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DIFFERENTIAL THERMAL-EXPANSION EFFECTS ON BRAZED JOINTS

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September 4, 1953

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ABSTRACT

Differential thermal-expansion effects in brazed joints involving Type 310 stainless steel and GE-62 brazing alloy were investigated. The work included dilation and modulus-of-elasticity measurements using homogeneous cast specimens and observations on bimetallic cantilevers made of the two constituents. No anomalies were found, although there were irregularities in the expansion of the brazing alloy which were ascribed to a solubility phenomenon. The elastic modulus of the brazing alloy was determined.

Cantilever deflections with temperature and with load were measured, and the results were interpreted using equations which treat the specimens as true bimetals consisting of two homogeneous components. The difference in thermal-expansion coefficients obtained in this way from the temperature-deflection data was consistent with the dilation measurements. The load measurements yielded an average elastic modulus for the bimetal which was about two-thirds of what would have been expected from knowledge of the components. This discrepancy probably arose from porosity which was observed in the braze component.

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INTRODUCTION

This work pertains to reactor design in which Type 310 stainless steel fuel elements would be brazed with GE-62 brazing alloy. Inasmuch as reactors may operate at temperatures up to 1800 F, design engineers have been concerned with the magnitude of stresses in the brazed joints arising from differential thermal expansion of the braze and fuel plates.

In regard to this problem, it was decided that linear thermal-expansion measurements of the separate materials, a determination of the elastic modulus of the brazing alloy, and differential-expansion studies using stainless steel - GE-62-alloy bimetal cantilevers should give useful information. It was recognized that such data might not permit accurate stress calculations in a complex reactor design, but that the information would be fundamental.

The problem of stress determinations for a stainless steel - braze joint would be complicated by the presence of a diffusion zone between the two materials, of uncertain depth and composition. Moreover, the characteristics of this diffusion zone could vary with time at temperature. For this reason, the linear-expansion-measuring program included different mixtures of stainless steel and braze to determine whether anomalies in expansion coefficient existed.

The most important work with bimetal cantilevers gave data on free deflection with temperature change. When interpreted as if the bimetal consisted of two homogeneous components, these data would give values for an effective difference in thermal-expansion coefficient. A comparison of this difference with the difference obtained by dilation measurements could indicate whether or not the actual system approximated an ideal bimetal.

In addition, the load required to return the cantilever to its original position was measured, since this gives a direct measure of the bending moment associated with the thermal stresses. In principle, this measurement could give a second check concerning the accuracy of treating the cantilever as an ideal bimetal, since the ratio of component thicknesses enters in a new way. However, this point is not important in practice if the Young's modulus values of the components are nearly equal and the thicknesses not too different, as in the present work. In fact, the information obtained from the load measurements here reduces to a rather reliable determination of the average Young's modulus for the two components which may be compared with values for the materials in bulk.

EXPERIMENTAL WORK

Dilation Measurements

Method

Specimens for linear-expansion measurements were prepared by arc melting the commercially pure metals under a helium atmosphere in a water-cooled copper crucible. To insure homogeneity, the alloys were remelted several times. The resultant bars were machined to cylinders, nominally 3/8 in. in diameter and 3 in. in length. Table 1 shows nominal analyses of the specimens measured.

Linear-dilation measurements were made in a recording dilatometer at pressures of approximately 5×10^{-5} mm mercury. An automatic temperature control provided a maximum heating and cooling rate of 5-1/2 F per min. Each specimen was given at least two thermal cycles, each cycle consisting of heating and cooling from approximately 70 to 1800 F.

Results

Figure 1 shows average linear-expansion values of two thermal cycles plotted as mean values from 68 F to the temperature shown. In general, the heat treatment of materials high in braze increased the expansion coefficient,

TABLE 1. NOMINAL ANALYSES OF SPECIMENS USED FOR THERMAL-LINEAR-EXPANSION MEASUREMENTS

Specimen	GE-62 Braze, wt %	Type 310 Stainless Steel, wt %	Condition
AC-1	100	0	As cast
AC-1-A	100	0	As cast
AC-1-B	100	0	As cast
AC-1-C	100	0	As cast
HT-1	100	0	Heat treated[a]
AC-2	75	25	As cast
HT-2	75	25	Heat treated[a]
AC-3	50	50	As cast
HT-3	50	50	Heat treated[a]
AC-4	25	75	As cast
HT-4	25	75	Heat treated[a]
AC-5	0	100	As cast
HT-5	0	100	Heat treated[a]

(a) Heat treated in vacuum at 1800 F for 24 hr.

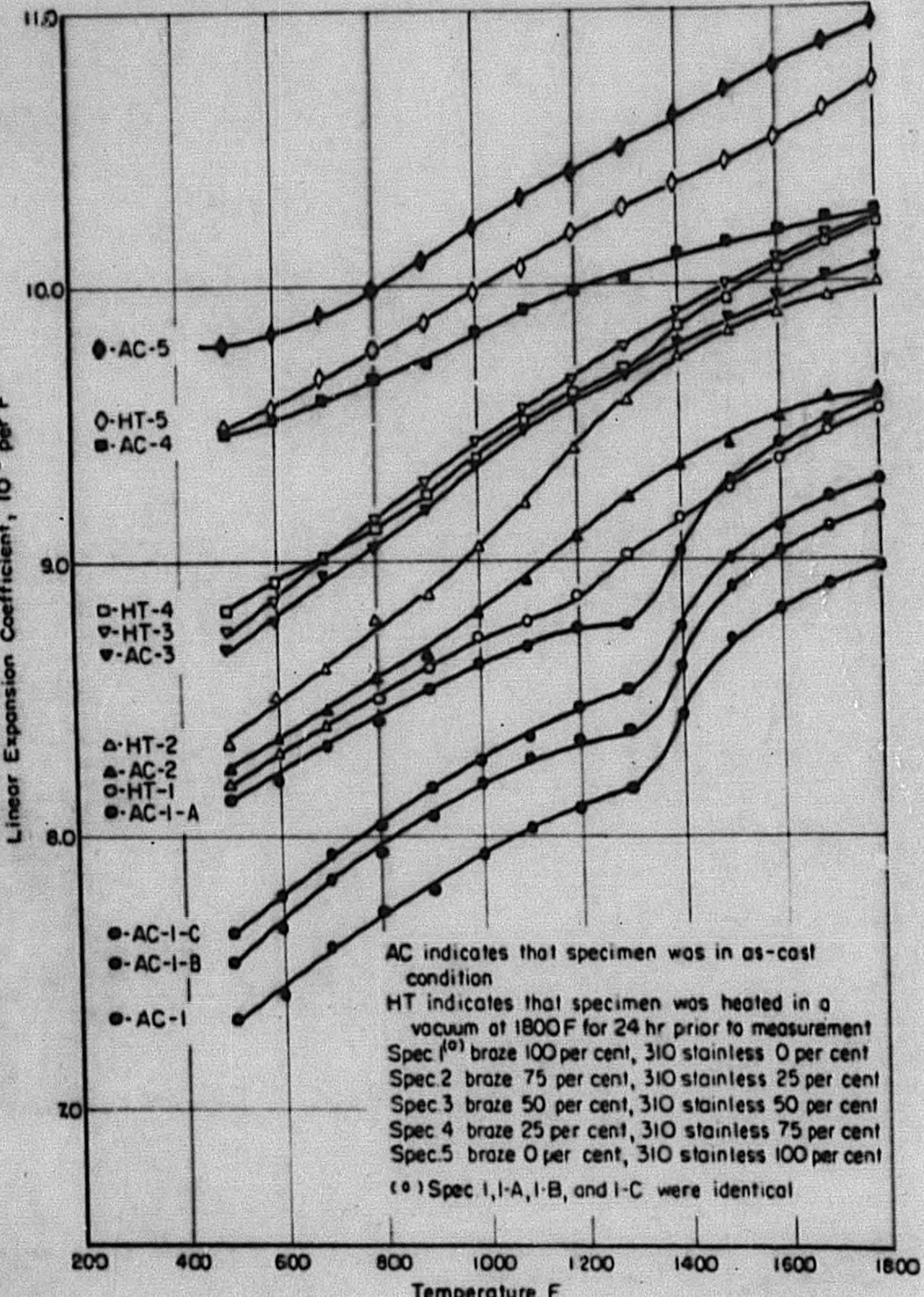

FIGURE 1. MEAN LINEAR EXPANSION COEFFICIENTS ON GE-62 BRAZE, TYPE 310 STAINLESS STEEL, AND ALLOYS OF THE TWO
Coefficients plotted are mean values between 68 F and temperatures shown. Each curve is an average of four curves from two thermal cycles (each cycle consisting of a heating and a cooling curve) for each specimen.

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whereas, for materials high in stainless steel, the heat treatment reduced the expansion coefficient.

It will be noted that the expansion-coefficient curves for Specimens AC-1, AC-1-A, AC-1-B, and AC-1-C show irregularities near 1300 F. This irregularity was almost entirely in the heating part of the first thermal cycle. This is shown in Figure 2, which presents the four curves (heating and cooling of two thermal cycles) which were averaged to give the plots for Specimens AC-1 and AC-1-A in Figure 1. The irregularity was not reversible over the temperature range investigated. Inasmuch as the specimens were in a cast and quenched condition, it appeared that phase precipitation during the first cycle could account for the irregularities near 1300 F.

To check this possibility, a short investigation was undertaken. Several GE-62 brazing-alloy specimens were solution treated at 1900 F for 5 hr, water quenched, and aged for 5 hr at 700, 900, 1110, 1300, 1500, and 1700 F. The results of both hardness and metallographic examinations of these specimens are shown in Figures 3 and 4. The increase in hardness and the visible precipitate over the temperature range of interest would tend to substantiate this explanation for the irregularities observed in dilation.

Also, it will be noted that there is considerable spread in mean linear-expansion-coefficient values for the four as-cast brazing-alloy specimens. The exact reason for this variation is not known. Chemical analyses of the ends of Specimens AC-1 and AC-1-A failed to show any segregation. Figure 2 shows that an unusually high expansion coefficient was obtained for the cooling half of the first cycle of Specimen AC-1-A which would increase the averaged coefficient for this specimen. It would appear that dimensional changes in the as-cast brazing alloy during the thermal cycling might have been responsible for the wide range of dilation values.

Modulus of Elasticity Measurements

Knowledge of the elastic moduli of the component alloys is of interest both for the interpretation of the cantilever measurements and for any use of the thermal-expansion data in the calculation of thermal stresses in reactor parts. The modulus of Type 310 stainless steel at room temperature is given in the literature as 29 to 30 x 10^6 psi* and has been determined dynamically to 1800 F**. The modulus of the other component, GE-62 brazing alloy, was unknown.

*Zapffe, C. A., Stainless Steels, ASM, 1949, p 220.

**Andrews, C. W., "Effect of Temperature on the Modulus of Elasticity", Metal Progr., 58, (1), 85-89, 96, 98, 100 (1950).

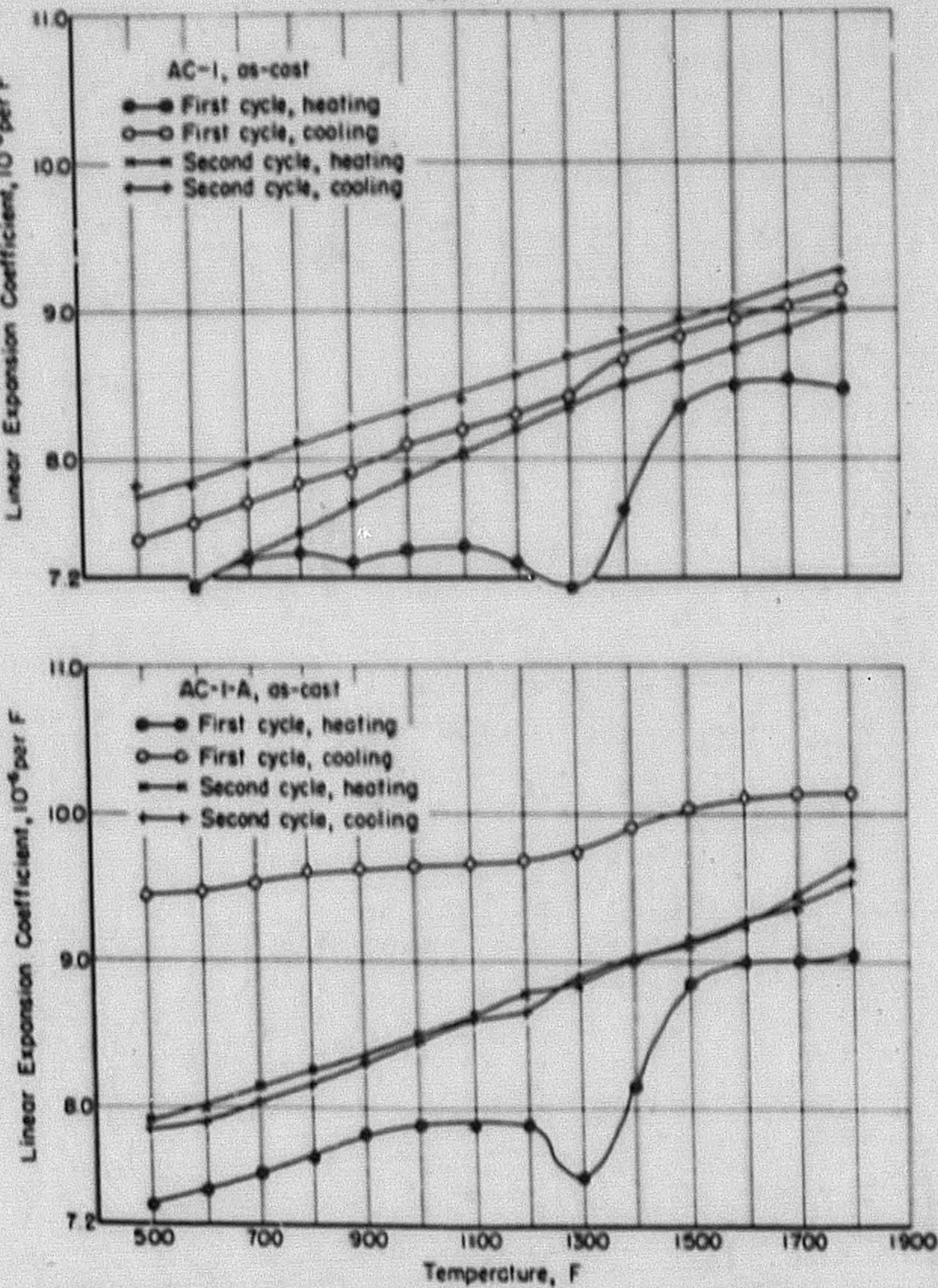

FIGURE 2. MEAN LINEAR EXPANSION MEASUREMENTS ON GE-62 BRAZE IN AS CAST CONDITION

Coefficients are mean values between 68 F and the temperatures shown.

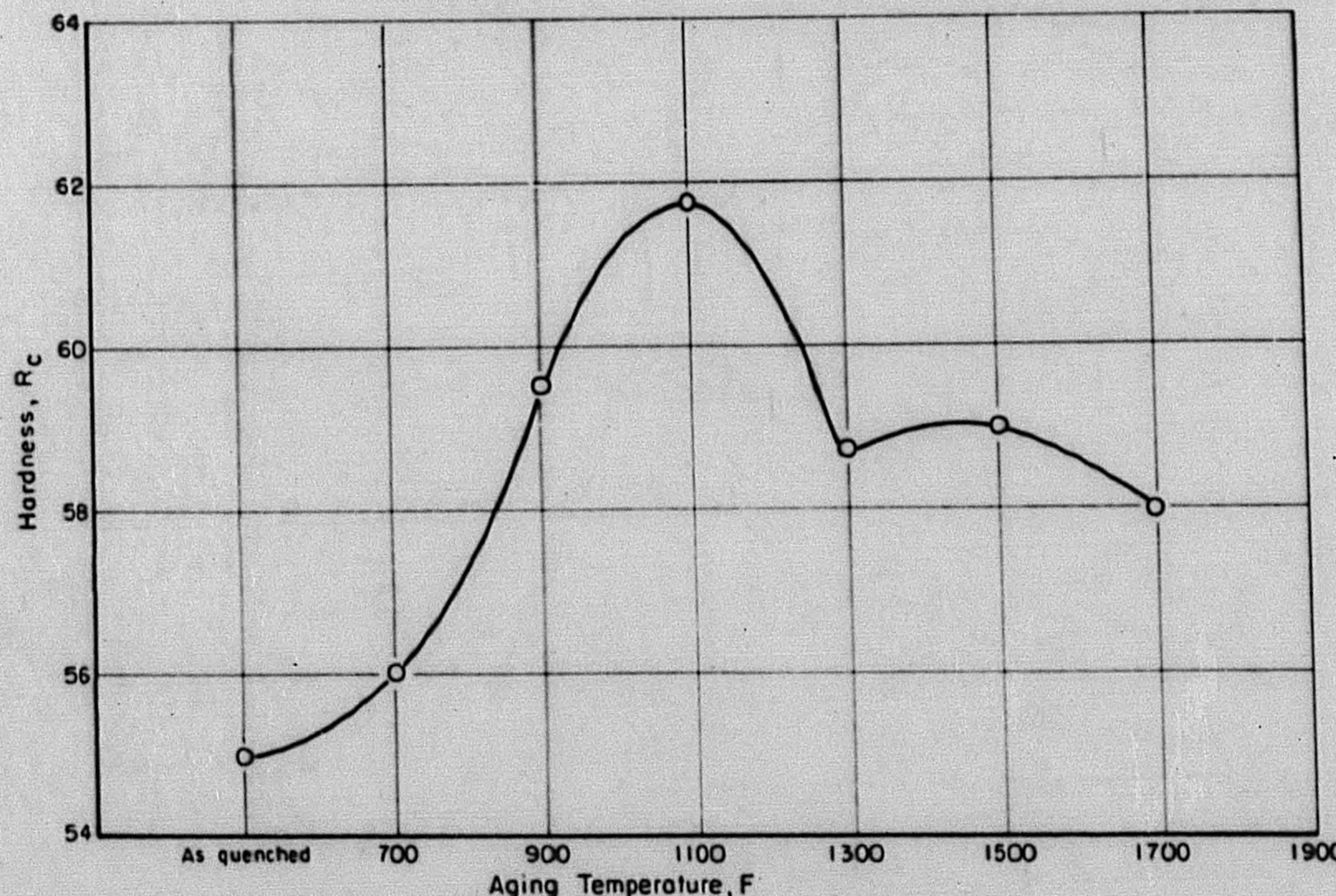

FIGURE 3. AGING EFFECTS IN GE-62 BRAZING ALLOY
Specimens solution treated at 1900 F for 5 hr, water quenched, and aged for 5 hr at various temperatures

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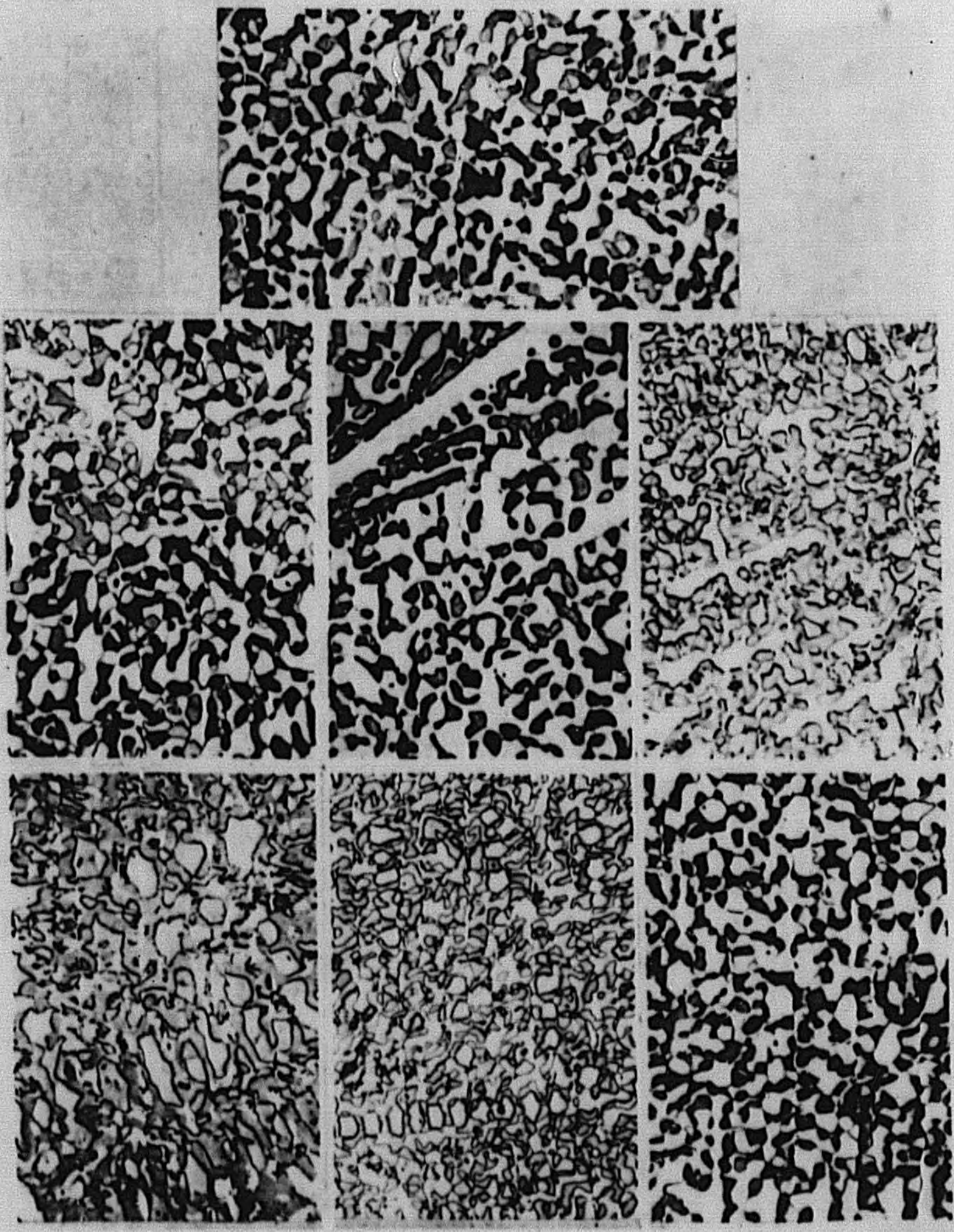

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FIGURE 4. GE-62 BRAZING ALLOY, SOLUTION TREATED AT 1900 F FOR 5 HR, QUENCHED, AND AGED AT VARIOUS TEMPERATURES

Top to bottom, left to right: as quenched, aged at 700, 900, 1100, 1300, 1500, and 1700 F

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The modulus of the brazing alloy was determined over the temperature range 70 to 1700 F dynamically and, at room temperature, by the usual tensile method. The alloys used for both types of test were prepared by arc melting in a water-cooled copper crucible under a partial pressure of helium using commercially pure nickel, electrolytic chromium, and lump silicon metal.

Dynamic Modulus

The dynamic modulus of elasticity in bending versus temperature was determined on cylindrical specimens 5 in. long and 1/4 in. in diameter. Four specimens were tested, two in the as-cast condition and two after a 24-hr anneal at 1800 F in vacuum. Measurements were taken in a horizontal tubular resistance furnace at temperatures up to 1700 F in an argon atmosphere. Results of these tests indicate that the heat-treated specimens had a slightly higher modulus at the lower temperatures than the as-cast specimens. Average dynamic-moduli values are given in Figure 5.

Tensile Modulus

The modulus of elasticity in tension of GE-62 brazing alloy was determined at room temperature as a check on dynamic-modulus values. The specimen used for this purpose was a 3 x 0. 50 x 0. 100-in. plate in the as-cast condition. Measurements were made using two SR-4 Type A-7 strain gages, one on each side of the specimen. A modulus value of about 26,000,000 psi was obtained in this manner. This value closely checked the room-temperature modulus obtained dynamically.

Bimetal Cantilevers

Fabrication

Bimetal cantilevers were prepared of Type 310 stainless steel and GE- brazing alloy for temperature-deflection and load-deflection tests. Both the final use as a simulated joint and the brittleness of the brazing alloy precluded fabrication by solid-phase bonding. Melting methods which would not require subsequent surface machining were investigated, but the resultant bimetals were unsatisfactory because of warpage, surface defects, or an insufficiently thick layer of brazing alloy. As a result of these experiments, it appeared necessary to cast (or braze) the brazing alloy on a relatively thick piece of stainless steel and grind to suitable dimensions, even though the stress pattern in the material might be altered thereby.

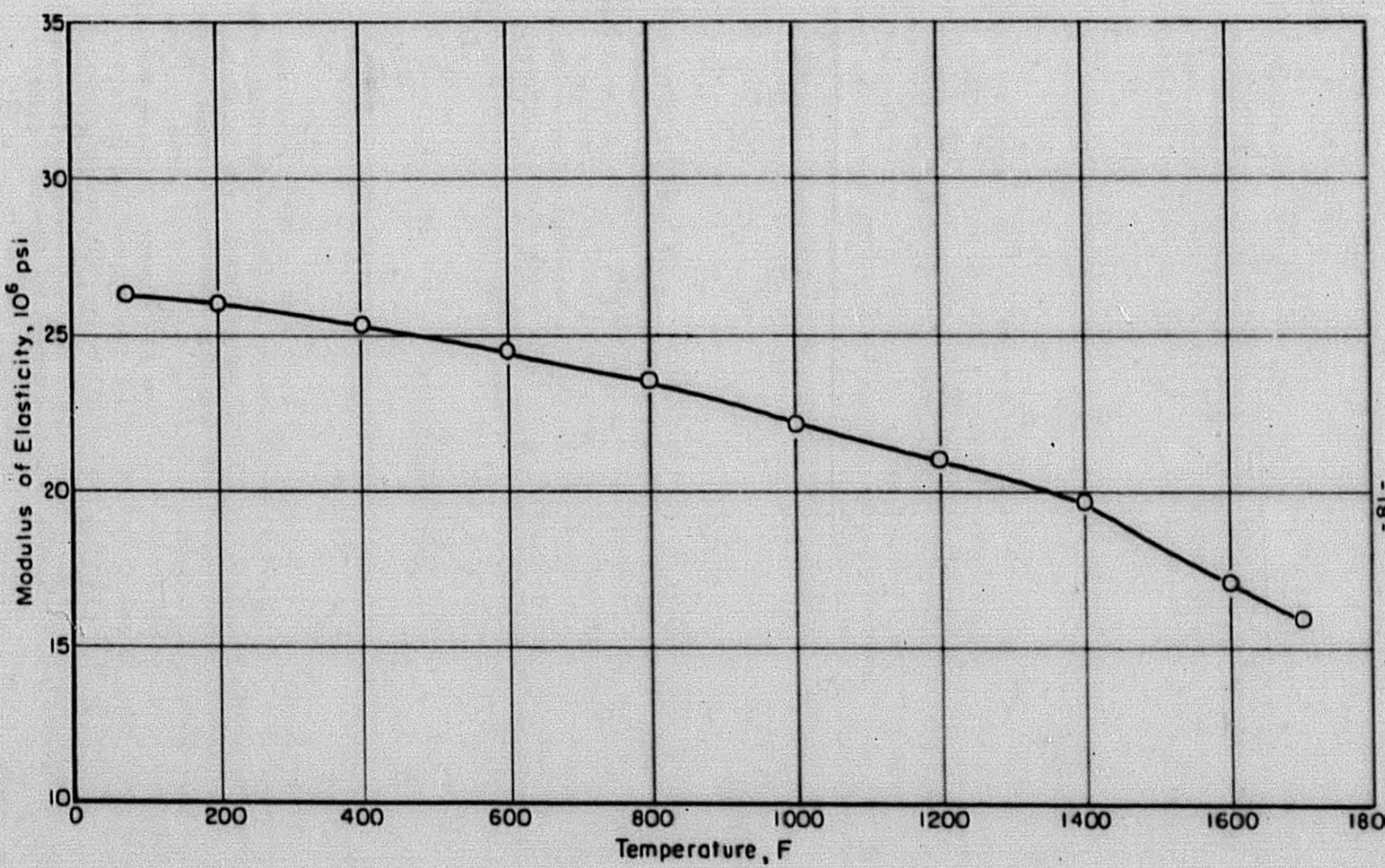

FIGURE 5. AVERAGE DYNAMIC MODULUS OF ELASTICITY IN BENDING VERSUS TEMPERATURE FOR GE-62 BRAZING ALLOY

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For this purpose, a stainless steel plate with a machined depression of uniform depth was used. Over-all dimensions of the plate were 3 x 4.5 x 0.150 in. with a depression of 2.5 x 2.75 x 0.050 in. About 30 g of minus 325-mesh GE-62 alloy was uniformly distributed in the depression and held for 20 min at 2175 F in a purified hydrogen atmosphere. The plate was only slightly warped after brazing, and the brazing alloy flowed well into the depression, with the exception of several isolated areas near the edge. The specimen was then ground to 0.040 in. ±0.001 in. total thickness, with braze and basis-metal layers approximately 0.020 in. each.

Figure 6 shows the constant-stress cantilever as cut from the bimetal stock with the aid of a filing and drilling jig. The cantilevers were designed for constant stress over the portion where the tapered sides would, if extended, intersect the hole or the point of load application. Blocks were clamped on the ends to immobilize that section of the cantilever that was not uniformly stressed when loaded. Only three of these cantilevers were made, as it was decided to terminate this investigation on the completion of testing the specimens on hand. For testing purposes, the specimens were numbered from one to three, but subsequent examination of Cantilever 1 showed the components to be too irregular in thickness for reliable test results.

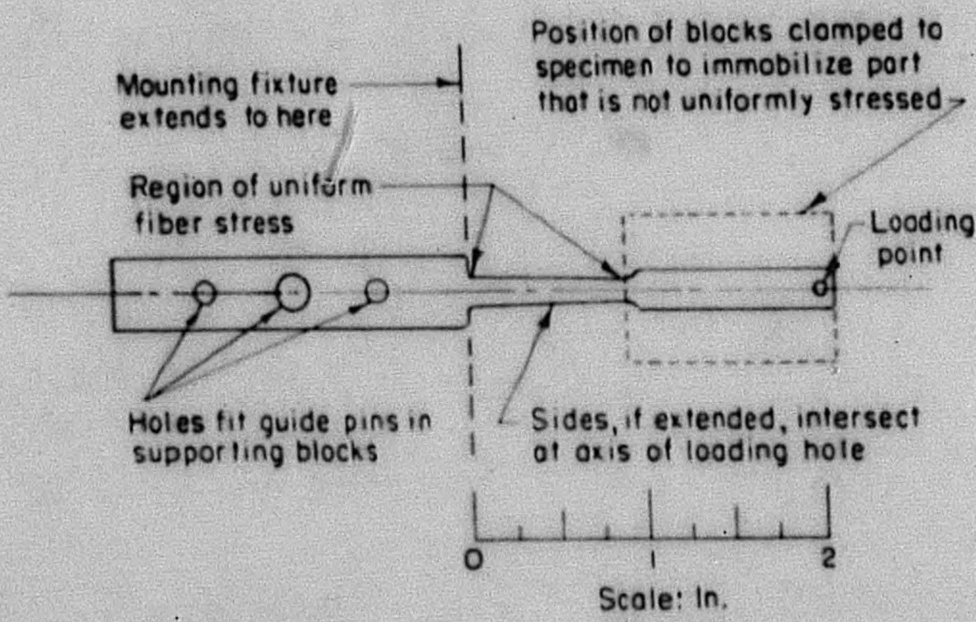

FIGURE 6. BIMETAL CANTILEVER DESIGN

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Measurements

Measurements were made of: (1) load versus deflection at room temperature, (2) temperature versus deflection, and (3) load to return the specimen at temperature to its original, unloaded position at room temperature. The cantilever and a reference measuring point were rigidly mounted on a stainless steel support and placed in a temperature-controlled muffle furnace, so that the cantilever would bend toward the reference point with an increase of temperature. A double Vycor window was installed in the furnace door to permit viewing the cantilever and reference point with a comparator telescope mounted in front of the furnace. Dead-weight loading, applied horizontally, pulled the cantilever away from the reference point.

Figure 7a shows a typical load-versus-deflection measurement at room temperature. Figure 7b shows plots of deflection versus temperature, and Figure 7c shows loads required to return the cantilevers, at temperature, to their original unloaded positions at room temperature.

The fabrication method used on the bimetal stock was not conducive to making sound or dimensionally accurate material. The uniform-stress section of Cantilever 2 was sectioned into five pieces and mounted for microscopic examination of transverse surfaces. Table 2 shows the relative thicknesses of GE-62 brazing alloy and Type 310 stainless steel in Cantilevers 2 and 3 for which data are presented. Cantilever 3 was not sectioned, measurements being taken along both edges.

Large regions of porosity or inclusions were seen in the braze material of Cantilever 2. Rough microscopic measurements indicated these ran in size up to 0.015-in. diameter. Figure 8 shows one of the best sections of Cantilever 2 for component proportion and soundness. A radiograph was taken of Cantilever 3, which presumably was similar to Cantilever 2 and is shown in Figure 9. This is a positive print of the radiograph negative and shows voids as lighter areas.

Analysis of Cantilever Measurements

At first, calculations concerning the behavior of the bimetal cantilevers were based on equations which treated them as consisting of two homogeneous components differing from each other in Young's modulus as well as in thickness and expansion coefficient. However, the modulus values of the component materials differ only by about 10 per cent, and the ratio of thicknesses is always less than 1.5. An examination of the general equations showed that, in such a case, no significant error is introduced by replacing the separate modulus values E_1 and E_2 by an average $\hat{E} = 1/2\,(E_1 + E_2)$.

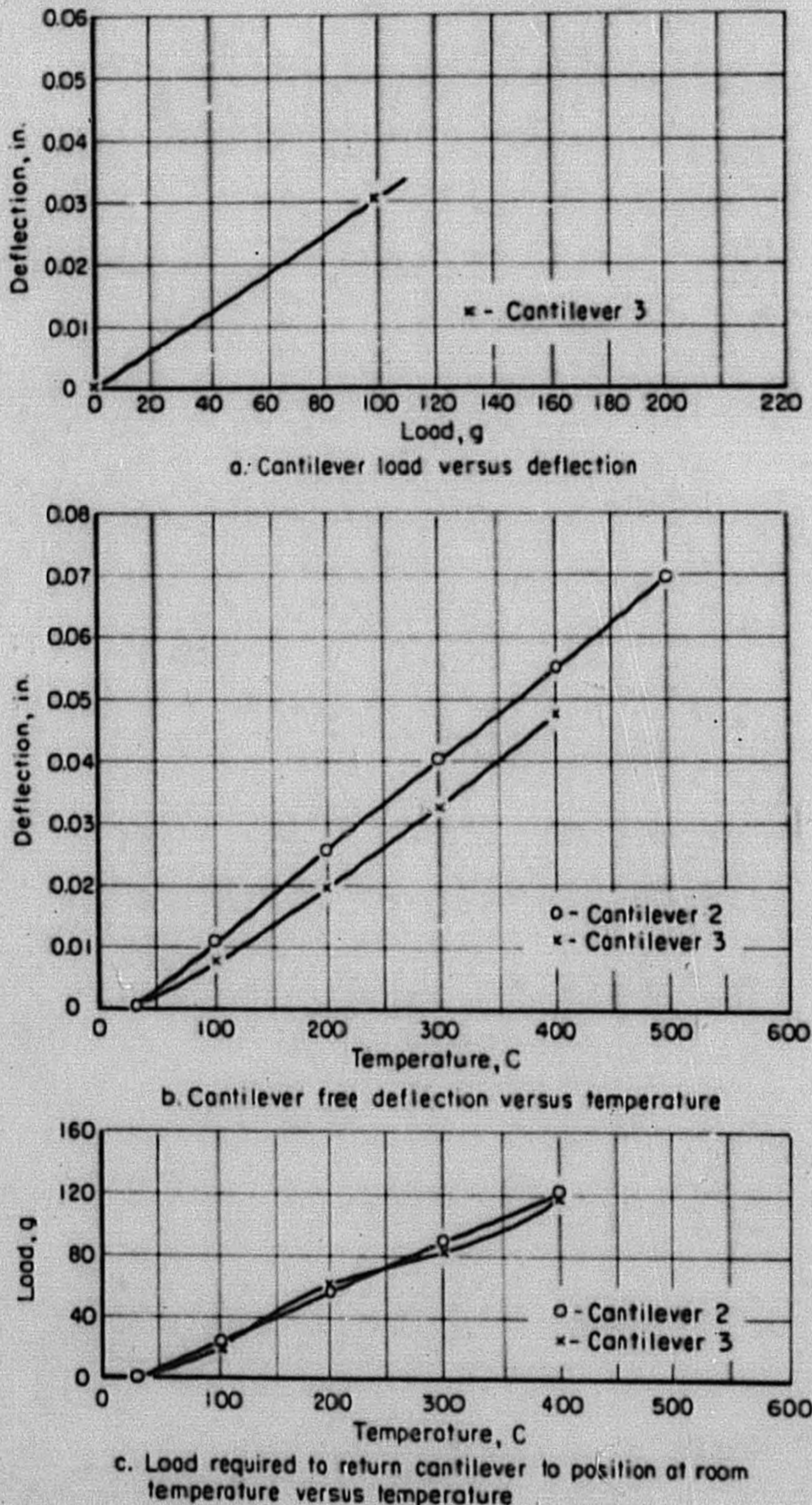

FIGURE 7 LOAD AND TEMPERATURE MEASUREMENTS OF BIMETAL CANTILEVERS OF GE-62 BRAZE AND TYPE 310 STAINLESS STEEL

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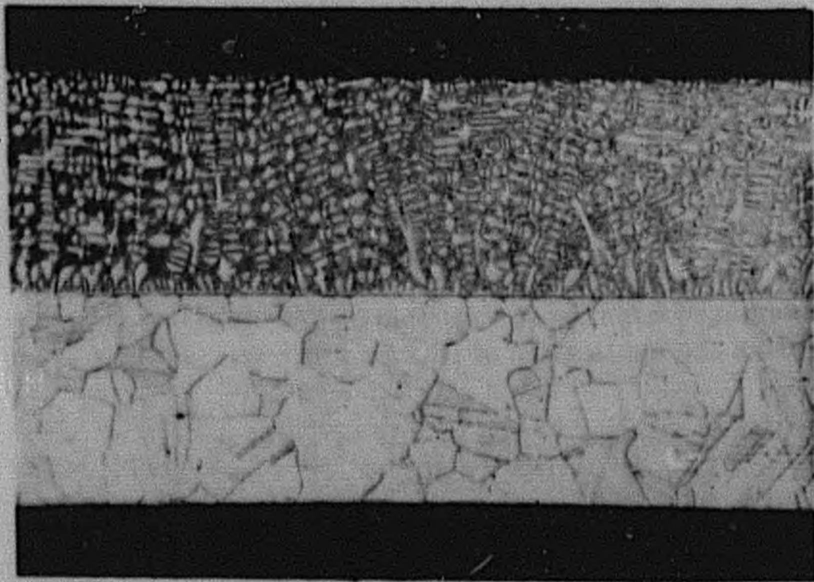
TABLE 2. RELATIVE THICKNESSES OF GE-62 BRAZING ALLOY AND TYPE 310 STAINLESS STEEL IN CANTILEVERS 2 AND 3

Cantilever		Sections, From Wide End to Narrow End of Uniform Stress Section, in.: 1		2		3		4		5	
		Braze	SS[(a)]	Braze	SS	Braze	SS	Braze	SS	Braze	SS
2	Edge	0.0197	0.0210	0.0206	0.0201	0.0221	0.0190	0.0223	0.0190	0.0181	0.0230
	Center	0.0198	0.0213	0.0209	0.0201	0.0218	0.0193	0.0215	0.0194	0.0180	0.0236
	Edge	0.0196	0.0212	0.0201	0.0197	0.0222	0.0193	0.0211	0.0201	0.0186	0.0229
3	Edge	0.0186	0.0230	Not measured		0.0197	0.0237	Not measured		0.0167	0.0254
	Edge	0.0199	0.0223			0.0198	0.0222			0.0196	0.0217

(a) Type 310 stainless steel.



50X Marble's Reagent Etch N3912

FIGURE 8. SECTION OF CANTILEVER 2 SHOWING GE-62 BRAZING ALLOY AT TOP AND TYPE 310 STAINLESS STEEL BELOW

Cantilever was brazed at 2200 F for 20 min.

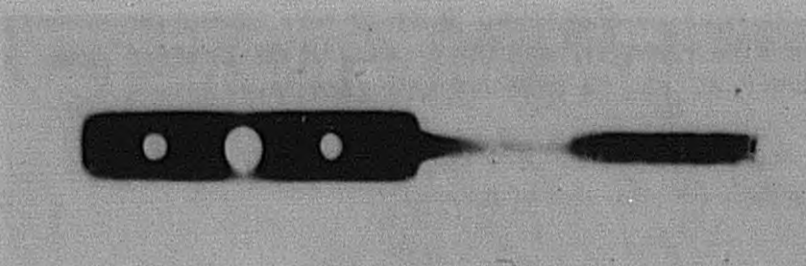


FIGURE 9. RADIOGRAPH OF CANTILEVER 3

Light areas show porosity.

The much simpler equations thus obtained give results which are correct to about 1 per cent and are the only ones actually quoted in this report.

As shown in Figure 6, the cantilever design provides a blocked section of length L′ which does not curve with load or with temperature change and a section of length L which acquires a uniform curvature under load as well as with temperature change. This uniform curvature under load is achieved by having the width w vary in proportion with the distance ℓ to the point of application of the load F, while keeping the thicknesses of components reasonably constant. The interpretation of the measurements may then be based upon three equations. The first two give the curvatures resulting from the application of load or from temperature change:

$$\frac{1}{R} = 12\left(\frac{\ell}{w}\right)\frac{F}{\bar{E}h^3} \quad , \qquad (1)$$

$$\frac{1}{R} = \frac{6f\,(1-f)}{h}(\bar{a}_2 - \bar{a}_1)\,(t - t_o) \quad . \qquad (2)$$

In these expressions, R is a radius of curvature, h is the total thickness of the bimetal, f is the fractional thickness of one component, and $(\bar{a}_2 - \bar{a}_1)$ is the difference in average linear expansion coefficients for the temperature range from t_o to t. The product f(1 - f) has the value 0.25 when the components have equal thicknesses. It decreases slowly for moderate departures from equality, and the measured thicknesses listed in Table 2 indicate that 0.25 may be used for both cantilevers.

The third equation relates the deflection D to curvature. For the small deflections which are of interest:

$$D = \frac{L\,(2L' + L)}{2R} \quad . \qquad (3)$$

The cantilever dimensions to be used in these equations are:

$$L = 0.77 \text{ in.}, \quad L' = 1.365 \text{ in.}, \quad \frac{w}{\ell} = 0.071 \quad ,$$

h = 0.041 in. (Cantilever 2) and = 0.042 in. (Cantilever 3) .

Free Deflection With Temperature. On combining Equations (2) and (3) and using the numerical values just given, the deflection in inches of Cantilever 2 is represented as:

$$D = 49\,(\bar{a}_2 - \bar{a}_1)\,(t - t_o) \quad . \qquad (4)$$

For Cantilever 3, the numerical coefficient is 48. From Equation (4), differences of expansion coefficient for comparison with dilation measurements may be computed. From the appropriate curves in Figure 7b, it is apparent that a temperature rise of 400 C (750 F) from room temperature results in deflections of 0.06 in. and 0.05 in. for Cantilevers 2 and 3, respectively. The corresponding values of $(\bar{\alpha}_2 - \bar{\alpha}_1)$ are 1.7×10^{-6} per F and 1.4×10^{-6} per F. The direction of deflection implied a higher expansion for stainless, so subscript 2 refers to this material. These results are consistent with the detailed dilation measurements and do not indicate any large effect of interdiffusion. As shown in Figure 1, the average expansion coefficients from room temperature to 800 F are approximately 10×10^{-6} per F for 100 per cent stainless and 8×10^{-6} per F for 100 per cent braze.

Deflection Under Load. On combining Equations (1) and (3) and solving for the average modulus, one obtains:

$$\bar{E} = \frac{6L\,(2L' + L)}{h^3}\left(\frac{\ell}{w}\right)\frac{F}{D} \quad . \tag{5}$$

Using the dimensions in inches of Cantilever 2, Equation (5) gives: $\bar{E} = 3.3 \times 10^6 \frac{F}{D}$, and for Cantilever 3, the numerical coefficient is 3.1×10^6 per in. The coefficient decreases slightly with rising temperature, but this effect amounts to less than 1 per cent and may be ignored.

Examination of the curves for deflection with temperature and load required to return to zero position shows that load divided by deflection is essentially constant for a given cantilever, being practically independent of temperature. The values are 4.8 lb per in. and 5.5 lb per in. for Cantilevers 2 and 3, respectively. The corresponding moduli are 16×10^6 psi and 17×10^6 psi. These are only about 60 per cent of the value (28×10^6 psi) which would have been expected from measurements on bulk samples of the components. A major reason for the discrepancy is probably the marked porosity found in the braze components of the cantilevers*. This

*If this is actually the correct reason, the moduli of the components are not nearly equal, as has been assumed. The modulus determined by Equation (5) would then be:

$$E_{eff} = \frac{E_1 E_2 (h_1 + h_2)}{E_1 h_1 + E_2 h_2} \quad .$$

For $h_1 = h_2$ and $E_2/E_1 = 2$, this differs from the arithmetic mean by about 10 per cent.

points out a possible source of uncertainty if stresses near an interface are inferred from the expansion coefficients and elastic moduli of bulk materials.

The load-deflection curve for Cantilever 3 at room temperature has a slope of 6.2 lb per in, corresponding to $E = 19 \times 10^6$ psi. Since the observations at various temperatures had not revealed any appreciable decrease of E with rising temperature, it is a little surprising that this room-temperature modulus does not agree better with the 17×10^6 psi obtained above. However, the comparison between cantilever modulus and the moduli of the bulk materials remains much the same.

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