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THERMAL EXPANSION OF COPPER-BERYLLIUM ALLOYS

By Peter Hidnert

ABSTRACT

Measurements were made on the linear thermal expansion of 12 samples of copper-beryllium alloys at various temperatures between 20 and 300 ° C, in order to determine the effects of chemical composition and treatments on the expansion of these alloys, which have come into industrial use during the past few years.

Table 1 gives the chemical composition and the treatment of each sample. The observations obtained on heating and cooling are shown in figures 9 to 13. The expansion curves of the quenched samples show critical regions which presumably were caused by changes in the structures of the alloys. Deformation or cold-work after quenching facilitates and accelerates these changes. Stabilization of copper-beryllium alloys may be accomplished either by cold-working or by tempering.

There is no simple relation between the coefficients of expansion, chemical composition, and heat treatment of the copper-beryllium alloys investigated. Figure 14 indicates the effects of beryllium content, cold-work, and heat treatment on the coefficients of expansion of these alloys. Table 2 gives the ranges of the coefficients of expansion. The coefficients of expansion of the copper-beryllium alloys do not differ from the corresponding value for copper by more than 8 percent of the latter value, whereas the differences indicated in figure 8 for the hardness, tensile strength, elongation, and reduction of area are considerably greater. For example, the tensile strength of copper-beryllium alloys may be more than 4 times as great as the tensile strength of copper.

CONTENTS

I. INTRODUCTION

Data on the linear thermal expansion of beryllium and aluminum-beryllium alloys were published by Hidnert and Sweeney [1] [1] in 1927. Data on the linear thermal expansion of another series of beryllium alloys, namely copper-beryllium alloys, are presented at the present time. This investigation was undertaken in order to determine the effects of chemical composition and treatments on the expansion of

[1] The numbers in brackets here and elsewhere in the text refer to the literature references at the end of this paper.

these alloys, which have come into industrial use during the past few years. Important applications of copper-beryllium alloys have been indicated by Illig [2], Davis [3], and in an anonymous article [4].

As it is known that various properties of copper-beryllium alloys (up to about 3 percent of beryllium) are subject to aging phenomena, it was assumed that the thermal expansion might be likewise affected. Consequently samples of each composition, in various conditions of heat treatment, were investigated. The beryllium contents ranged from 1.3 to 3.0 percent, for the results already obtained on other properties of the alloys indicated that this range included the useful alloys.

II. PREVIOUS DETERMINATIONS

Masing and Dahl [5] published a curve showing the linear thermal expansion of a quenched copper-beryllium alloy containing 2.5 percent of beryllium. This curve is reproduced in figure 1. They stated that owing to the heating, a decrease in length of about 0.24 percent took place, as is indicated by the distance between the intersection points of the heating and cooling curves with the ordinate axis. On reheating the same rod of copper-beryllium alloy to 500° C, they found that the expansion curve followed almost a straight line and after cooling an additional shortening of 0.01 percent took place. They concluded as follows: "Due to aging, a shortening of about 0.25 percent results with the 2.5-percent alloy. This shortening occurs in the temperature range above that for age hardening and therefore is not an age-hardening effect like the increase in hardness, but is simply due to the disintegration of the α-solid solution."

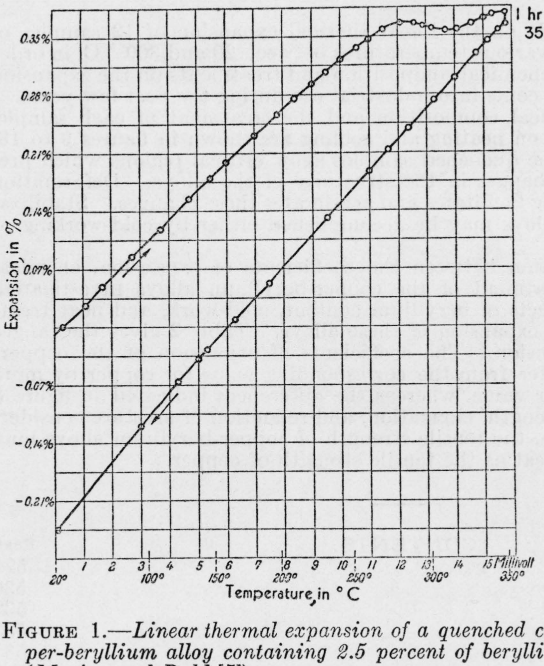

FIGURE 1.—*Linear thermal expansion of a quenched copper-beryllium alloy containing 2.5 percent of beryllium (Masing and Dahl* [5]).

Figures 2 and 3 show the differential dilatometric curves obtained by Haas and Uno [6] on a copper-beryllium alloy containing 2.5 percent of beryllium. Figure 2 shows six curves for various heat treatments. They stated that precipitation of γ crystals begins at about 220° C in the alloy air-cooled from 800° C, agglomeration starts at 400° C, and at approximately 500° C the transformation from γ into β takes place. Curve 4 for the alloy aged at 200° C shows slight anomalies, for during the aging the precipitation occurred, In the alloy aged at 300° C, the precipitation and agglomeration of the γ constituent took place, as is evident from curve 5. They further

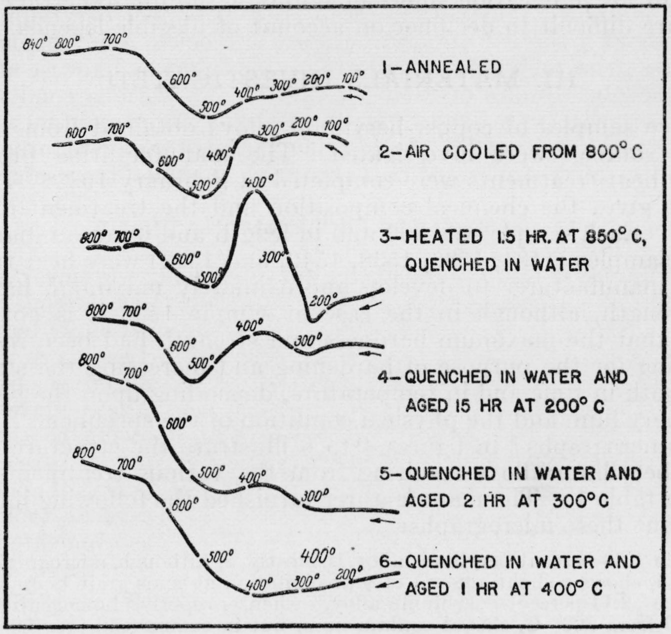

FIGURE 2.—*Dilatometric curves of a copper-beryllium alloy containing 2.5 percent of beryllium* (*Haas and Uno* [6]).

stated that neither an expansion nor contraction effect of the γ crystals can be observed in curve 6 for the alloy aged at 400° C.

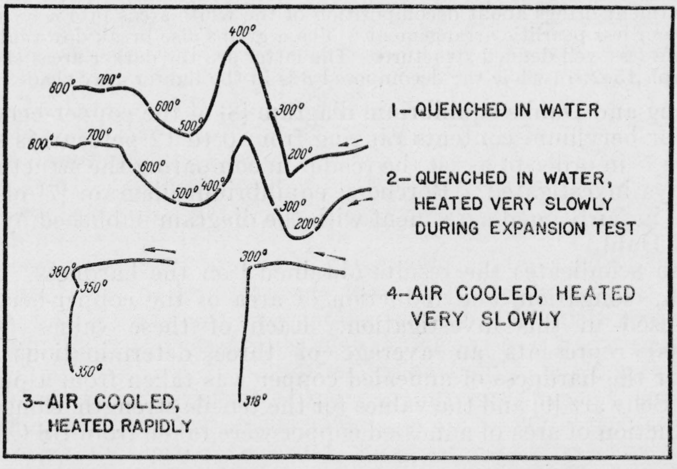

FIGURE 3.—*Temperature displacement of the hardening effect with various heating rates on a copper-beryllium alloy containing 2.5 percent of beryllium* (*Haas and Uno* [6]).

Figure 3 shows that slow heating causes the maximum of the differential expansion curve to shift to a lower temperature.

Borchers [7] used the dilatometric method in an investigation of the equilibrium diagram of the copper-beryllium alloys. Figures 10 and 11 of his publication show some differential dilatometric curves, which are difficult to decipher on account of illegible legends.

III. MATERIALS INVESTIGATED

Twelve samples of copper-beryllium alloys obtained from a commercial source,[2] were investigated. The manufacturing processes and the heat treatments were completed in February 1933. Table 1 (sec. V) gives the chemical composition and the treatment of each sample. Each sample was 300 mm in length and 6 mm in diameter.

Five samples (1534, 1536, 1538, 1540, and 1542) were heat treated by the manufacturer to develop approximately maximum hardness and strength, although in the case of sample 1536 it is not quite certain that the maximum hardness and strength had been reached. The aging for the purpose of hardening and increasing the strength varies both in time and in temperature, depending upon the percentage of beryllium and the physical condition of the specimen.

The micrographs [3] in figures 4 to 6 illustrate the structure of the copper-beryllium alloys resulting from the various treatments indicated in table 1. The manufacturer furnished the following information about these micrographs:

(a) The 1.33-percent-beryllium alloy is mostly α, although micrograph 1536, in figure 4, shows a slight amount of γ precipitation at some grain boundaries.

(b) The 2.14-percent-beryllium alloy, when properly homogenized and quenched from 800° C, should contain no β, but in commercial practice a little of the β constituent is found, as shown in figure 5. The precipitation of $\alpha+\beta$ at the grain boundaries is shown distinctly in micrograph 1540, figure 5.

(c) The 3.03-percent-beryllium alloy, when homogenized at 800° C and quenched, contains α and β grains, as shown in micrograph 1541, figure 6. The solid white areas are the β, the darker and cross-hatched areas the α. After heat treatment of this alloy the structure appears as shown in figure 6, micrographs 1542, 1542(a), and 1542(b), at 75, 500, and 1,000 diameters, respectively. The heat treatment brings about decomposition of the white areas into $\alpha+\gamma$ usually in a more or less pearlitic arrangement. The α grains also break down into $\alpha+\gamma$ but with a less well defined structure. The latter are the darker areas shown in micrograph 1542(b), while the decomposed β is in the lighter gray shade.

Masing and Dahl's equilibrium diagram [8] of the copper-beryllium alloys for beryllium contents ranging from 0 to 12 percent, is shown in figure 7, in order to assist the reader in comparing the structures of the alloys investigated. Borchers' equilibrium diagram [7] of these alloys is in fairly good agreement with the diagram published by Masing and Dahl.

Figure 8 indicates the results obtained [4] on the hardness,[5] tensile strength, elongation, and reduction of area of the copper-beryllium alloys used in this investigation. Each of these values (except hardness) represents an average of three determinations. The value for the hardness of annealed copper was taken from a publication by Schwarz [9] and the values for the tensile strength, elongation, and reduction of area of annealed copper were taken from BS Circular 73 [10].

[2] American Brass Co.
[3] Micrographs by American Brass Co.
[4] By the American Brass Co., in February 1933.
[5] Rockwell B hardness (100-kg load with 1/16-inch ball).

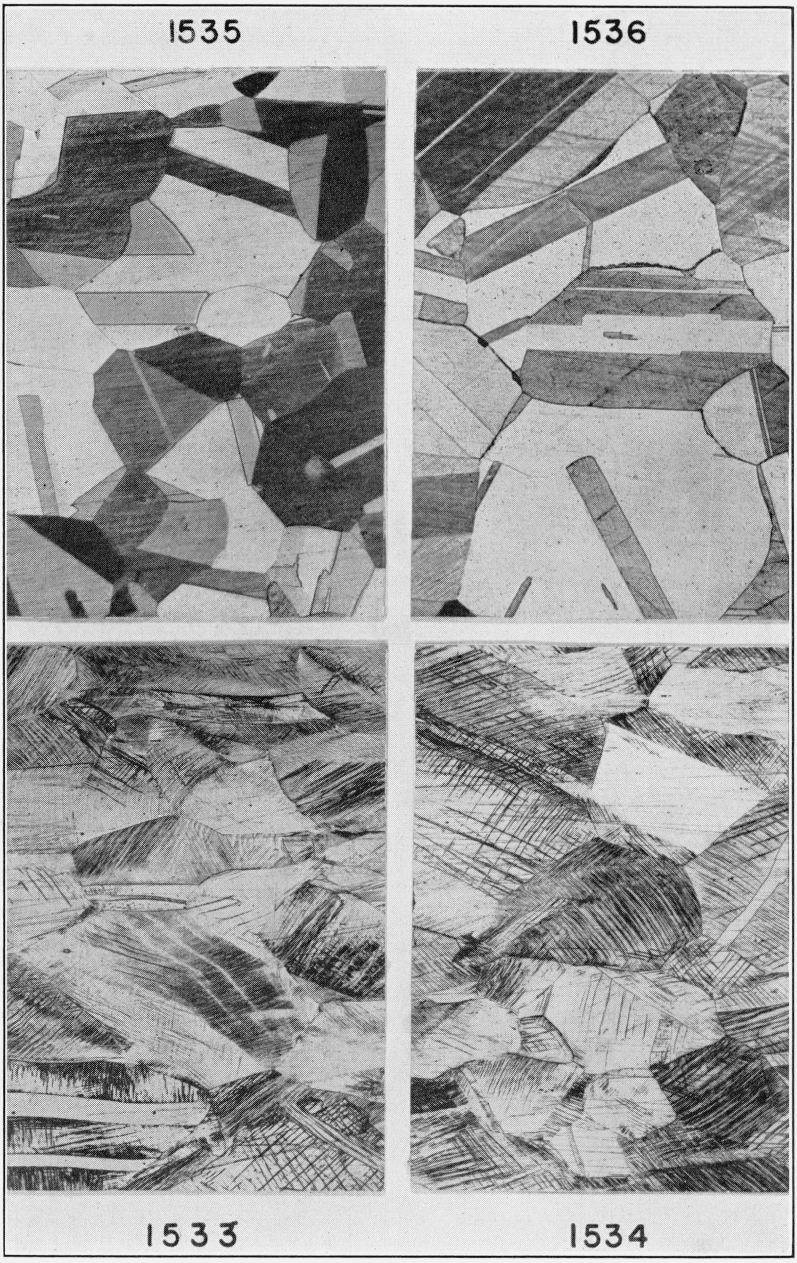

FIGURE 4.—*Microstructure of copper-beryllium alloy (copper 98.54, beryllium 1.33 silicon 0.02, iron 0.03 percent),* ×75.

Sample 1535—quenched from 800° C. Sample 1536—quenched from 800° C and aged 5 hours at 350° C. Sample 1533—quenched from 800° C and hard-drawn (30 percent reduction). Sample 1534—quenched from 800° C, hard-drawn and aged 5 hours at 325° C.

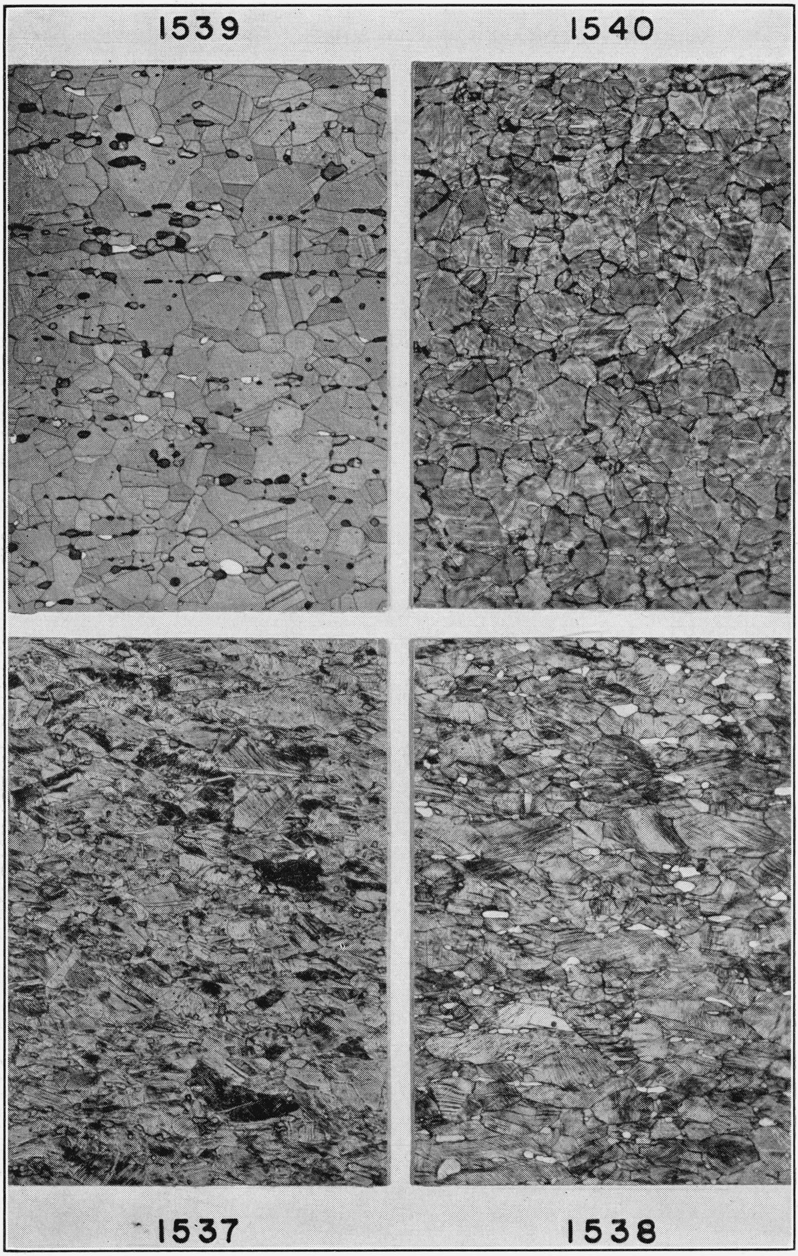

FIGURE 5.—*Microstructure of copper-beryllium alloy (copper 97.78, beryllium 2.14, silicon 0.02, iron 0.06 percent), ×75.*

Sample 1539—quenched from 800° C. Sample 1540—quenched from 800° C and aged 2½ hours at 300° C. Sample 1537—quenched from 800° C and hard-drawn (30 percent reduction). Sample 1538—quenched from 800° C, hard-drawn and aged 2 hours at 275° C.

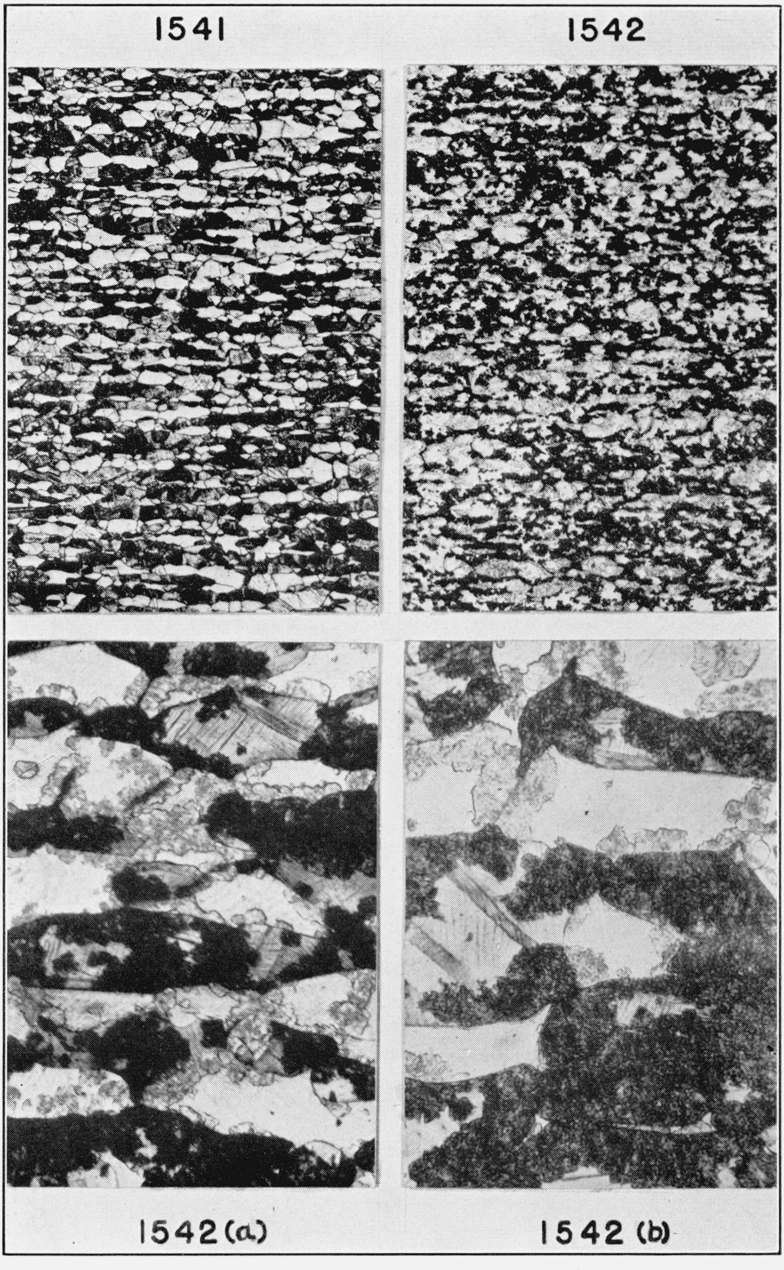

FIGURE 6.—*Microstructure of copper-beryllium alloy (copper 96.98, beryllium 3.03, silicon 0.02, iron 0.03 percent).*

Sample 1541—quenched from 800° C and hard-drawn (20 percent reduction), ×75. Sample 1542—quenched from 800° C, hard-drawn and aged 1¾ hours at 300° C, ×75. Sample 1542 (a)—same treatment as 1542, ×500. Sample 1542 (b)—same treatment as 1542, ×1,000.

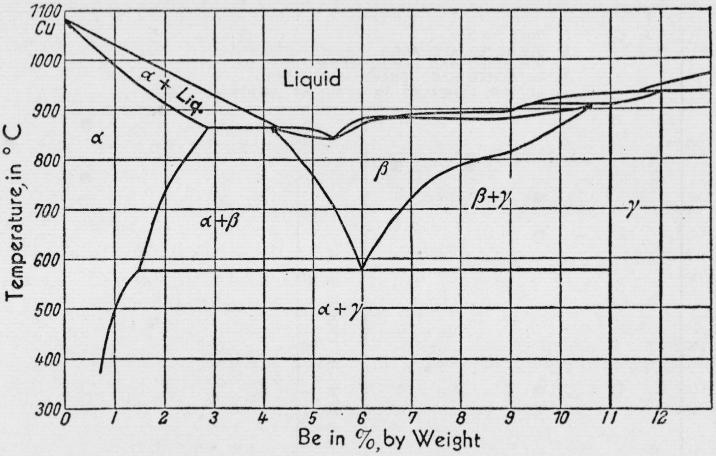

FIGURE 7.—*Equilibrium diagram of copper-beryllium alloys* (*Masing and Dahl* [8])

IV. APPARATUS

All samples except 1541A were investigated in the stretched-wire bath furnace described in BS Scientific Papers S410 and S524. The air furnace described in BS Scientific Paper S524 was used for sample 1541A.

The stretched-wire thermal-expansion apparatus referred to herein was originally designed and used by Dr. Arthur W. Gray, formerly of this Bureau, and was described by him in the Journal of the Washington Academy of Sciences, vol. II, no. 10, p. 248, 1912, and in the Bulletin of the Bureau of Standards, vol. 10, Scientific Paper S219, 451, (1914). The apparatus has been modified and improved by subsequent workers, and, in its later forms, has been described, in detail and by reference, in a large number of scientific papers by W. Souder, P. Hidnert, L. W. Schad, and other research workers at the National Bureau of Standards. Among these papers the following may be mentioned as of particular value in describing the apparatus: Scientific Papers S352, S433, and S524, by W. Souder and P. Hidnert, and S410 by P. Hidnert.

V. RESULTS

Observations were made on the linear thermal expansion of the copper-beryllium alloys at various temperatures between 20 and 300° C. The results obtained on heating and cooling are shown in figures 9 to 13. Each expansion curve is plotted from a different origin in order to display the individual characteristics of each curve. The numbers adjoining the observations on each curve that showed critical regions, represent the time, in hours, from the time of the initial observation.

Two or more tests were made on each sample except 1541A, on which only one test was made. The results obtained on the first heating apply for the samples having the treatments indicated in table 1, but the results obtained in the second and third tests apply

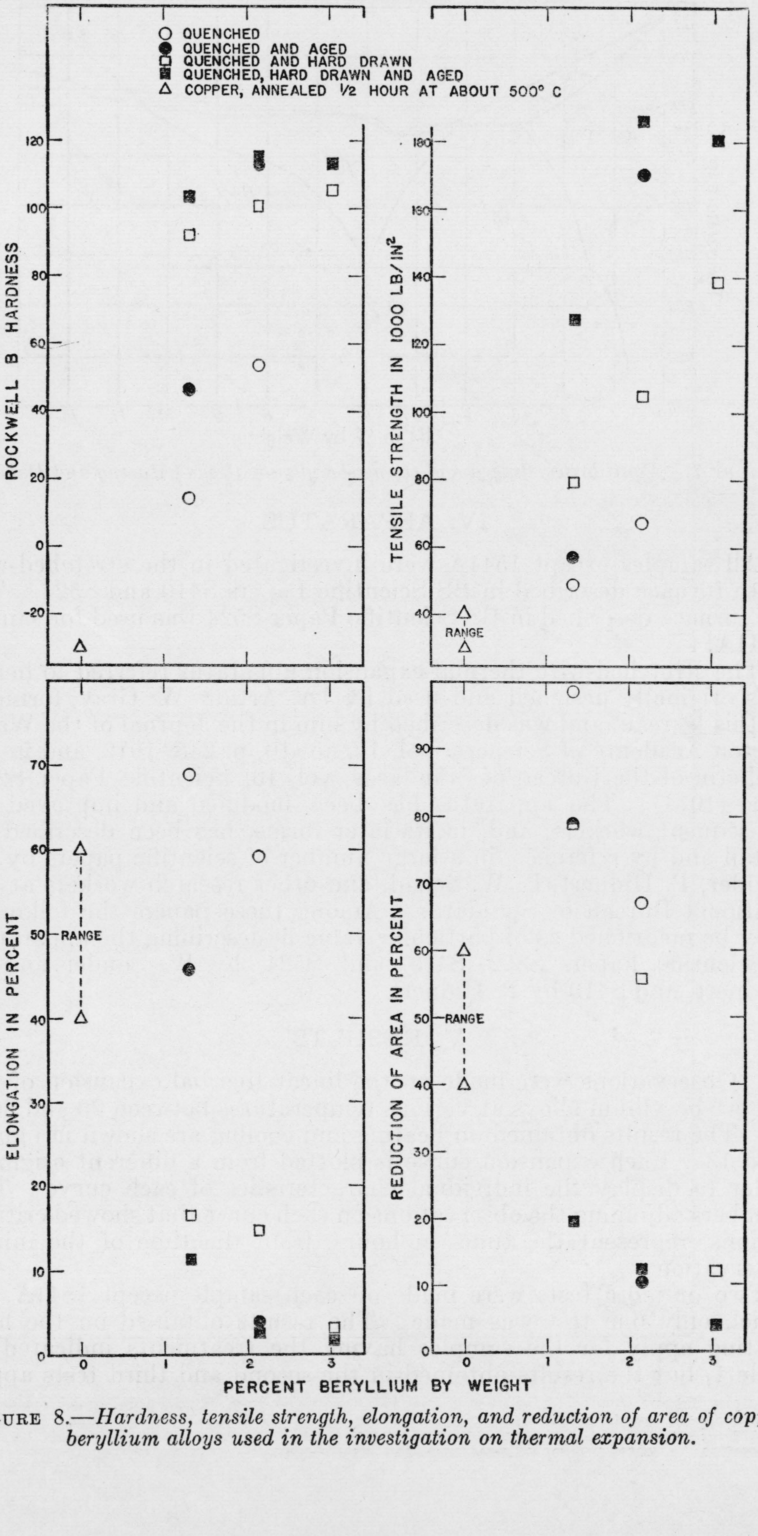

FIGURE 8.—*Hardness, tensile strength, elongation, and reduction of area of copper-beryllium alloys used in the investigation on thermal expansion.*

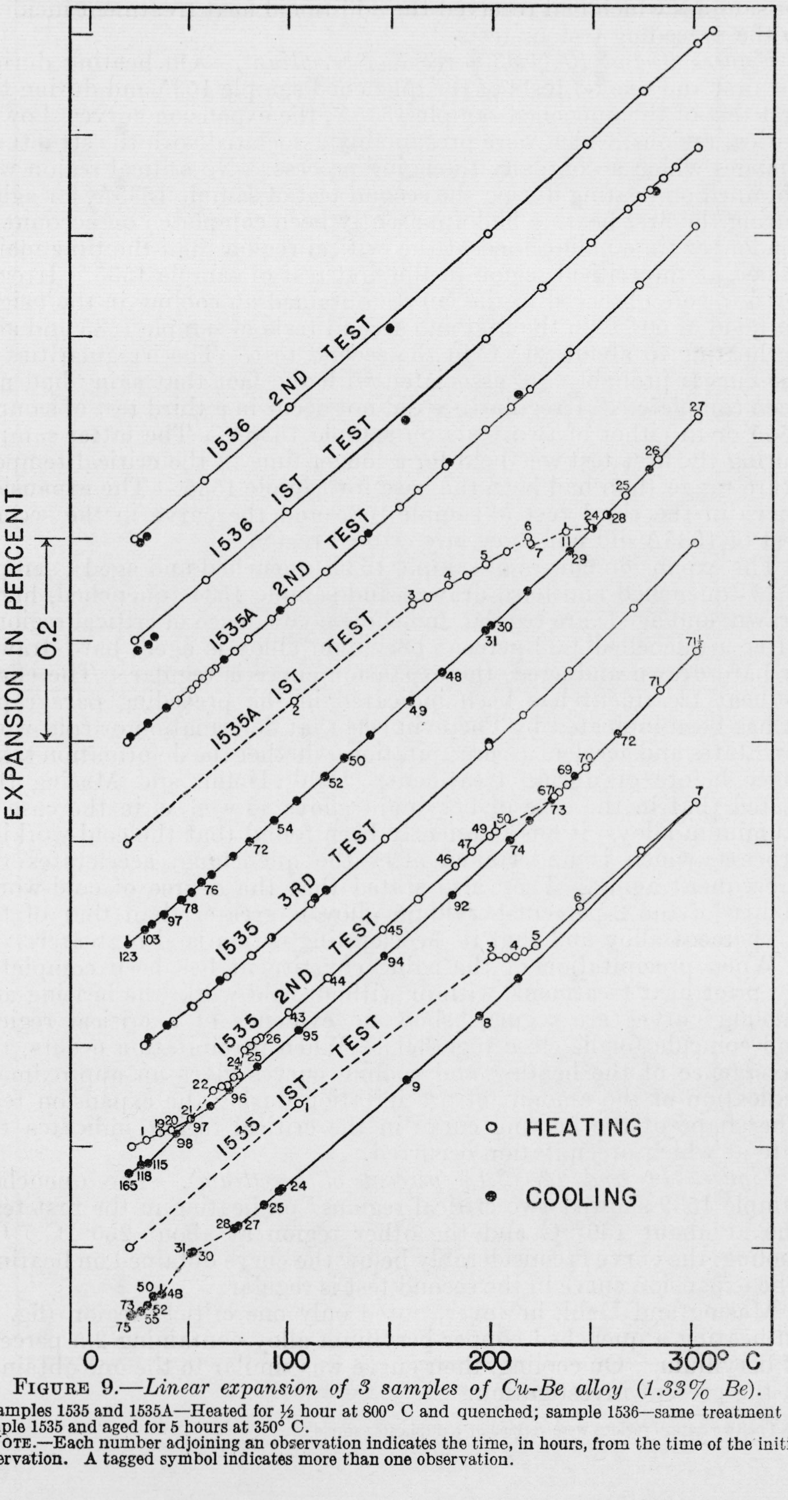

FIGURE 9.—*Linear expansion of 3 samples of Cu-Be alloy (1.33% Be).*

Samples 1535 and 1535A—Heated for ½ hour at 800° C and quenched; sample 1536—same treatment as sample 1535 and aged for 5 hours at 350° C.

NOTE.—Each number adjoining an observation indicates the time, in hours, from the time of the initial observation. A tagged symbol indicates more than one observation.

for samples which had received the additional heat treatment incident to the preceding test or tests.

Figures 9 and 10 (1.33 percent of beryllium).—On heating during the first and second tests of the quenched sample 1535 and during the first test of the quenched sample 1535A, the expansion curves showed critical regions, which were presumably associated with the structural changes which accompany the aging process. No critical region was obtained on heating during the second test of sample 1535A, for aging during the first heating had apparently been completed on account of the longer time maintained at the critical region than the time maintained at the critical region in the first test of sample 1535. Irregularities were observed in the curves obtained on cooling in the neighborhood of 50° C in the first and second tests of sample 1535 and also on heating to about 80° C in the second test. The irregularities in the curves probably are associated with the fact that aging had not been completed. Irregularities did not occur in a third test of sample 1535 or in either of two tests on sample 1535A. The latter sample during the first test was held for a longer time in the critical temperature range than had been the case for sample 1535. The expansion curve in the third test of sample 1535 and the curve in the second test of 1535A did not show any critical region.

The expansion curves of sample 1536 (quenched and aged), sample 1533 (quenched and hard-drawn) and sample 1534 (quenched, hard-drawn, and aged) are regular and show no evidence of critical regions. After a quenched 1.33-percent beryllium allloy is aged, hard-drawn, or hard-drawn and aged, the expansion curve is regular. The effect of heat treatment has been indicated in the preceding paragraph. It has been indicated by Portevin [11] that deformation or cold-work facilitates and accelerates precipitation, whether the deformation takes place before or during treatment. Dahl, Holm, and Masing [12] stated that in the case of beryllium alloys as well as in the case of aluminum alloys, it has frequently been found that the cold-working process, which is undertaken after the quenching, accelerates the subsequent aging. They also stated that the degree of cold-workability of the 2-percent-beryllium alloy is greater than that of the 2.5-percent alloy and that its accelerating action is also greater.

When precipitation of the aging constituent has been completed by prior heat treatment, with or without cold-work, the heating and cooling curves are regular, show no evidence of a critical region, and coincide (or lie close together). When precipitation occurs, the divergence of the heating and cooling curves gives an approximate indication of the amount of precipitation during the expansion test. The shape of the heating curve in the critical region indicates the rate at which precipitation occurred.

Figures 11 and 12 (2.14 percent of beryllium).—The quenched sample 1539 showed two critical regions [6] on heating in the first test, one at about 150° C and the other region at about 250° C. On cooling, the curve is considerably below the curve obtained on heating. The expansion curve in the second test is regular.

Masing and Dahl, however, noted only one critical region (fig. 1) on heating a quenched copper-beryllium alloy containing 2.5 percent of beryllium. On cooling, their curve was similar to the one obtained in the present investigation.

[6] The two critical regions were verified on a duplicate sample.

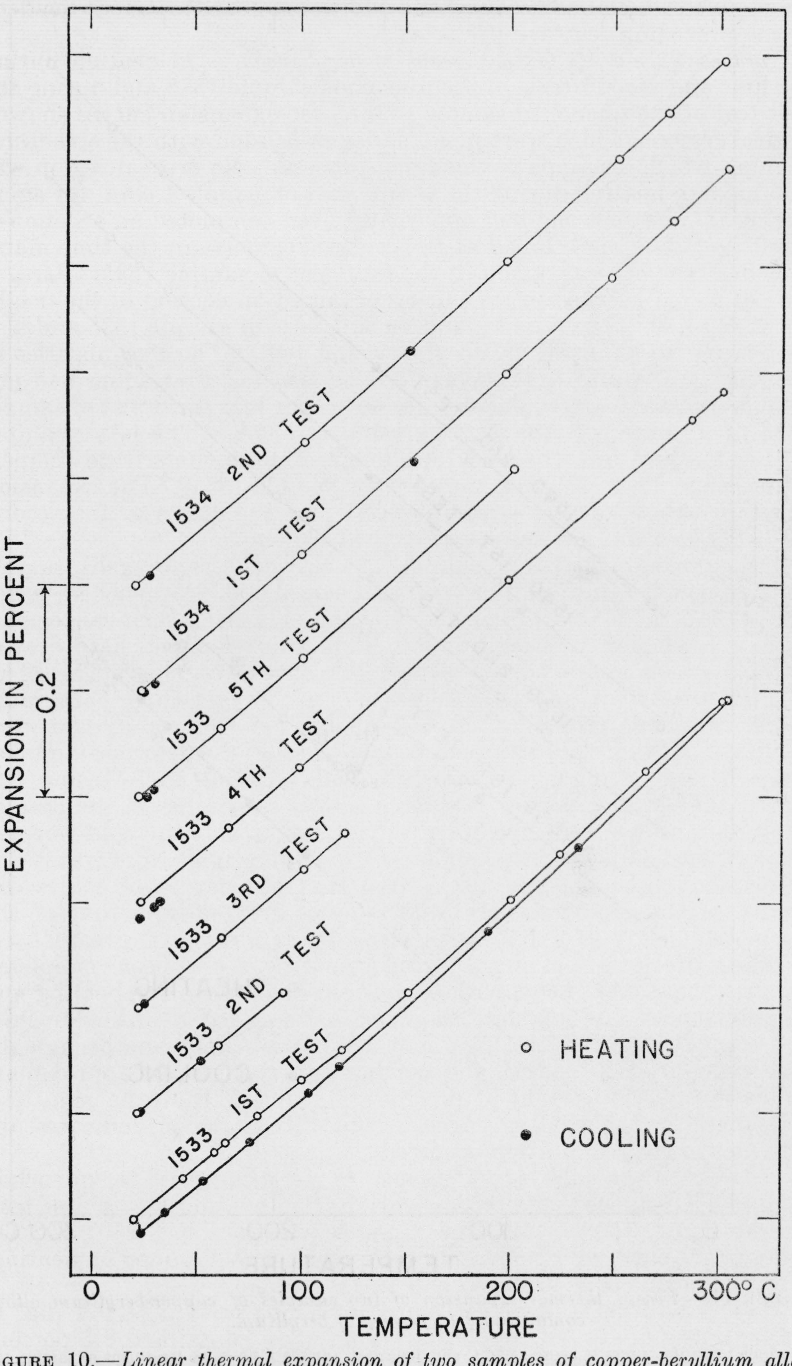

FIGURE 10.—*Linear thermal expansion of two samples of copper-beryllium alloy containing 1.33 percent of beryllium.*

Sample 1533—Quenched from 800° C and hard-drawn, with 30 percent reduction; sample 1534—same treatment as sample 1533 and aged for 5 hours at 325° C.

The tagged symbol indicates more than one observation.

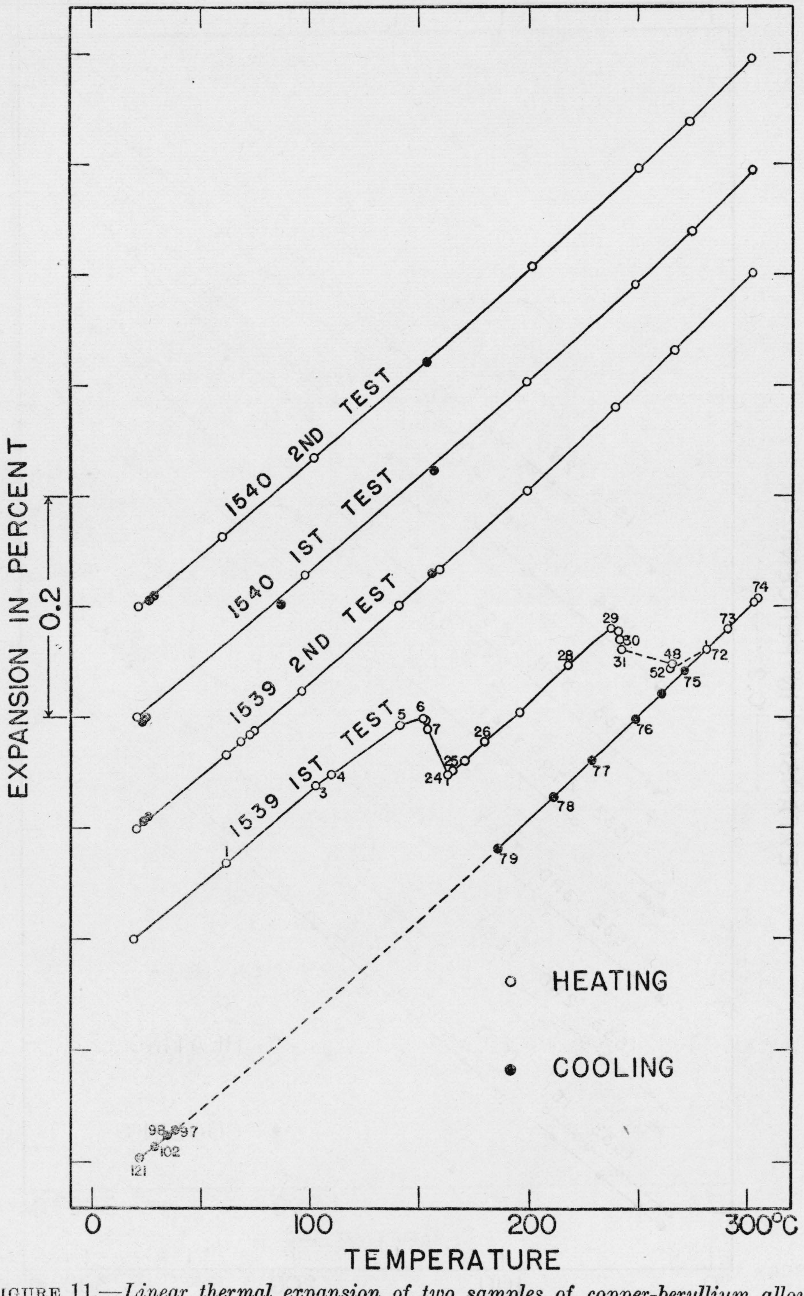

FIGURE 11.—*Linear thermal expansion of two samples of copper-beryllium alloy containing 2.14 percent of beryllium.*

Sample 1539—Heated for ½ hour at 800° C and quenched; sample 1540—same treatment as sample 1539 and aged for 2½ hours at 300° C.

NOTE.—Each number adjoining an observation in the first test of sample 1539, indicates the time, in hours, from the time of the initial observation.

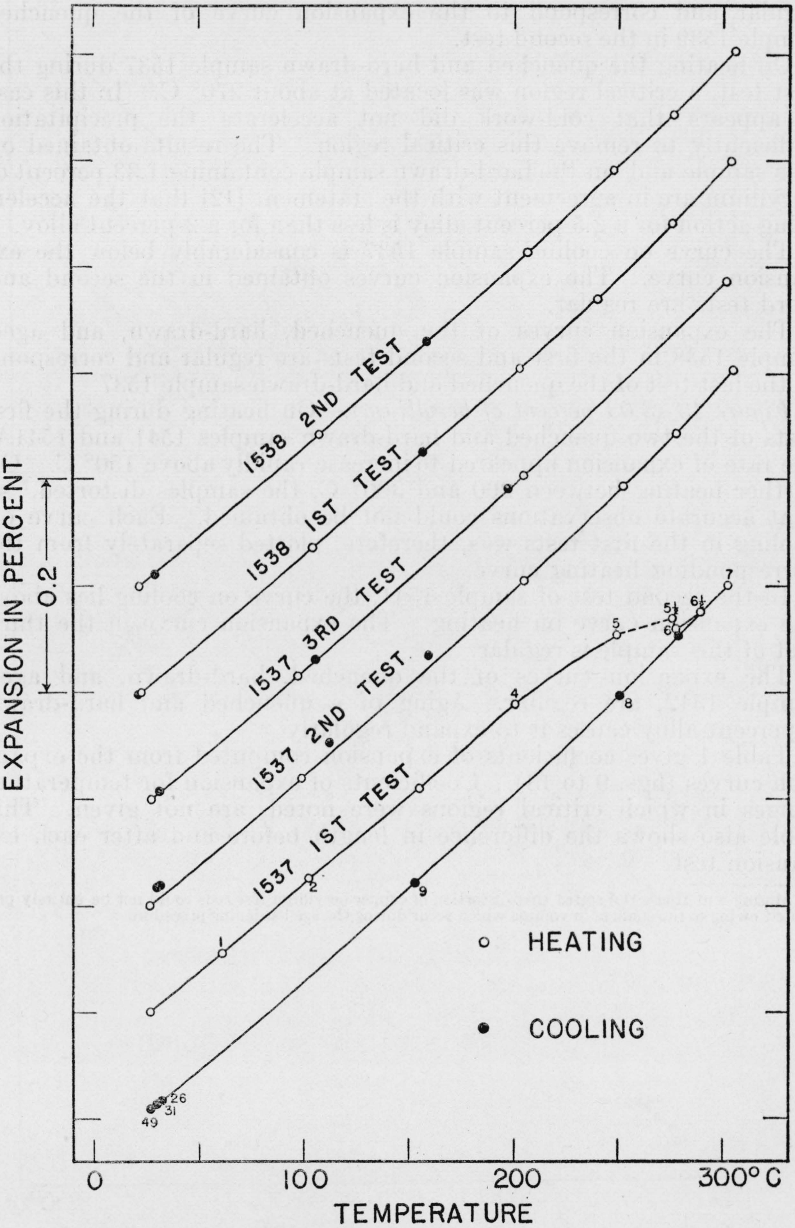

FIGURE 12.—*Linear thermal expansion of two samples of copper-beryllium alloy containing 2.14 percent of beryllium.*

Sample 1537—Quenched from 800° C and hard-drawn, with 30-percent reduction; sample 1538—same treatment as sample 1537 and aged for 2 hours at 275° C.

NOTE.—Each number adjoining an observation in the first test of sample 1537, indicates the time, in hours, from the time of the initial observation.

The expansion curves of the quenched and aged sample 1540 are regular and correspond to the expansion curve of the quenched sample 1539 in the second test.

On heating the quenched and hard-drawn sample 1537 during the first test, a critical region was located at about 270° C. In this case it appears that cold-work did not accelerate the precipitation sufficiently to remove this critical region. The results obtained on this sample and on the hard-drawn sample containing 1.33 percent of beryllium are in agreement with the statement [12] that the accelerating action for a 2.5-percent alloy is less than for a 2-percent alloy.

The curve on cooling sample 1537 is considerably below the expansion curve. The expansion curves obtained in the second and third tests are regular.

The expansion curves of the quenched, hard-drawn, and aged sample 1538 in the first and second tests are regular and correspond to the last test of the quenched and hard-drawn sample 1537.

Figure 13 (3.03 percent of beryllium).—On heating during the first tests of the two quenched and hard-drawn samples 1541 and 1541A, the rate of expansion appeared to increase rapidly above 150° C. On further heating between 200 and 300° C, the samples distorted,[7] so that accurate observations could not be obtained. Each curve on cooling in the first tests was, therefore, plotted separately from the corresponding heating curve.

In the second test of sample 1541, the curve on cooling lies above the expansion curve on heating. The expansion curve in the third test of this sample is regular.

The expansion curves of the quenched, hard-drawn, and aged sample 1542, are regular. Aging of a quenched and hard-drawn 3-percent alloy causes it to expand regularly.

Table 1 gives coefficients of expansion computed from the expansion curves (figs. 9 to 13). Coefficients of expansion for temperature ranges in which critical regions were noted, are not given. This table also shows the difference in length before and after each expansion test.

[7] Masing and Haase [13] stated that distortion of copper-beryllium test rods could not be entirely prevented owing to the changes in volume which occur during the age-hardening procedure.

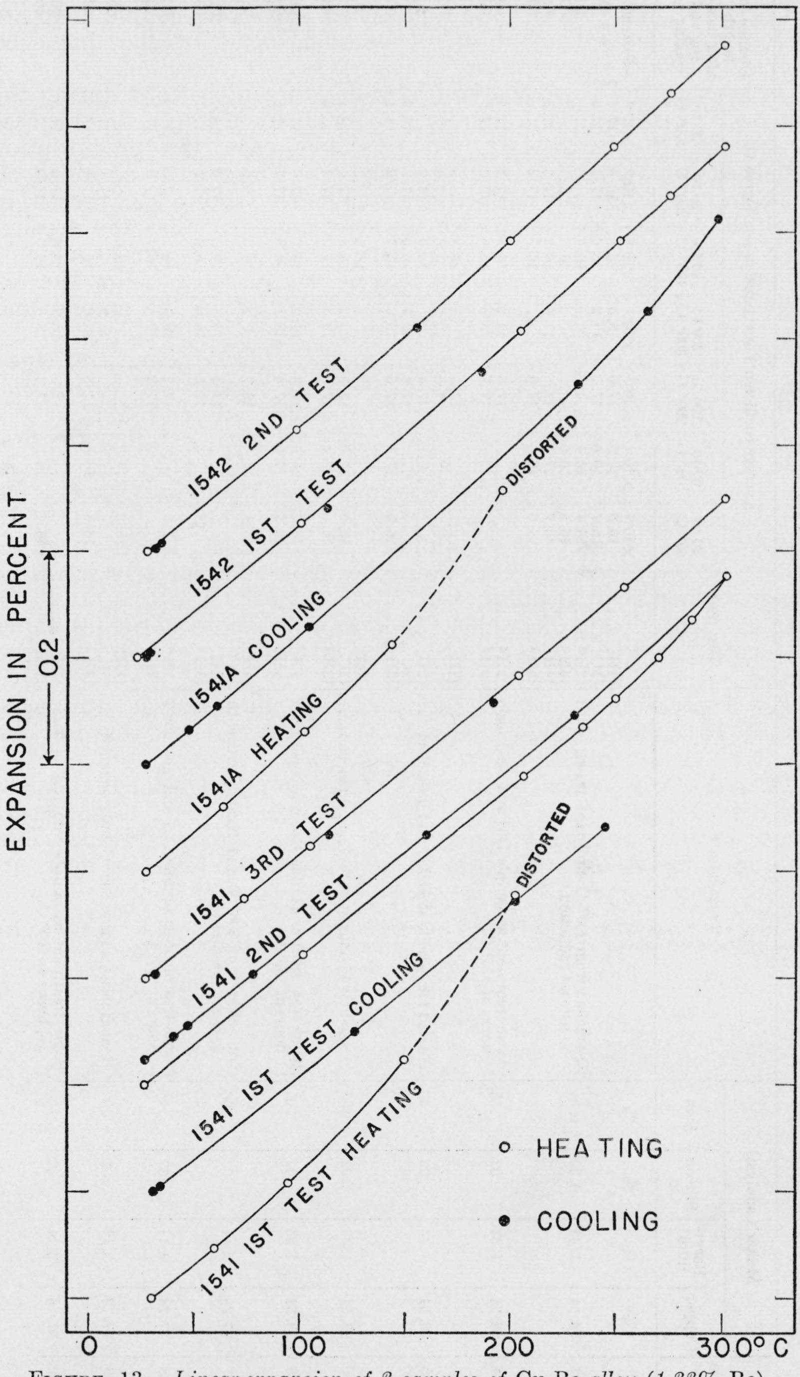

FIGURE 13.—*Linear expansion of 3 samples of* Cu-Be *alloy* (*1.33%* Be).

Samples 1541 and 1541A—Quenched from 800° C and hard-drawn, with 20 percent reduction; sample 1542—same treatment as sample 1541 and aged for 1¾ hours at 300° C.

NOTE.—The curves obtained on cooling in the first tests of samples 1541 and 1541A are not continuations of the corresponding curves obtained on heating.

TABLE 1.—*Average coefficients of linear expansion of copper-beryllium alloys*

Sample	Maker's analysis				Treatment [a]	Test no.[b]	Average coefficients of expansion per degree C							Change in length after heating and cooling [c]
	Copper	Beryllium	Silicon	Iron			20 to 60° C	60 to 100° C	100 to 200° C	200 to 300° C	20 to 100° C	20 to 200° C	20 to 300° C	
	%	%	%	%			×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	*Percent*
1533	98.54	1.33	0.02	0.03	Quenched from 800° C and hard-drawn with 30 percent reduction.	1H	16.6	16.5	17.0	18.6	16.5	16.8	17.4	−0.019 (1H, 1C)
						1C	16.7	16.6	17.7	19.2	16.6	17.2	17.9	
						2H[d]	16.4	16.4	------	------	16.4	------	------	−.000
						3H[d]	16.8	16.5	------	------	16.6	------	------	−.000
						4H	16.7	17.1	17.6	17.4	16.9	17.3	17.3	−.015
						5H[d]	16.6	16.8	17.6	------	16.7	17.2	------	−.004
1534	98.54	1.33	.02	.03	Same treatment as sample 1533 and aged for 5 hours at 325° C.	1H[d]	------	------	17.6	18.2	16.8	17.2	17.6	−.004
						2H[d]	------	------	17.7	18.3	16.8	17.3	17.6	−.002
1535	98.54	1.33	.02	.03	Heated for ½ hour at 800° C and quenched	1H	------	------	15.2	------	16.8	15.9	------	−.069 (1H, 1C)
						1C	------	------	17.6	19.7	16.6	17.2	18.1	
						2H	------	------	17.4	------	16.9	17.2	------	−.025 (2H, 2C)
						2C	------	------	17.8	20.1	16.6	17.3	18.3	
						3H[d]	16.3	17.1	17.6	19.6	16.7	17.2	18.1	+.003
1535A[e]	98.54	1.33	.02	.03	Heated for ½ hour at 800° C and quenched	1H	------	------	------	------	16.8	------	------	−.101 (1H, 1C)
						1C	16.6	17.0	17.9	20.2	16.8	17.4	18.4	
						2H[d]	16.6	17.4	17.6	19.3	17.0	17.3	18.0	+.003
1536	98.54	1.33	.02	.03	Same treatment as sample 1535 and aged for 5 hours at 350° C.	1H	16.6	16.8	17.3	17.9	16.7	17.0	17.4	−.012
						2H	16.6	17.0	17.4	18.1	16.8	17.2	17.5	−.007
1537	97.78	2.14	.02	.06	Quenched from 800° C and hard-drawn with 30-percent reduction.	1H	16.1	17.0	16.7	------	16.6	16.6	------	−.092 (1H, 1C)
						1C	------	------	------	------	------	------	17.8	
						2H	------	------	17.4	19.7	16.5	17.0	18.0	+.012
						3H[d]	------	------	17.5	18.9	16.6	17.1	17.7	+.002
1538	97.78	2.14	.02	.06	Same treatment as sample 1537 and aged for 2 hours at 275° C.	1H[d]	------	------	17.2	19.3	16.7	17.0	17.8	.000
						2H[d]	------	------	17.2	19.1	16.7	17.0	17.7	−.001
1539	97.78	2.14	.02	.06	Heated for ½ hour at 800° C and quenched	1H	16.2	17.0	------	------	16.6	------	------	−.202 (1H, 1C)
						1C	------	------	------	18.9	------	17.1	17.8	
						2H[d]	16.3	16.8	17.5	19.0	16.5	17 1	17.8	+.002
1540	97.78	2.14	.02	.06	Same treatment as sample 1539 and aged for 2½ hours at 300° C.	1H[d]	------	------	17.3	18.3	16.6	17.0	17.5	−.008
						2H[d]	16.4	16.9	17.3	18.6	16.6	17.0	17.6	−.002

1541	96.98	3.03	.02	.03	Quenched from 800° C and hard-drawn with 20-percent reduction.	1H	15.9	17.9	----	----	16.9	----	----	----
						1C	----	----	15.9	----	15.4	15.7	----	
						2H	----	----	15.9	19.2	16.4	16.1	17.2	+.024
						2C	15.7	15.8	----	----	15.7	----	16.4	
						3H[d]	16.0	15.8	16.0	17.0	15.9	16.0	16.4	−.003
1541A[f]	96.98	3.03	.02	.03	Quenched from 800° C and hard-drawn with 20-percent reduction.	1H	16.4	18.2	----	----	17.3	----	----	----
						1C	16.3	17.1	----	----	16.7	----	18.9	
1542	96.98	3.03	.02	.03	Same treatment as sample 1541 and aged for 1¾ hours at 300° C.	1H[d]	----	----	17.3	17.9	16.3	16.9	17.3	−.006
						2H[d]	----	----	17.4	18.1	16.3	16.9	17.4	−.003

[a] By American Brass Co.
[b] H indicates heating and C cooling.
[c] Determined from the expansion curve on heating and the contraction curve (or observations) on cooling. The plus (+) sign indicates an increase in length and the minus (−) sign a decrease in length.
[d] Observations on cooling close to expansion curve on heating.
[e] Cut from same rod as sample 1535.
[f] Cut from same rod as sample 1541.

Figure 14 indicates the coefficients of expansion [8] of the copper-beryllium alloys for three temperature ranges. Values for copper [14] are included. This figure shows the effects of beryllium content,

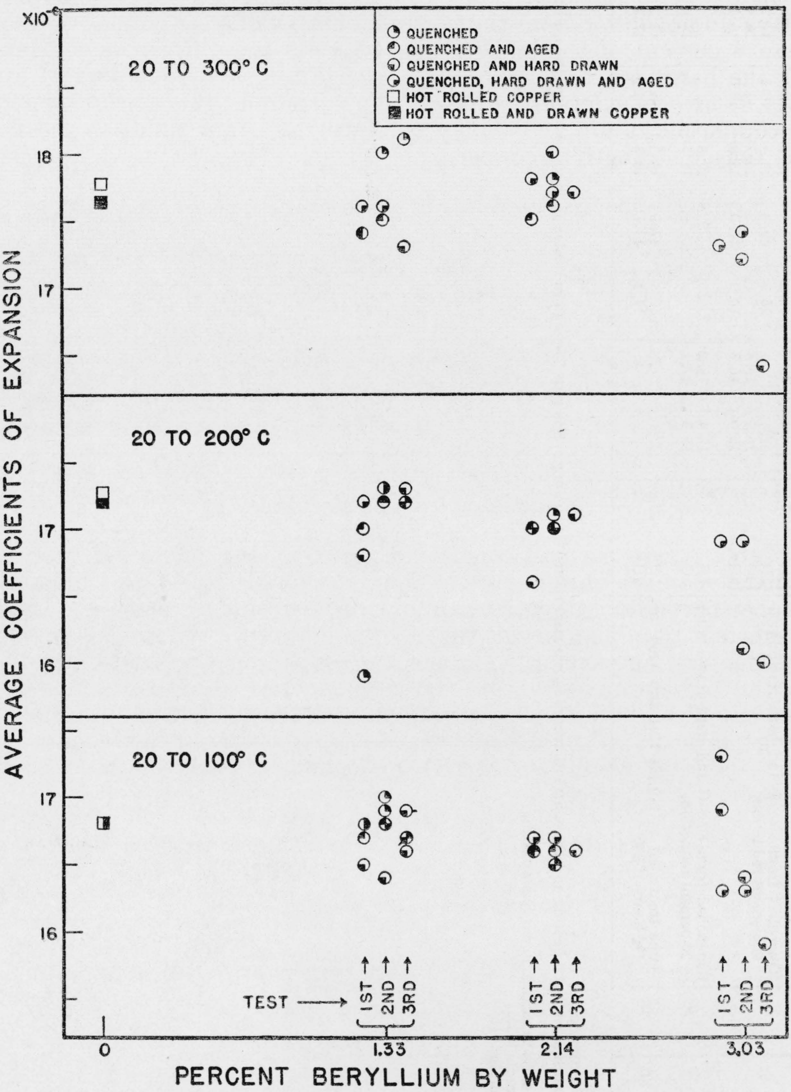

FIGURE 14.—*Effects of beryllium content, cold-work, and heat treatment on the coefficients of expansion of copper-beryllium alloys.*

NOTE.—A tagged symbol indicates a value obtained in a fourth or fifth test.

cold-work, heat treatment, etc., on the coefficients of expansion of these alloys. There is no simple relation between the coefficients of expansion, chemical composition, heat treatment, etc. The differences in the coefficients of expansion between the first and succeeding

[8] On heating.

tests are attributed to changes in the alloys on account of the heat treatments incident to the tests.

Table 2 gives the ranges of the coefficients of expansion indicated in figure 14. The coefficients of expansion of the copper-beryllium alloys do not differ from the corresponding value for copper by more than 8 percent of the latter value, whereas the differences indicated for the hardness, tensile strength, elongation, and reduction of area (fig. 8) are considerably greater. For example, the tensile strength of copper-beryllium alloys may be more than four times as great as the tensile strength of copper.

TABLE 2.—*Ranges of coefficients of expansion of copper-beryllium alloys* [a]

Beryllium content	Average coefficients of expansion [b] per degree C		
	20 to 100° C	20 to 200° C	20 to 300° C
Percent	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
0.00	16.8 (2)	17.2 to 17.3 (2)	17.6 to 17.8 (2)
1.33	16.4 to 17.0 (14)	15.9 to 17.3 (11)	17.3 to 18.1 (8)
2.14	16.5 to 16.7 (9)	16.6 to 17.1 (8)	17.5 to 18.0 (7)
3.03	15.9 to 17.3 (6)	16.0 to 16.9 (4)	16.4 to 17.4 (4)

[a] This table does not include coefficients of expansion for temperature ranges in which critical regions were observed (fig. 9 to 13).
[b] Each number in parenthesis represents the number of determinations.

Table 3 gives several coefficients of expansion computed from the expansion curve obtained by Masing and Dahl (fig. 1) on a quenched copper-beryllium alloy containing 2.5 percent of beryllium. The coefficient obtained for the range from 300 to 20° C on cooling, is in satisfactory agreement with the corresponding coefficient obtained in the present investigation on the quenched alloy containing 2.14 percent of beryllium. However, the coefficient of expansion for the range from 20 to 100° C on heating is appreciably lower than the corresponding coefficient for the quenched 2.14-percent alloy of the present investigation.

TABLE 3.—*Coefficients of expansion of a quenched copper-beryllium alloy containing 2.5 percent of beryllium*

[Computed [a] from data by Masing and Dahl [5]]

Temperature range	Average coefficient of expansion per degree C
°C	$\times 10^{-6}$
20 to 100	14.2
100 to 200	15.4
20 to 200	14.9
300 to 20	[b] 18.2

[a] By Hidnert.
[b] From curve on cooling.

Table 4 shows the length changes, the densities before and after the expansion tests, and the volume changes of the samples of copper-beryllium alloys. The changes in length, density, and volume noted for both the quenched and the hard-drawn samples are somewhat larger than the small changes noted for the aged alloys. The changes in length, volume, and density of a quenched copper-beryllium alloy depend upon the temperature and the time of aging. Masing and Dahl [5] obtained a volume change of 0.60 percent on a quenched copper-beryllium alloy containing 2.5 percent of beryllium, after

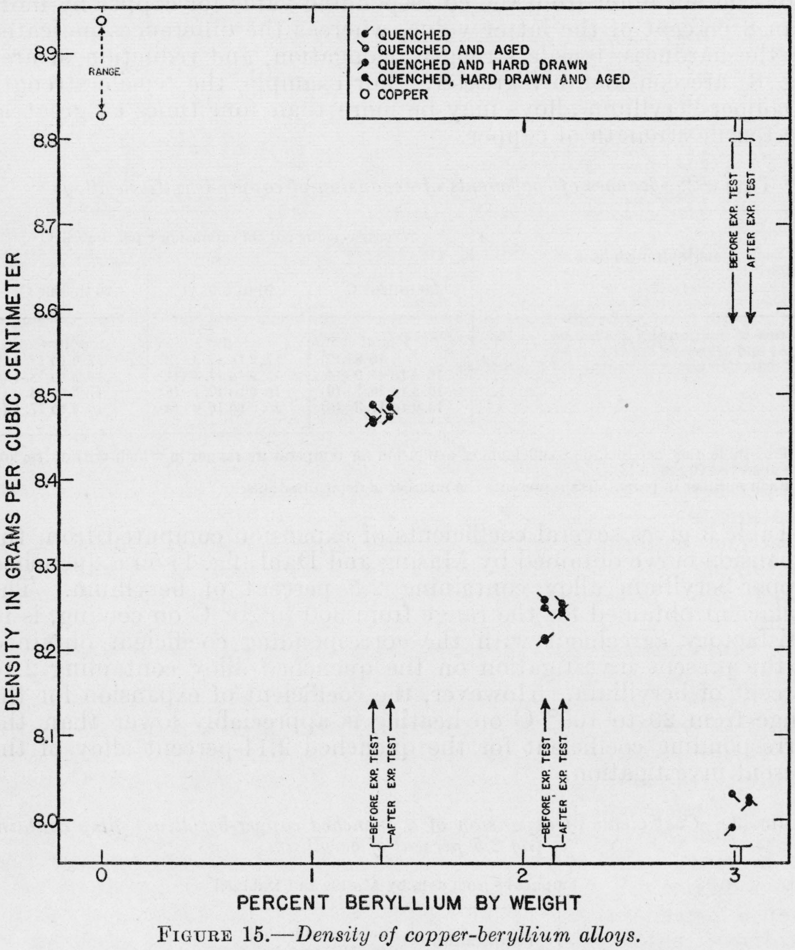

FIGURE 15.—*Density of copper-beryllium alloys.*

heating 78 hours at 250° C. They concluded that the change in volume is determined only by the quantity of γ crystals separated out and not by the form of the precipitate, as is the case with the hardness and electrical conductivity.

Figure 15 shows the densities of the samples indicated in table 4. The range of densities for copper, taken from BS Circular 73 [15], is included in the figure. The data show that the density of copper-beryllium alloys decreases with increase of beryllium.

TABLE 4.—*Changes in length, density, and volume of copper-beryllium alloys*

Sample	Beryllium content	Treatment	Change in length [a]	Density at 25° C: Before expansion tests [b]	Density at 25° C: After expansion tests [c]	Change in volume [d]
	Percent		*Percent*	g/cm³	g/cm³	*Percent*
1535	1.33	Quenched	[e]−0.09	8.468	8.492	−0.28
1535A	1.33	Quenched	−.10	8.466	8.492	−.30
1536	1.33	Quenched and aged	−.02	8.472	8.474	−.03
1533	1.33	Quenched and hard-drawn	−.04	8.471	8.475	−.05
1534	1.33	Quenched, hard-drawn, and aged	−.01	8.488	8.485	+.04
1539	2.14	Quenched	−.20	8.212	8.246	−.41
1540	2.14	Quenched and aged	−.01	8.260	8.254	+.07
1537	2.14	Quenched and hard-drawn	−.08	8.213	8.246	−.40
1538	2.14	Quenched, hard-drawn, and aged	−.00	8.250	8.243	+.09
1541	3.03	Quenched and hard-drawn	([f])	7.991	8.020	−.36
1542	3.03	Quenched, hard-drawn, and aged	−.01	8.031	8.025	+.07

[a] Each value is the algebraic sum of the changes in length (noted in the last column of table 1) for each sample.
[b] Density determined by W. S. Clabaugh of this Bureau.
[c] Density determined by L. J. Clark of this Bureau.
[d] Computed from the density before and after the expansion tests. The plus (+) sign indicates an increase in volume and the minus (−) sign a decrease in volume.
[e] At end of second expansion test.
[f] Distortion occurred during the first expansion test.

VI. SUMMARY

1. Data have been obtained on the linear thermal expansion of copper-beryllium alloys of three compositions and various heat treatments.

2. The expansion curves of quenched copper-beryllium alloys containing 1.33 and 2.14 percent of beryllium, showed critical regions which may be associated with structural changes accompanying aging.

3. Stabilization of copper-beryllium alloys may be accomplished either by tempering or by cold-working.

4. There is no simple relation between the coefficients of expansion, chemical composition, and heat treatment of the copper-beryllium alloys investigated. Figure 14 indicates the effects of beryllium content, cold-work, and heat treatment on the coefficients of expansion of these alloys.

5. Table 2 gives the ranges of the coefficients of expansion obtained on heating. The coefficients of expansion of the copper-beryllium alloys do not differ from the corresponding value for copper by more than 8 percent of the latter value, whereas the differences for the hardness, tensile strength, elongation, and reduction of area (fig. 8) are considerably greater. For example, the tensile strength of copper-beryllium alloys may be more than four times as great as the tensile strength of copper.

6. The changes in length, density, and volume noted for both the quenched and the hard-drawn alloys are somewhat larger than the small changes noted for the aged alloys (table 4). The changes in length, volume, and density of quenched copper-beryllium alloys depend upon the temperature and the time of aging.

7. The density of copper-beryllium alloys decreases with increase of beryllium (fig. 15).

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