardness. As would be expected, the effects of heat are revealed earlier in the case of the greater reduction in area. It was thus shown that it is possible to heat cold-worked leaded brass tubing in a moderate temperature range without materially reducing the hardness.

[19] R. J. Anderson and E. G. Fahlman, Development of a Method for Measurement of Internal Stress in Brass Tubing, B. S., Tech. Paper No. 257; 1924. A method for measuring internal stress in brass tubes. Jour. (Brit.) Inst. Metals, October, 1924, meeting.

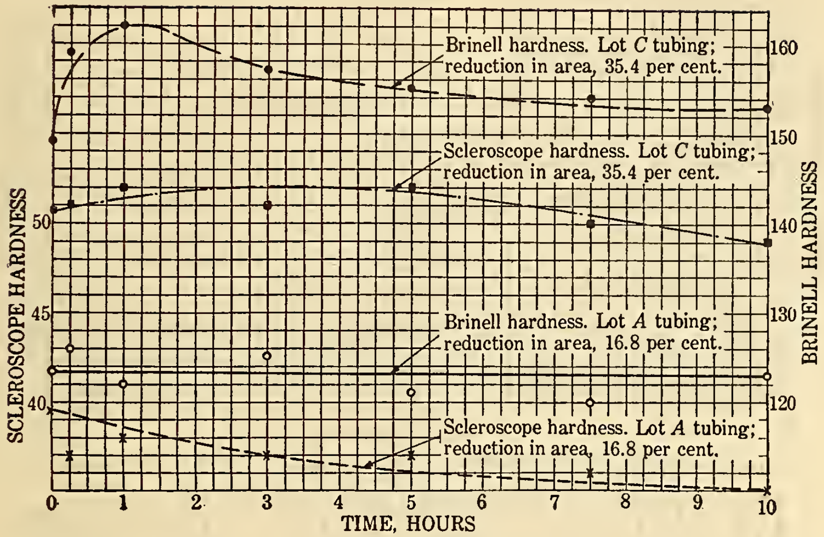

Fig. 3.—*Effect of heat at 250° C. on the hardness of leaded brass tubing*

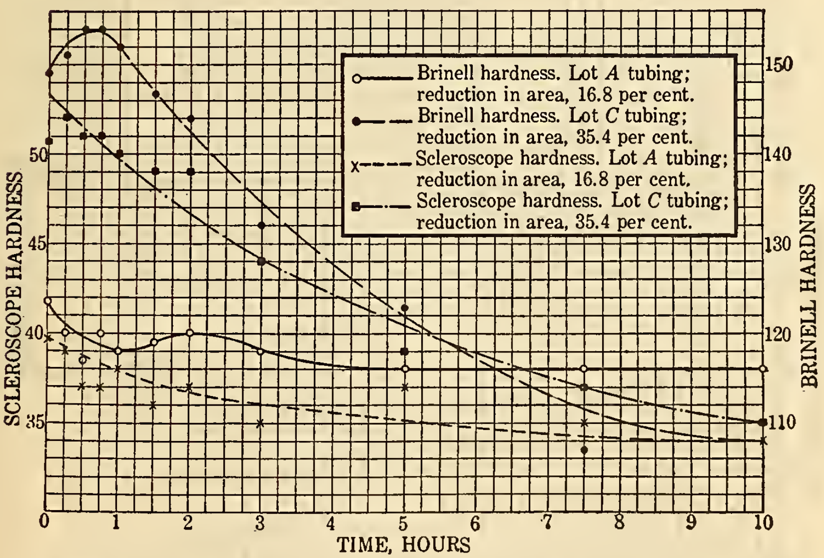

Fig. 4.—*Effect of heat at 300° C. on the hardness of leaded brass tubing*

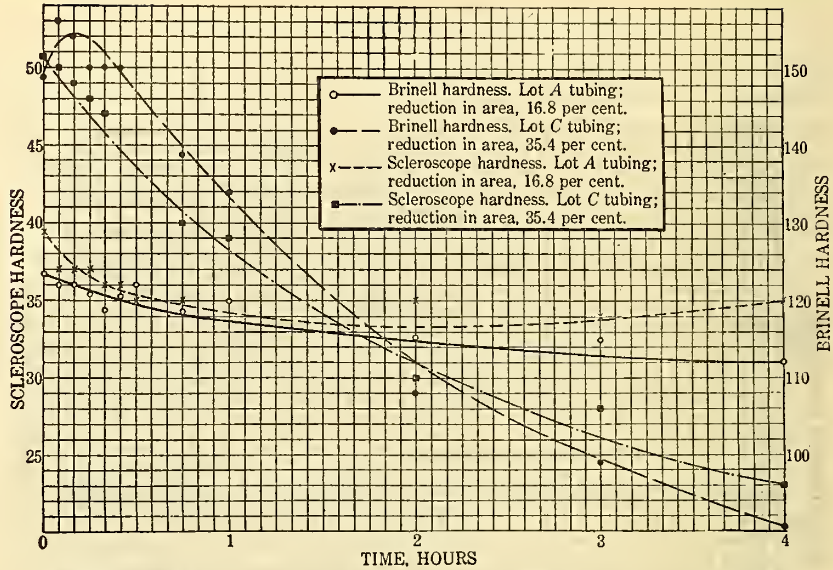

Fig. 5.—*Effect of heat at 325° C. on the hardness of leaded brass tubing*

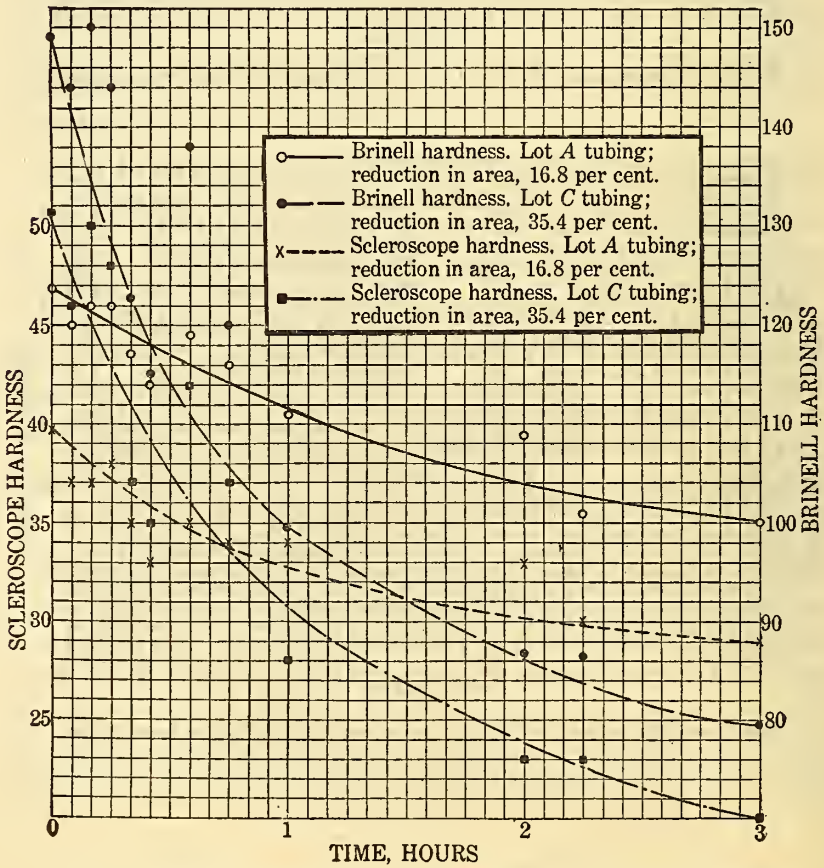

Fig. 6.—*Effect of heat at 350° C. on the hardness of leaded brass tubing*

V. EFFECT OF HEAT ON THE RESULTANT MICROSTRUCTURE OF THE TUBING

Metallographic examination was made of heat-treated samples, particularly for the purpose of trying to ascertain whether there was any visible change in the microstructure accompanying heating without softening, but with stress release. So far as could be ascertained by examination up to 2,000 diameters, there was no evidence of microstructural change accompanying stress release by heat unless there was actual softening. Even slight, but still measurable, softening, as effected by heat is accompanied by the formation of small recrystallized units. This agrees with the work of Mathewson and Phillips,[20] who state that it is proved beyond any doubt "that any positive indication of softening by the scleroscope can be detected in the form of recrystallization under the microscope."

The accompanying photomicrographs of Figures 9 to 12, inclusive, show the special tubing, lots A and C (reduction in area, 16.8 and

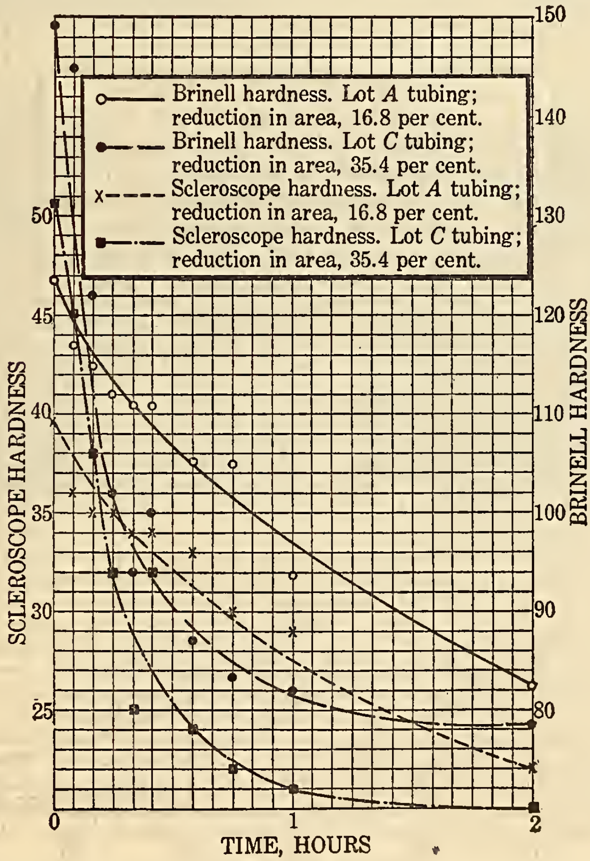

FIG. 7.—*Effect of heat at 375° C. on the hardness of leaded brass tubing*

[20] See footnote 3, p. 236.

35.4 per cent, respectively) heated at 350° C. for different periods of time. This temperature of treatment was selected because it covers a range where stress diminution is effected without softening for short-time exposures, but where longer exposures cause softening with simultaneous recrystallization. For the lot A tubing (reduced 16.8 per cent), 60 minutes is the germinating time for the temperature 350° C., and small recrystallized units appear as is shown in Figure 10a. Actual softening of the tubing so heat treated is also shown by the hardness values, the drop being about 12 points Brinell and 5 points scleroscope. In *b* and *c* of Figure 10 are shown the microstructure of the tubing after heating for three hours at 350° C. Recrystallization has proceeded considerably further than in the case of the material heated for 60 minutes. The structures shown in *b* and

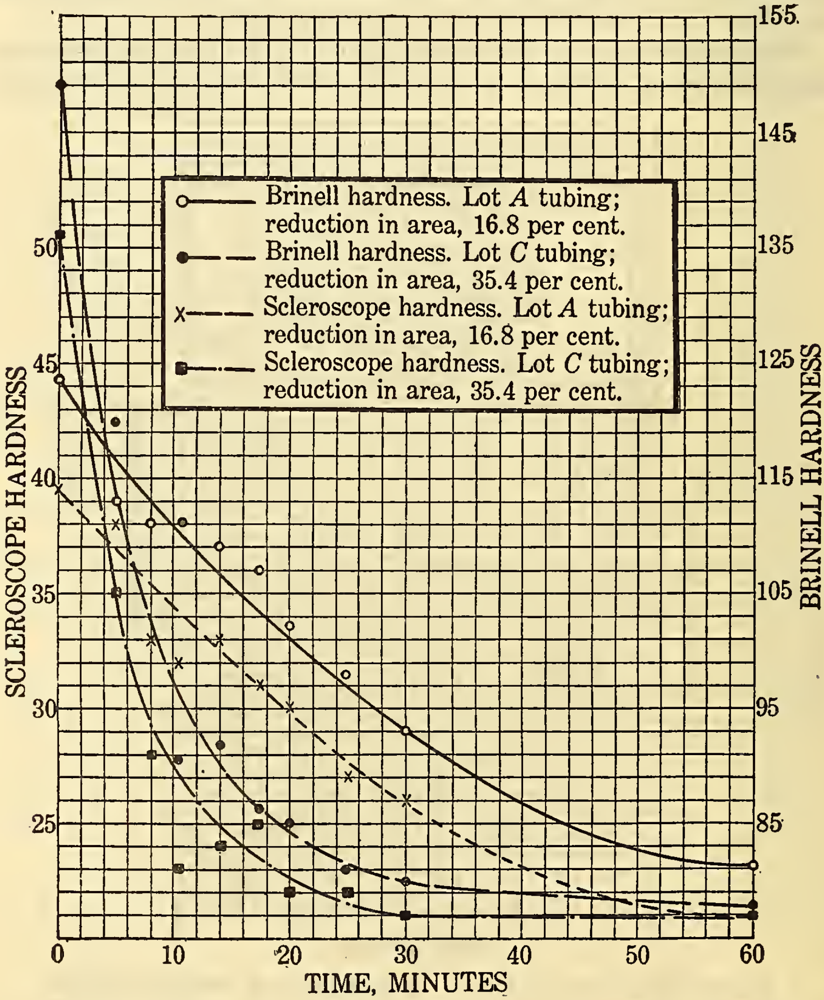

Fig. 8.—*Effect of heat at 400° C. on the hardness of leaded brass tubing*

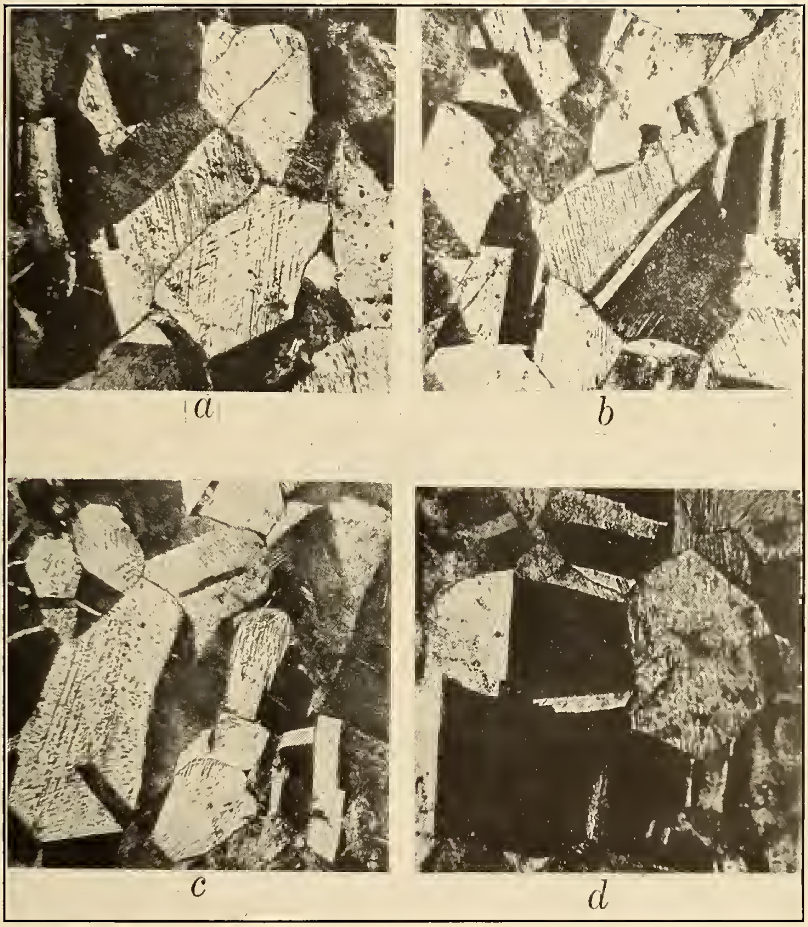

FIG. 9.—*Effect of heating for relatively short periods of time at 350° C. on microstructure of Lot A tubing.* × 200

Reduction of area in cold-drawing, 16.8 per cent:
a, 5 minutes, no visible recrystallization
b, 15 minutes, no visible recrystallization
c, 45 minutes, no visible recrystallization
d, 60 minutes, suggestion of recrystallization. (Compare fig. 10*a*)
Etched as in Figure 1

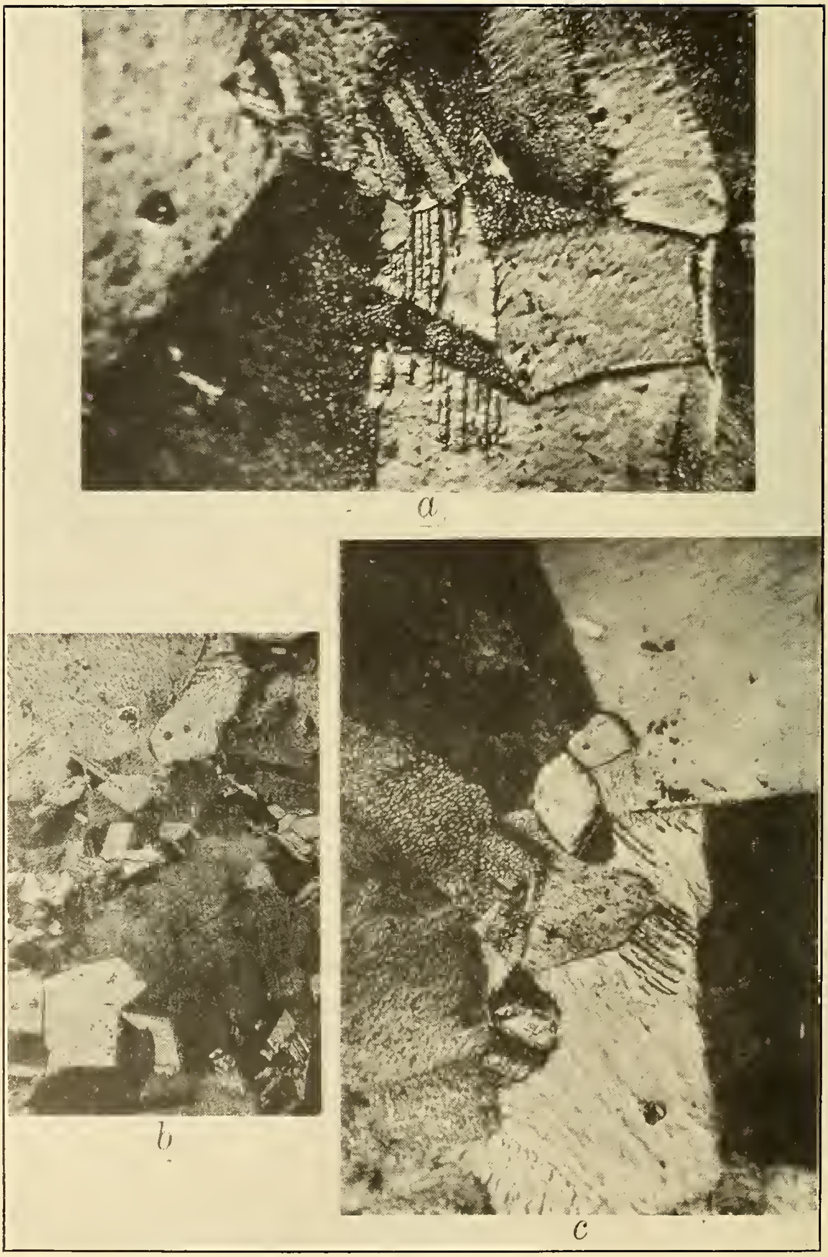

Fig. 10.—*Effect of heating for longer periods of time on the microstructure of Lot A tubing. (Compare fig. 9)*

a, 60 minutes, × 1,000. (Compare fig. 9*d*)
b, 3 hours, × 200, recrystallization very evident
c, same as *b*, × 1,000
Etched as in Figure 1

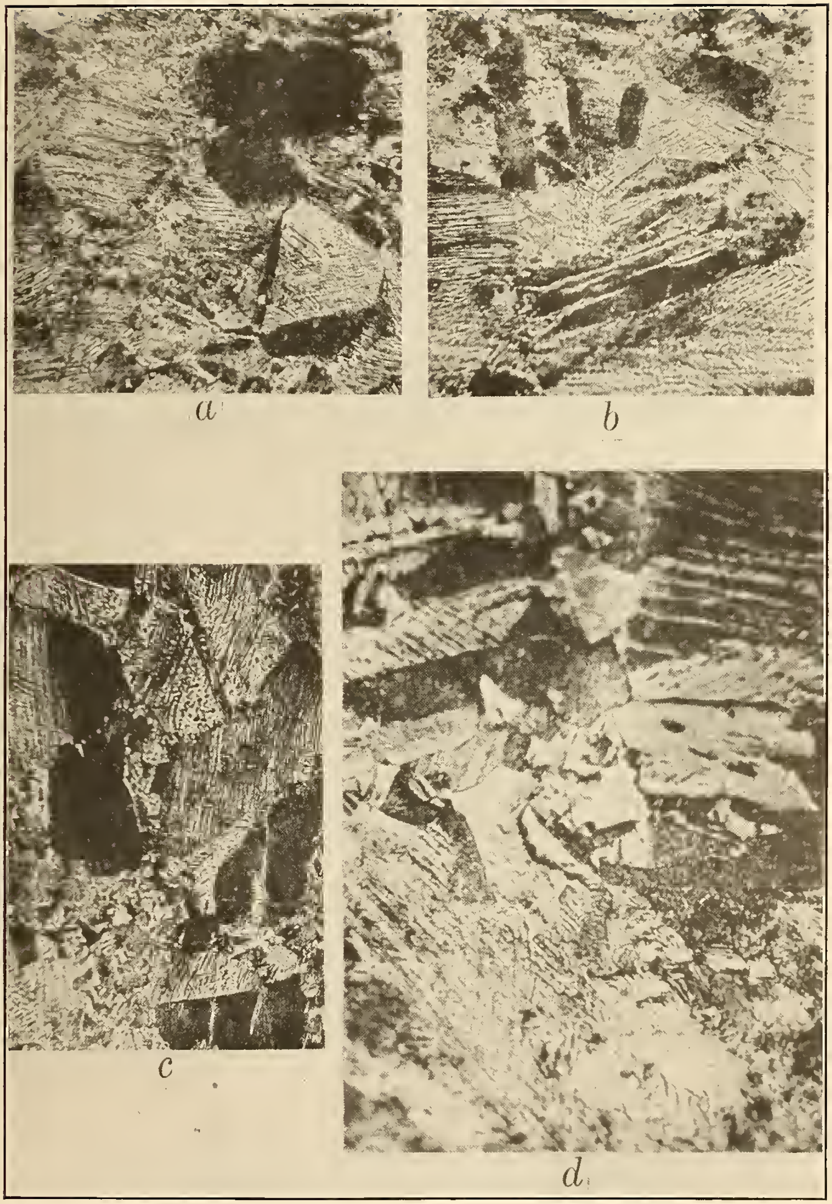

FIG. 11.—*Effect of heating for relatively short periods of time on the microstructure of Lot C tubing*

Reduction of area in cold-drawing, 35.4 per cent:
a, 5 minutes, × 200, no recrystallization visible
b, 15 minutes, × 200, no recrystallization visible
c, 45 minutes, × 200, recrystallization begun
d, same as *c*, × 1,000
Etched as in Figure 1

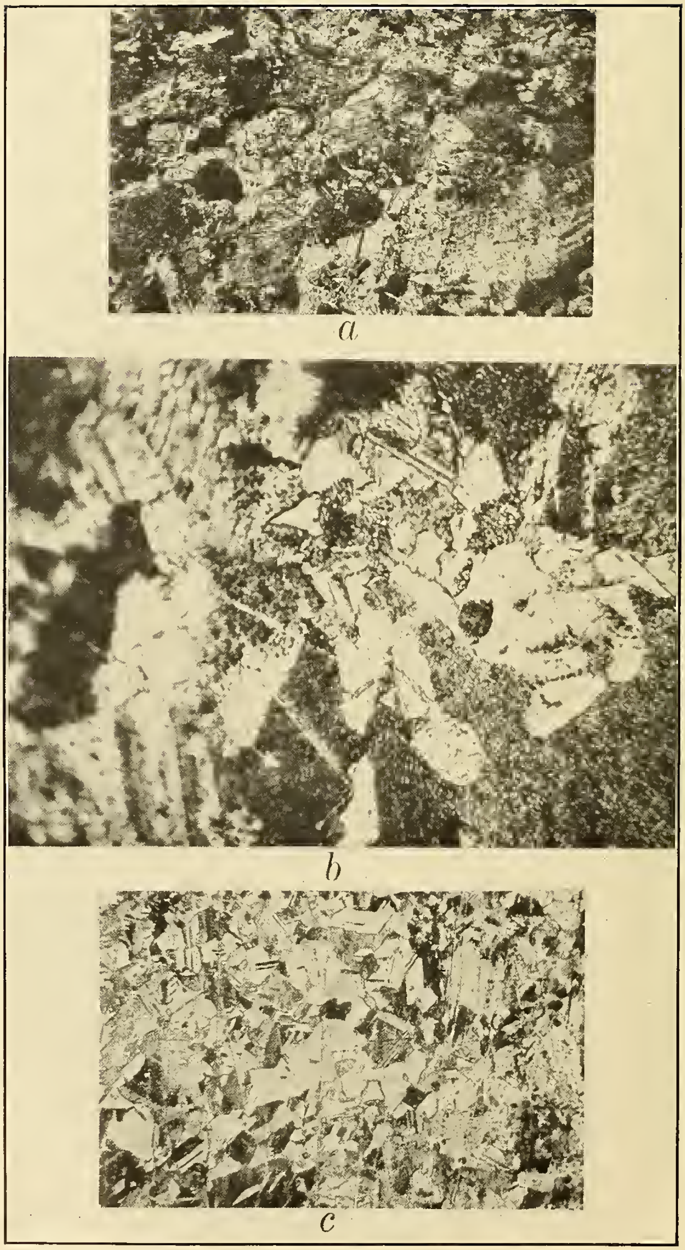

FIG. 12.—*Effect of heating for long periods of time on the microstructure of Lot C tubing.* (*Compare fig. 11*)

a, 60 minutes, × 200, recrystallization very evident
b, same as *a*, × 1,000
c, 3 hours, × 200
Etched as in Figure 1

c of Figure 10 correspond to a drop in hardness of about 24 points Brinell and 10 points scleroscope.

In the lot C tubing (reduced 35.4 per cent in the cold), as shown by Figures 11 and 12, 5 minutes or 15 minutes at 350° C. had no effect on the hardness or structure; but after heating for 45 minutes recrystallization commenced and is shown not only by the microstructure, but also by a drop in hardness of about 29 points Brinell and 13 points scleroscope. On heating for 60 minutes recrystallization proceeded still further, and there was a drop in hardness of about 50 points Brinell and 22 points scleroscope. After heating for three hours recrystallization was complete, grain growth started, and the hardness is about 80 Brinell and 20 scleroscope or a drop of about 70 points Brinell and 30 points scleroscope.

In all the samples examined, it was possible to follow microscopically fairly closely the drop in hardness as effected by heating, and quite easily the ranges in which loss of hardness was rapid. In no case was it possible to find change of microstructure on heating unless accompanied by softening.

VI. EFFECT OF HEAT ON THE PHYSICAL PROPERTIES OF COLD-ROLLED LEADED BRASS SHEET

While experiments on the different lots of tubing had shown that the material could be heated over a considerable time-temperature range without noticeably altering the microstructure and without marked reduction in hardness, it was desired to ascertain more pre-

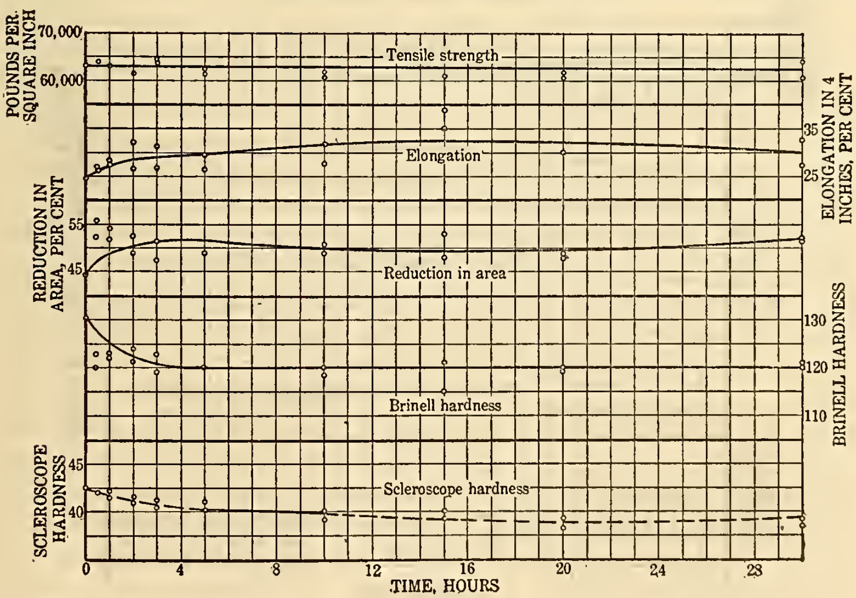

FIG. 13.—*Effect of heating at 300° C. for different periods of time on the physical properties of the leaded brass sheet*

cisely the effect of the heat treatments upon the tensile properties. Since it was undesirable to attempt to prepare test pieces for tensile test from the tubing, it was decided to make the experiments on leaded brass sheet having properties similar to the stock tubing. A supply of brass sheet of substantially the same composition as the tubing was rolled with the same cold reduction in area on the last pass as the reduction in area of the stock tubing. The reduction in area is taken as 22.4 per cent, although the microstructure of the sheet indicated less distortion than in the correspondingly reduced tubing.

The average chemical composition of the sheet was as follows:

	Per cent
Copper	66. 60
Zinc	32. 85
Lead	. 46
Iron	. 06

The average physical properties of the sheet were as follows:

Tensile strength	pounds per square inch	62, 800
Elongation 4-inch gauge length	per cent	24. 2
Reduction in area	do	44. 2
Brinell hardness		130
Scleroscope hardness		42. 6

The brass sheet was cut up into tensile-test pieces of a usual form (the tension specimen with 4-inch gauge length, 0.5 inch wide in the breaking section specified in International Aircraft Standards Board

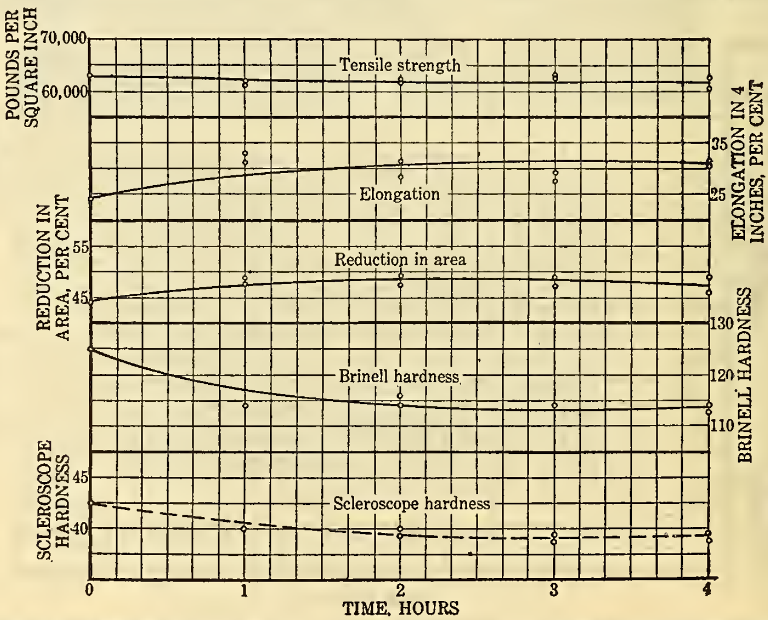

FIG. 14.—*Effect of heating at 325° C. for different periods of time on the physical properties of the leaded brass sheet*

Specifications 1G1 for sheet metal being used), and the samples were heated for different periods of time, from 3 minutes to 30 hours, in the range of temperature 300 to 400° C. The results of the tests are shown graphically in Figures 13 to 16, inclusive.

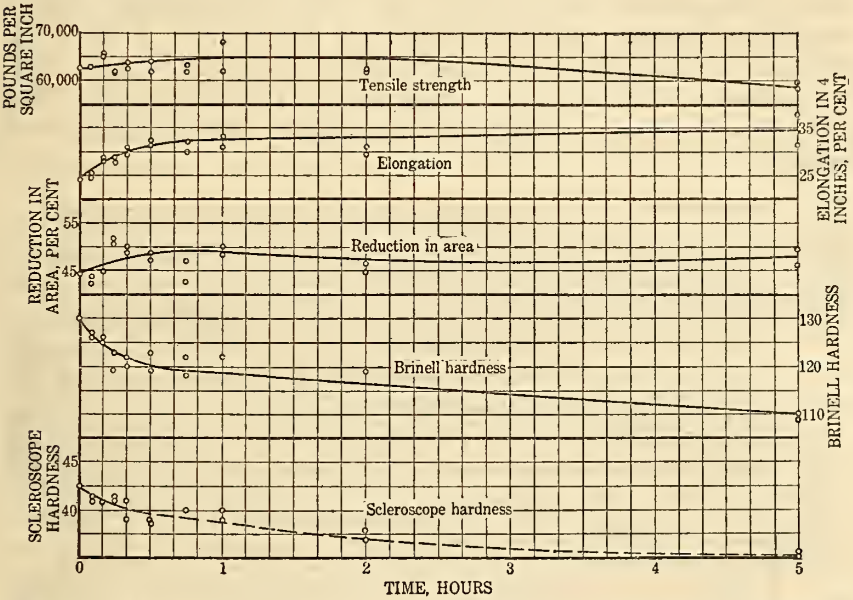

Fig. 15.—*Effect of heating at 350° C. for different periods of time on the physical properties of the leaded brass sheet*

Heating the sheet to 300° C. for various times up to three hours had very little effect (fig. 13) upon the tensile strength. The average strength on heating for periods of 10 hours and longer is about 1,000 to 2,000 pounds less than the average strength of the original sheet. The elongation increases from about 25 to 30 per cent, and the reduction in area likewise increases a little with increasing time period of exposure at the temperature. Brinell hardness of the heat-treated samples is roughly about 8 points less than that of the original sheet, and the scleroscope hardness is a little less. There is a tendency for the hardness, by both methods, to decrease slightly with increasing time of exposure. In the case of the samples heated for various periods up to four hours at 325° C. (fig. 14) the tensile strength remains substantially the same, the elongation increases from about 25 to 30 per cent, and the reduction in area likewise increases. The Brinell hardness drops about 11 points, and the scleroscope hardness is about 3 points lower. On samples heated for various periods of time up to five hours at 350° C. (fig. 15), the tensile strength remains about the same up to a period of five hours, when it drops about 3,000 pounds. The elongation increases with the length of exposure from roughly 25 to 33 per cent, and the reduction in area increases similarly from

33994°—25——3

about 44 to 49 per cent. The Brinell hardness drops off with increasing length of exposure from about 130 to 110; it starts dropping quite rapidly after two hours' exposure. Figure 16 shows the results of heating the sheet at 400° C. for various periods of time up to one hour. The tensile strength falls off about 3,000 pounds with a 45-minute exposure, and the drop with one hour is about 4,000 pounds. The elongation rises from roughly 25 to 41 per cent, while the reduction in area increases from about 44 to 51 per cent. The Brinell hardness starts falling off fairly rapidly after exposure of 15 minutes.

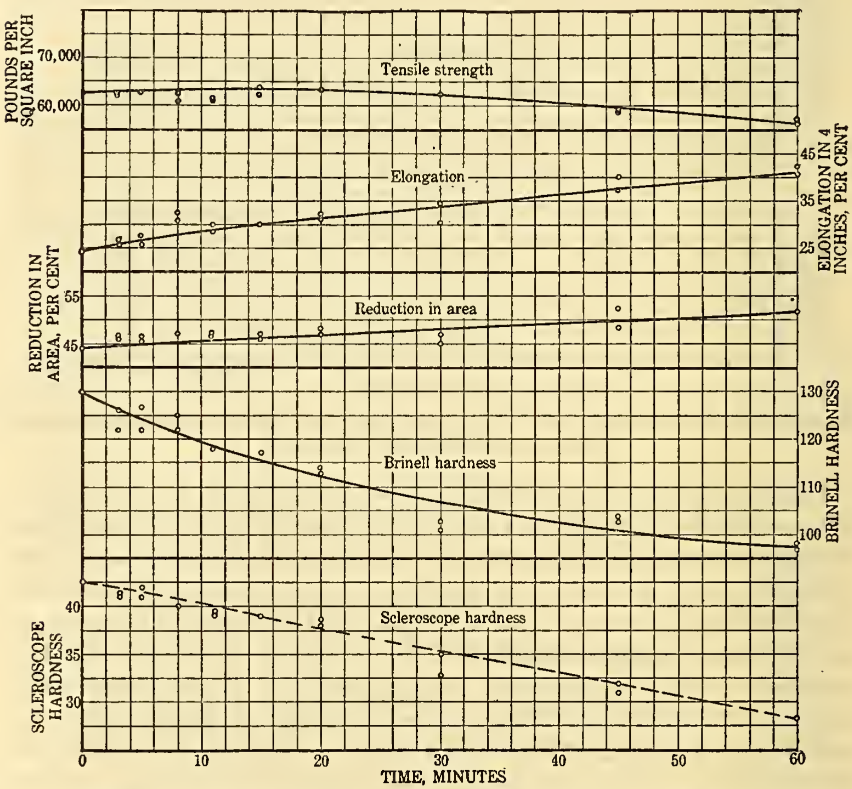

Fig. 16.—*Effect of heating at 400° C. for different periods of time on the physical properties of the leaded brass sheet*

The Brinell hardness of the material corresponds well with the effect of heat on the strength. A very small decrease in strength is accompanied by a relatively large drop in the hardness, and the Brinell test may be regarded as a sensitive indicator of the effect of heat treatment. The scleroscope test is not so sensitive.

Heating in the moderate temperature ranges and for the periods of time employed has practically no effect upon the strength of worked brass of 22.4 per cent reduction in area.

VII. EFFECT OF HEAT TREATMENT ON STRESS RELEASE AS SHOWN BY THE STRIP METHOD

The material employed for the study of stress release consisted of the stock, and specially drawn tubing. Pieces 3.25 inches long were cut from the different lots of tubing, and strips 2.75 inches long were cut therein for determining the stress before and after heat treatment in the manner described for carrying out the estimation of stress by the strip method.

1. EXPERIMENTS ON RELEASE OF STRESS IN THE STOCK TUBING

Table 2 gives the results of some internal-stress determinations by the strip method on 12 samples, three each being cut from four different 6-foot lengths of stock tubing of commercial grade as supplied by a brass maker to a user, at one end, center, and other end. No relation was found between the stress and the position in the tube length from which the different samples were removed. The average Brinell hardness of these samples was 144.5 and the indicated average stress 6,300 lbs./in.^{2} Table 3 gives the results of internal stress-determinations in the case of a number of samples selected at random from a large lot. Strips were cut on opposite sides of the tube samples at 180° in order to note the variation of stress at two positions. It is to be pointed out specially that the stock tubing was not uniformly stressed, and no definite value can be assigned as the average stress. Roughly, the variation is from about 2,000 to 12,000 lbs./in.^{2}, with an indicated average of 6,000 to 7,000 pounds. Irregularity of stress is also indicated by the warping of this tubing in storage.

TABLE 2.—*Stress distribution in 6-foot lengths of stock tubing*[1]*; reduction in area 22.4 per cent*

Sample No.	Position in the original tube length	Brinell hardness	Stress
			Lbs./in.^{2}
4	End	143	4,040
5	Center	145	5,580
6	End	145	5,870
7	do	148	4,720
8	Center	143	6,930
9	End	143	3,850
10	do	145	11,700
11	Center	147	7,610
12	End	147	6,540
13	do	142	5,680
14	Center	143	6,070
15	End	142	6,860
Average		144.4	6,288

[1] Outside diameter, 1.094 inches.

TABLE 3.—*Variation in springing out and internal stress in stock tubing;* [1] *reduction in area, 22.4 per cent*

Sample No.	Thickness of tubing	Measured spring on cutting strip		Calculated stress	
		One side	Other side	One side	Other side
	Inch	*Inch*	*Inch*	*Lbs./in.²*	*Lbs./in.²*
27	0.057	0.086	0.061	8,425	5,980
28	.058	.101	.071	10,080	7,090
29	.056	.069	.059	6,640	5,680
31	.056	.042	.040	4,040	3,850
32	.056	.018	.058	1,730	5,580
34	.055	.040	.061	3,780	5,770
38	.056	.112	.105	10,780	10,100

[1] Outside diameter, 1.094 inches.

In carrying out the heat-treatment experiments, strips were cut in the wall of each tube sample in order to determine the original stress. The sample was then heat treated and the resultant stress was measured by cutting another strip in the wall at 180° with the first strip (fig. 2). In some samples the variation in stress at two positions in the wall was noted by cutting strips on opposite sides of a given piece (cf. Table 3 and samples Nos. 30, 33, 35, 36, and 37 of Table 4). It might be asked whether cutting a strip in a tube would not largely release the stress throughout the sample, so that cutting a second strip on the opposite side would not give the stress at the second position. In Table 3, where strips were cut at 180° as indicated in order to determine the original stress, it will be seen that whereas the indicated stress in samples Nos. 27, 28, 29, and 38 was greater in the first strip cut (one side) that in the second strip (other side), it was less in the case of samples Nos. 32 and 34. The indicated stress in samples Nos. 31 and 38 was substantially the same. For the purpose of the present work it may be considered that there is no appreciable release of stress in remote parts of a sample by cutting a strip at one position, and that by cutting a strip at a second position the stress at that position can be obtained. In certain of the samples—for example, samples Nos. 29, 31, and 38—there appeared to be fairly uniform distribution of stress, indicating the absence of large strain gradients. In other samples—for example, sample No. 32—the stress distribution is not uniform.

Samples of the stock tubing were heated in the range 300 to 375° C., and the residual internal stress measured by cutting strips at 180° with the first cut strips. The results of the stress-release experiments are summarized in Table 4. Since the measurements of the stress in the cold-worked tubes do not give the absolute initial stress, the measurements of stress after heat treatment indicate tendencies rather than absolute results.

The original indicated stress in the samples heated at 300° C. varies from 6,540 to 7,610 lbs./in.², and that after heat treatment from

1,930 to 2,985 pounds by heating in the range 5 to 11 hours. The indicated-stress reduction is roughly 4,500 pounds. Heating at the temperature and for the different periods of time employed, caused a small loss in hardness, but not sufficient to indicate appreciable loss in strength. In the case of samples heated at 325° C., the time used was three hours in all cases except one, this duration being chosen because other experiments on the effect of heat on the resultant hardness had indicated that the probable suitable heat treatment would entail heating for three hours at 325° C. There is appreciable indicated stress release in the samples, while the hardness is not much affected. The average hardness of the original stock tubing was 142, and the variable hardness of the samples after heating is explainable by the variation in hardness of the original tubing from 132 to 148 and by inequalities in manufacture prior to the last draft. In the case of samples heated at 350° C. for various times, the results are comparable to those obtained by heating at the lower temperatures. There was substantial indicated reduction in stress on heating for periods of time up to 45 minutes without appreciable drop in hardness, but on heating for longer periods of time the hardness fell off. In the case of samples heated at 375° C. there is substantial drop in hardness, and in the case of the sample heated for one hour, this is reflected in the small indicated residual stress remaining.

From the experiments on the stock tubing, it appears that the first effects of heat are to cause a rapid drop in the stress; thereafter, the stress release is slow until recrystallization is effected, whereupon the stress drops to zero. The variation in hardness on heat treatment (cf. Table 4) probably indicates inequalities in the manufacture of the tubing as to annealing temperature between draws, especially immediately prior to the last draft, variable deformation in the different stages of drawing, and other factors.

TABLE 4.—*Effect of heat at various temperatures and for different periods of time on the release of stress in the stock tubing;*[1] *cold reduction in area, 22.4 per cent*

EFFECT OF HEAT AT 300° C.

Sample number	Time period of heating	Measured springing out			Calculated stress			Brinell hardness	
		Before heating	After heating	Additional spring	Before heating	After heating	Stress reduction indicated	Before heating	After heating
	Hours	*Inch*	*Inch*	*Inch*	*Lbs./in.*²	*Lbs./in.*²	*Lbs./in.*²		
2	5	0.073	0.031	0.122	7,030	2,985	4,045	132	128
11	8	.079	.030	.126	7,610	2,885	4,725	147	140
12	11	.068	.020	.107	6,540	1,930	4,610	147	138

[1] Diameter of tubing, 1.094-inch; wall thickness, 0.056-inch.

TABLE 4.—*Effect of heat at various temperatures and for different periods of time on the release of stress in the stock tubing; cold reduction in area, 22.4 per cent*—Continued.

Sample number	Time period of heating	Measured springing out			Calculated stress			Brinell hardness	
		Before heating	After heating	Additional spring	Before heating	After heating	Stress reduction indicated	Before heating	After heating
EFFECT OF HEAT AT 325° C.									
	Hours	*Inch*	*Inch*	*Inch*	*Lbs./in.^{2}*	*Lbs./in.^{2}*	*Lbs./in.^{2}*		
3	2	0.067	0.017	0.102	6,540	1,637	4,813	--------	128
10	3	.116	.038	.188	11,700	3,660	8,040	145	132
14	3	.062	.019	.103	6,070	1,860	4,210	143	128
30	3	.078	.023	.135	6,930	2,215	4,715	--------	144
		.058	.013	.100	5,590	1,215	4,375	--------	144
33	3	.072	.014	.108	7,060	1,373	5,687	--------	128
		.044	.010	.082	4,315	980	3,335	--------	128
35	3	.057	.033	.103	5,380	3,120	2,260	--------	142
		.051	.031	.092	4,820	1,983	2,837	--------	142
36	3	.055	.021	.103	5,300	2,020	3,280	--------	--------
		.022	.008	.044	2,120	770	1,350	--------	--------
37	3	.109	.012	.183	10,690	1,177	9,513	--------	127
		.095	.011	.150	9,315	1,078	8,237	--------	127
EFFECT OF HEAT AT 350° C.									
8	1/6	0.072	0.030	0.112	6,930	3,885	3,045	143	142
6	1/3	.061	.020	.103	5,870	1,930	3,940	145	132
13	3/4	.058	.035	.103	5,680	3,430	2,250	142	139
5	1	.058	.024	.103	5,580	2,310	3,270	145	122
7	2 1/4	.049	.020	.087	4,720	1,930	2,790	148	91.8
15	2 1/4	.070	.013	.110	6,860	1,275	5,585	142	117
EFFECT OF HEAT AT 375° C.									
4	1/2	0.042	0.025	0.052	4,040	2,410	1,630	143	119
9	1	.040	.002	.061	3,850	190	3,660	143	95.5

2. EXPERIMENTS ON RELEASE OF STRESS IN THE SPECIALLY DRAWN TUBING

In the study of the release of stress in the specially drawn tubing (lots A to D, inclusive) stress determinations were made on samples cut from the original tubes as received. The average internal stress was roughly as follows:

	Pounds
Lot A (reduction in area, 16.8 per cent)	5,800
Lot B (reduction in area, 27.2 per cent)	3,400
Lot C (reduction in area, 35.4 per cent)	2,500
Lot D (reduction in area, 55.9 per cent)	5,200

It will be noted the initial stress in the stock tubing (6,000 to 7,000 lbs./in.^{2}) was more than that found in the specially drawn materials, even though the last three lots were harder and were reduced in area more on the last draft. This is due to the fact that there is less reduction in internal diameter in the special lots than in the stock material in relation to the reduction in area. The absolute hardness of the tubing is no criterion of the internal stress present, but the stress, as determined by the strip method, appears to be a function of the amount of reduction in internal diameter and of the reduction in area. Data on the internal stress in the specially drawn lots are given in Tables 5 to 8, inclusive.

TABLE 5.—*Effect of heat treatment on stress release and hardness of special tubing; lot A, reduction in area, 16.8 per cent*

Heat treatment		Brinell hardness	Stress
Time period of heating (hours)	Temperature		
	° C.		Lbs./in.²
As received	Original tubing	124	4,050 4,630 6,070 4,530
1	250	121	2,700 3,565
10	250	123	1,925 4,235
1	300	117	2,215 2,025
2	300	122	2,890 1,930
4	300	114	2,890 1,350
10	300	118	1,445 1,445
2.5	325	119	2,410 2,025
2.25	340	113	964 1,060
1	350	114	578 1,640
2	350	108	965 1,830
1	400	83	382 96

TABLE 6.—*Effect of heat treatment on stress release and hardness of special tubing; lots B and B1, reduction in area, 27.2 per cent*

LOT B

Heat treatment		Brinell hardness	Stress
Time period of heating (hours)	Temperature		
	° C.		Lbs./in.²
As received	Original tubing	140	3,950 4,850 3,370 4,915
2	300	142	2,410 1,930
4	300	144	1,610 1,445
2.5	325	114	1,540 1,445
2.25	340	121	867 675

LOT B1

As received	Original tubing	141	2,175 1,230
2	300	145	1,610 1,135
4	300	140	0 473
2.5	325	135	0 0
2.25	340	97	378 852

TABLE 7.—*Effect of heat treatment on stress release and hardness of special tubing; lots C and C1, reduction in area, 35.4 per cent*

LOT C

Heat treatment		Brinell hardness	Stress
Time period of heating (hours)	Temperature		
	° C.		Lbs./in.²
As received	Original tubing	150	2,605 1,350 2,315 2,025
1	250	156	2,505 2,025
10	250	154	1,445 2,120
1	300	151	1,640 2,120
2	300	144	964 1,060
4	300	132	1,250 964
10	300	116	675 765
2.5	325	111	1,060 578
2.25	340	100	1,252 482
1	350	99	1,060 193
2	350	87	1,255 1,155
1	400	78	0 0

LOT C1

Heat treatment		Brinell hardness	Stress
Time period of heating (hours)	Temperature		
As received	Original tubing	147	3,750 2,695
2	300	150	1,735 1,640
4	300	147	1,350 1,060
2.5	325	139	1,830 1,350
2.25	340	95	482 578

TABLE 8.—*Effect of heat treatment on stress release and hardness of special tubing; lot D, reduction in area, 55.9 per cent*

Heat treatment		Brinell hardness	Stress
Time period of heating (hours)	Temperature		
	° C.		Lbs./in.²
As received	Original tubing	176	4,220 5,195 6,080 5,190
2	300	121	1,080 491
4	300	118	393 590
2.5	325	105	294 196
2.25	340	95	1,078 392

Table 5 gives the results of some heat-treatment experiments made on the lot A tubing, reduced 16.8 per cent. It will be noted that there is substantial indicated stress reduction without appreciable softening by employing different time-temperature ranges. Table 6 gives the results of the experiments on the lots B and B1 material reduced 27.2 per cent. There is considerable indicated stress reduction in lot B by heating in the time-temperature ranges employed, and a falling off in hardness by heating at 325° C. and above. The apparent residual stress falls to low values by heating at 340° C. for 2¼ hours, but there is also a 20-point drop in the Brinell hardness. In the case of the lot B1 material, the results given here do not check those given for the lot B, although the materials employed were the same, but taken from different lengths of tubing. It will be noticed that there was only a 6-point drop in hardness on heating for 2.5 hours at 325° C., and there was no residual stress remaining. Table 7 gives the results of experiments on the lots C and C1 material, reduced 35.4 per cent. In the case of lot C, stress release is indicated at the heat treatment employed and there is an earlier falling off in hardness than in the case of the lots A, B, and B1, where the percentage of reduction in area was less. This was to be expected, since the effects of heat on deformed alloys appear earlier, the greater amount of cold work. The results obtained on the lot C1 material are comparable to those obtained on the lot C, but the reduction in hardness on heating for 2.5 hours at 325° C. was small in the case of the lot C1 and quite appreciable with lot C. Table 8 gives the results of the experiments on the lot D tubing, reduced 55.9 per cent. The figures show an indicated stress reduction accompanied by loss in hardness.

The data appear to show that, in the case of the stock and special tubing employed, a level is reached on heat treatment beyond which stress can not be further released until recrystallization is effected. The internal stress drops off rapidly at first with exposure to heat at any temperature in the range 300 to 375° C., then the residual stress decreases very slowly, until there is appreciable recrystallization, whereupon the stress drops off immediately to zero. The indication given by the experiments on the effect of heat on hardness; that is, that the original hardness is no criterion of the resultant physical properties on exposure to heat, is confirmed by the experiments on stress release. Variations must have existed in the mill practice on the tubing. However, these data show that stress release can be effected without simultaneous softening.

3. EXAMINATION OF CONDENSER TUBING

After the greater part of the work above described had been completed, two separate lots of 70:30 brass condenser tubing were submitted by a tube mill for determination of the internal stress. In the case of the tubing previously used, the internal stresses were longitudinal, but in the case of these two later lots of tubing it was found that circumferential stress was present although it was less than the longitudinal stress. The stress determinations are given in Table 9.

TABLE 9.—*Measured stresses in two lots of 70:30 brass condenser tubing*

Sample	Size of tubing		Reduction in area	Longitudinal stress	Circumferential stress	Behavior in mercury-salt cracking test
	External diameter	Thickness				
	Inches	*Inch.*	*Per cent*	*Lbs./in.*²	*Lbs./in.*²	
P-1	1.304	0.086	33.3	7,340	1,200	Did not crack.
P-2	1.132	.080	44.2	17,330	5,650	Cracked.
P-3	.991	.067	59.1	23,410	6,080	Do.
P-4	.887	.059	70.0	14,610	6,760	Do.
P-5	.751	.051	78.0	14,630	2,710	Did not crack.
S-1	.623	.070		60,300	51,700	
S-2	.623	.070		60,300	46,200	
S-3	.623	.070		47,200	40,500	

VIII. RELATION OF MANUFACTURING DETAILS TO INTERNAL STRESS

The experimental work shows that the hardness and reduction in area by work, at least within the limits of up to about 180 Brinell hardness and up to about 56 per cent reduction in area, are not criteria as to the amount of internal stress or as to the liability to season cracking. The view put forward here is that the amount of cold reduction in area is not the sole criterion of the amount of internal stresses induced in a tube by working. According to a brass metallurgist,[21] 70:30 brass tubes which were reduced in the cold as much as 90 per cent in cross-sectional area failed to crack on treatment with an accelerating cracking agent, and this was supposed to be due to a condition of balanced stresses. The authors incline toward another explanation, that the failure to crack should be attributed to the stresses being below the limiting value required for cracking or to the direction of the induced stresses. The conclusion that the amount of cold reduction in area and the hardness of worked brass are not criteria of the liability to season cracking agrees with the work of Moore and his collaborators, and that of Masing.

From the manufacturing data on the drawing of the tubing it would appear that the final draft after complete annealing might be

[21] Private communication, June 7, 1922.

so made that no appreciable stress would be set up. Examination of the manufacturing data for the five lots of tubing (cf. Table 10) indicates that the stress increases directly with increase in reduction of the internal diameter and decreases directly with increase in the reduction in cross-sectional area. The effects of the two different factors are obscured somewhat by their interrelated effects on the stress, but the indications seem fairly clear. Thus in the case of the tubing of lot A (Table 10), the reduction in internal diameter was 4.5 per cent and the reduction in cross-sectional area was 16.8 per cent, while the average internal stress was 5,800 pounds. On comparing this with the stock tubing, it is seen that the reduction in internal diameter was twice as much, and the reduction in cross-sectional area a little higher, giving an average internal stress of 6,500 pounds. In the case of lot B, the reduction in internal diameter is about the same as that of the stock tubing and about twice that of lot A; the reduction in area of lot B is a little more than that of the stock tubing, but nearly twice that of lot A, and the average stress in lot B is considerably less than that of either. A special series of tests would be required before any definite conclusions could be drawn, but there are indications that both the reduction in internal diameter and in cross-sectional area are variables affecting the induced stresses in tubes. This question appears to merit investigation by tube makers.

TABLE 10.—*Relation of reduction in inside diameter to reduction in cross-sectional area v. internal stress in five lots of tubing*

Material	Internal diameter		Reduction in—		Ratio, K[1]	Average stress
	Before final draw	After final draw	Inside diameter	Cross-sectional area		
	Inches	*Inch*	*Per cent*	*Per cent*		*Lbs./in.*[2]
Stock tubing	1.089	0.982	9.8	22.4	0.437	6,500
Special tubing, lot A	1.028	.982	4.5	16.8	.268	5,800
Special tubing, lot B	1.079	.982	9.0	27.2	.331	3,400
Special tubing, lot C	1.061	.982	7.4	35.4	.209	2,500
Special tubing, lot D	1.167	.982	15.9	55.9	.284	5,200

[1] $K = \frac{\text{per cent reduction in internal diameter}}{\text{per cent reduction in cross-sectional area}}$

Vaudry and Ballard [22] indicate that the stresses present in drawn tubes are in some direct proportion to the reduction in internal diameter, and they also point out the beneficial effect of an increase in the reduction in area on the decrease of internal stress. If the least stress is induced by the least reduction in internal diameter and the most stress by the greatest reduction in internal diameter, and the least stress by the greatest reduction in cross-sectional area,

[22] See footnote 8, p. 237.

then there must be some definite possibilities in the direction of producing tubes with the least stress.

Moore and Beckinsale [23] state that the "distribution of hardness has no necessary influence on internal stress, and cold-work operations which develop a high degree of hardness in one part of an object and leave other parts soft do not necessarily result in severe internal stresses, although they may sometimes induce them. In general, it may be stated that internal stress is largely independent of hardness or distribution of hardness, with the reservation that when internal stress arises it is usually developed by operations which at the same time increase the hardness, and that the harder the material the higher is the maximum stress it is capable of sustaining without yielding." It has been shown by the data reported in the present investigation that cold work itself does not necessarily induce high internal stresses, and the lot D tubing (reduced 55.9 per cent) which has been hardened very considerably by cold work was less stressed than other lots not so much hardened.

The data given show that worked tubing can be heated over a fairly wide range of time and temperature without material loss of hardness and are, in general, confirmatory of the work of Moore and his collaborators. In some instances apparently anomalous results were obtained, for example, samples of tubing which had been reduced the same amounts gave different hardness values on identical heat treatment. This is attributed to variations in mill practice, as has already been pointed out. The anomalous results referred to are explained nicely by the work of Upthegrove and Harbert,[24] who have shown that for low-temperature heat treatments, following cold reduction by rolling, the Brinell hardness of cartridge brass is appreciably influenced by the anneal previous to rolling, the higher the temperature of anneal prior to rolling the lower the Brinell hardness of the brass on heat treatment after rolling in the case of heat exposures to 300° C. Moore and Beckinsale [25] have indicated the minimum times in which any noticeable softening effect was produced by heating in the range 200 to 300° C. in the case of 70:30 brass rolled to Brinell hardness in the range 90 to 200 Brinell (2 mm ball, 40 kg). There is no direct comparison between their results and those of the authors, but Table 11 will serve to indicate the effect of heat on the resultant hardness of the tubing reduced from about 17 to 56 per cent. Confirmation of a known law is had from the data, viz, the greater the percentage of cold reduction in area, the lower the temperature and the shorter the time of heating required to cause a loss in hardness.

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[23] See footnote 6, p. 237.

[24] C. Upthegrove and W. G. Harbert, Physical properties of cartridge brass; trans. Am. Inst. Min. & Met. Eng., 48, p. 725; 1923.

[25] See footnote 5, p. 236.

TABLE 11.—*Minimum periods of time in which appreciable softening was effected by heating different lots of tubing at different temperatures*

STOCK TUBING: REDUCTION IN AREA, 22.4 PER CENT; ORIGINAL BRINELL HARDNESS, 142

Temperature of heating °C.	Time at which softening started
250	No reduction in hardness up to 10 hours.
275	No reduction in hardness up to 8 hours.
300	No reduction in hardness up to 11 hours.
325	No reduction in hardness up to 3 hours.
350	Hardness falls off after 2¼ hours.
375	Hardness falls off after 30 minutes.
400	Hardness falls off after 10 minutes.

SPECIAL TUBING, LOT A: REDUCTION IN AREA, 16.8 PER CENT; ORIGINAL BRINELL HARDNESS, 124

Temperature of heating °C.	Time at which softening started
250, 300	No reduction in hardness up to 10 hours.
325	Hardness falls off after 2 hours.
350	Hardness falls off after 25 minutes.
375	Hardness falls off after 15 minutes.
400	Hardness falls off after 5 minutes.

SPECIAL TUBING, LOT C: REDUCTION IN AREA, 35.4 PER CENT; ORIGINAL BRINELL HARDNESS, 149

Temperature of heating °C.	Time at which softening started
250	No reduction in hardness up to 10 hours.
300	Hardness falls off after 3 hours.
325	Hardness falls off after 30 minutes.
350	Hardness falls off after 20 minutes.
375	Hardness falls off after 10 minutes.
400	Hardness falls off after less than 5 minutes.

With brass worked in the range 17 to 56 per cent reduction, no appreciable softening will be effected under a heat treatment which is adequate to remove the greater part of the injurious internal stress. In any practical development of a heat treatment for stress removal without simultaneous loss of hardness, the manufacturing data as to the production of the tubing should be in hand, and a heat treatment to be applicable to a given variety of tubing can be used only on tubing of uniform heat-treating characteristics.

The statement that the original hardness is not a criterion of the resultant hardness after heat treatment, but that mill variations as to variability of draft and different annealing temperatures between passes determine the heat-treatment characteristics, is consistent with the work of Smith.[26] He has shown that "brass which has received an anneal at a low temperature previous to a given deformation will recrystallize at a lower temperature and develop a finer grain than that which was originally annealed at a higher temperature; in other words, with a given deformation, the recrystallization and resultant grain size vary directly with the temperature of anneal before deformation." Brass which has received an anneal

[26] F. F. Smith, Grain growth in alpha brass, Trans. Am. Inst. of Min. and Met. Engs., 64, pp. 159–186; 1921.

at a low temperature previous to a given deformation will soften at a lower temperature than one which was annealed at a higher temperature. Evidently the amount of prior deformation has an effect also. It is shown by the stress-release data and also by the experiments on the effect of heat on the hardness of the tubing that variations as to anneal and deformation must have existed in the mill practice prior to the last draft. Hence, in commercial heat-treatment practice for stress removal, if this is to be done in ranges at all in the neighborhood of the recrystallization range, then tubing must be produced according to a definitely controlled scheme of mill practice. If lots of nonuniform tubing are heated in a given time-temperature range, some of the pieces may soften while others will not.

IX. SUMMARY

1. EFFECT OF HEAT ON THE TENSILE PROPERTIES OF WORKED BRASS

Experiments on cold-worked brass sheet showed that there was no loss in strength by heating in certain of the time-temperature ranges employed, and that the Brinell test is a much more sensitive indicator of heat effects than the scleroscope test or the tensile test. The data taken are comparable with the figures given by Moore and Beckinsale [27] on the effect of heat on the tensile properties of 70:30 brass. These investigators find that heating at moderate temperatures, in some ranges, considerably raises the limit of proportionality of worked brass, as well as the elastic limit. By suitable choice of time and temperature, a worked tube may be heat treated so as to release the stress and increase the elastic limit without loss of strength or hardness. Brass tubes, therefore, may be so heat treated at a moderate temperature for the removal of internal stress without injuring the mechanical properties, and in fact by accurate control of manufacturing conditions and subsequent heat treatment, the stress could be very largely removed with simultaneous improvement in mechanical properties.

2. EFFECT OF HEAT ON MICROSTRUCTURE

Stress release can not be detected microscopically. In samples so heated that there was considerable indicated stress reduction accompanied by no appreciable loss of hardness there was no evidence of microstructural change up to 2,000 diameters. The exact nature of the structural changes which occur in worked metals and alloys on heating to moderate temperatures is not known, and attempts to study these changes by means of the microscope have been fruitless because the structural alterations, if any, are of too small an order of magnitude to be revealed by the metallographic microscope.

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[27] See footnotes 7 and 8, p. 237.

3. EFFECT OF HEAT ON STRESS RELEASE

Internal stress can be removed rapidly and to a very large extent by heat treatment in a moderate time-temperature range which will not effect recrystallization and softening, but recrystallization must be complete before the stress is removed entirely. The work of Moore and Beckinsale [28] would indicate that, at the temperatures employed by the authors, complete or nearly complete removal of stress should be had in the tubing, but this was not found to be true. The contradiction between the results of Moore and Beckinsale and those of the present authors may, perhaps, be explained by the difference in the stresses worked with. In the case of the tubing experiments here reported, the longitudinal stress in the tubes is considered to be the summation of the stress present in each infinitesimal length of the material; that is, the total springing out at the end of the 2.75-inch long cut strip is the summation of the springing out of each infinitesimal length. In the case of the work of Moore and Beckinsale, definite stresses were set up in restrained brass strips, and the stress in the strips is comparable to that in a beam loaded at the end.

4. THEORETICAL ASPECTS OF THE MECHANISM OF STRESS RELEASE ON HEATING

The question naturally arises: What is the mechanism of stress release on heating a worked metal or alloy which is internally stressed? It has been shown that considerable stress release can be effected by heating without loss in hardness or other mechanical properties. It has also been shown by microscopic examination that there is no detectable microstructural change associated with the effect. The study of cold-worked metals by the X-ray spectrometer indicates [29] that lattice stress; that is, distortion of the arrangement of the atoms may occur. A distorted space lattice would tend to assume its equilibrium position on heating, and such a submicroscopic change appears consistent with the observed facts of release of stress on heating without detectable alteration in microstructure. Moore's explanation of the mechanism of stress release is based on plastic flow at the temperatures employed. The gradual plastic flow at moderate temperatures shown to occur by Moore and Beckinsale may be due to increased freedom in the space lattice with the simultaneous release of stress.

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[28] See footnotes 7 and 8, p. 237.

[29] Czochralski, J., The basis of hardening by cold work, Z. Metallkund, 15, p. 7; 1923. Jour., Inst. of Metals, 30, p. 448; 1923. Chem. Abstracts, 18, p. 2313; 1924. Kakinuma, U., The atomistic mechanism of metal rolling, Proc., Phys. Math. Soc., Japan, 5, p. 150; 1924. Chem. Abstracts, 18, p. 2827; 1924.

5. CONCLUSIONS

Commercial cold-worked brass tubing can be heat treated so as to release internal strains without loss in physical properties. Heating the tubing for two or three hours at 325° C. or for four hours at 300° C. in the case of material reduced 22.4 per cent in area will materially reduce the stresses without greatly affecting the hardness and with practically no loss in tensile strength. In the case of tubing of ordinary commercial manufacture there is no definite assurance that the above will invariably follow for the reason that variations in the mill practice may change the heat treatment characteristics; thus, certain lots of tubing may soften appreciably in the heat-treatment ranges mentioned while others will not soften. Consequently, it is necessary that the mill control of separate lots of tubing be substantially identical if a given heat treatment is to be applied to the material. Of course, from the point of view of stress release and of machining, it would be preferable to effect complete recrystallization as by heating for one hour at 400° C. The material so heat treated would be much softer than that heated at lower temperatures (300° C.), but it would not suffer much loss in strength. It is frequently important that the increased strength and hardness imparted by cold work should be retained in some brass articles for use under service conditions, while at the same time it is equally important that such articles should be substantially free from internal stress. This can be accomplished by low temperature heat treatment after cold working. Although relatively small internal stresses (those of magnitude less than would be required for cracking under an accelerated test) might not be regarded as injurious in the case of some spun and drawn articles, such as condenser tubes, they are decidedly injurious in articles for purposes where any slight warping or movement due to stress release would occur, on maturing.

The conclusions drawn by the authors from the experimental work may be stated as follows:

1. Accelerating cracking agents, such as mercurous nitrate, do not detect the presence of a stressed condition in worked brass unless the initial stress is above a certain limiting value, or of a definite nature.

2. Neither the cold reduction in area nor the hardness of worked brass is a sure criterion of initial stress or of the liability to season cracking.

3. In the brass tubes examined, the major internal stresses are longitudinal. The stress appears to be distributed as follows: That stress in the wall of the tube in a direction toward the external surface is a longitudinal tensile stress while that in a direction toward the internal surface is a longitudinal compressive stress.

4. The longitudinal internal stress in drawn tubes may be estimated approximately quantitatively by cutting a strip and measuring the amount of springing out.

5. Lack of appreciable circumferential stress in drawn tubes is shown by the failure to spring out on slitting diametral-cut rings.

6. Longitudinal internal stress in drawn tubes appears to be in some direct proportion to the amount of reduction in internal diameter on the cold draw and in some inverse proportion to the reduction in area.

7. With certain reductions in area, tubes may probably be produced free, or substantially free, from longitudinal internal stress by drawing with no reduction in internal diameter on the last pass, or temper draft.

8. Hardness after heat treatment at moderate temperatures is a function of the time and temperature of anneal prior to the last pass and the amount of deformation on intermediate passes during breaking down.

9. In commercial practice, variations in mill operations during drawing determine the heat-treatment characteristic of brass tubing as to hardness, stress, and physical properties on exposure to moderate temperatures.

10. Brass tubing which has been reduced from about 17 to 56 per cent in the cold can be heated over a fairly wide time-temperature range without loss in hardness, but with substantially complete release of longitudinal internal stress.

11. Cold-drawn brass tubes may be heat treated in certain temperature ranges (at about 300° C.) for the removal of internal stress without injury to the mechanical properties, and, in fact, by accurate control of manufacturing operations and subsequent heat treatment, the stress may be very largely removed with simultaneous improvement in mechanical properties.

12. Diminution of stress is effected by heating without alteration of microstructure.

13. Appreciable measurable softening of worked brass is accompanied by the formation of small recrystallized units in the microstructure.

14. Internal stress can be removed rapidly and to a very large extent by heat treatment in a moderate time-temperature range which will not effect softening and recrystallization, but recrystallization must be complete before the stress is entirely removed.

WASHINGTON, December 13, 1924.