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RESEARCH MEMORANDUM

OBSERVATIONS ON BAUSCHINGER EFFECT IN COPPER AND BRASS

By H. Schwartzbart, M. H. Jones, and W. F. Brown, Jr.

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The effect of prestrain in tension upon the stress-strain characteristics in compression have been studied for copper and brass. The residual stress phenomenon known as the Bauschinger effect is of primary importance in cyclic loading, inasmuch as it serves to reduce the yield strength of plastically strained metal to deformation of the opposite sign.

Compression testing of copper prestrained in tension various amounts yielded the following results: The Bauschinger effect developed at very small prestrains was essentially independent of prestrain and disappeared after the strain in the subsequent compression test exceeded $\delta = 0.01$. Tensile prestrain weakened the material in subsequent compression and affected the shape of the stress-strain curve obtained.

An examination of the effect of stress relief annealing on the Bauschinger effect in copper and three brass alloys all prestrained in tension $\delta = 0.01$ yielded the following results: For copper, annealing raised the compression yield strength and lowered the tensile yield strength approximately equal amounts. For the brasses, annealing raised the compression yield strengths a large amount but made little change in the tension yield strengths.

Investigation of cubically alined and isotropic copper demonstrated that the residual stresses responsible for the Bauschinger effect are intragranular.

INTRODUCTION

The stress-strain properties of a given engine component may be considerably influenced by the previous plastic-deformation history. This history includes the deformations received during forming and any deformations produced by loading conditions during earlier operation. Loading under operating conditions may result in plastic strain at points of stress concentration or because of the combined effects of time and temperature. Loading conditions may change during the operating cycle and in some cases the direction of loading may be reversed. Such cyclic changes in the loading conditions that result in plastic flow cause a continuous change in the yield strength of the material and the general shape of its stress-strain curve.

One of the phenomena associated with repeated loading is the Bauschinger effect, first observed in 1881 with iron. If a metal is strained plastically in tension or compression, the yield strength in subsequent deformation of the opposite sign is reduced.

The explanation of the Bauschinger effect commonly accepted until recently was advanced by Masing and Mauksch (references 1 to 4) and was concerned with the anisotropy and varying orientation of the individual grains in a polycrystalline specimen. According to their theory, if a polycrystalline specimen is given some plastic strain in tension and then unloaded, a balanced system of stresses will exist between the grains because the varying yield strengths of the different grains will have allowed some to flow plastically more than others. After unloading, the grains that have flowed the greatest amounts plastically have residual compressive stresses that result in and are balanced by residual tensile stresses in the other grains. Because of the residual stresses, the specimen will then require a lower external load in compression to cause plastic flow.

This residual stress explanation will account for practically all of the difference in yield strengths between tension and compression tests of plastically prestrained specimens. There is, however, a small component of this difference in yield strengths which is not a residual stress phenomenon although it always has been, and will be in this report, referred to as Bauschinger effect. This component is associated with the fact that prestrain in tension actually weakens material in subsequent compression. In other words, the tensile prestrain affects the height which the subsequent compression stress-strain curve attains in relation to the virgin curves. More will be said about this effect later in the report but it is important at this point to realize that the entire difference between tension and compression yield strengths of tensile prestrained specimens is not due to residual stresses but that an additional effect is operating.

Zener (reference 5) has pointed out that one cannot speak of residual stresses between grains because the deformation in any one grain is not uniform and homogenous. He attributes the phenomenon to the residual shear stresses that exist between the slip bands and the elastic matrix in a strained specimen. As evidence in support of his viewpoint, he cites the fact that Sachs and Shoji (reference 6) observed the Bauschinger effect in single crystals of brass. The fact that their crystals were rather badly segregated may, however, have influenced the results.

Although the Bauschinger effect was first observed in 1881, systemic investigations of the nature of the present one have been few.

In general, previous experiments are incomplete in the following respects: (1) The influence of strain hardening was not eliminated. A single specimen was carried through a number of cycles of tension and compression with intermediate anneals (references 1, 2, and 6) and the yield strengths were compared from cycle to cycle. In this case the yield strengths were influenced by the entire previous history and not only the preceding cycle. (2) No attempts were made to select a metal having identical flow curves in tension and in compression. (3) The effects of alloying additions were not determined; and (4) the presence or absence of the effect in single crystals has not been definitely established.

The present experiments serve to further clarify some of the phenomena associated with repeated loading. The variation of Bauschinger effect with prestrain to high prestrains has been examined for copper, for which the flow curves in tension and compression agreed to within ±3 percent or better. The relationship between the flow curves after prestrain to the virgin curves was examined.

Experiments were performed to determine the effect of stress relief annealing on the subsequent tension and compression curves for 1 percent tensile prestrained specimens. Copper and three brass alloys were investigated to study the effects of composition on the Bauschinger effect and on its removal.

Zener's hypothesis, which explains the Bauschinger effect in single crystals by attributing it to residual shear stresses between slip bands and the adjacent elastic material, was investigated in the following fashion. Klingler and Sachs (reference 7) have shown that logitudinal and transverse specimens cut from cold-rolled sheet exhibit differences in yield strengths similar to the Bauschinger effect. Specimens taken transverse to the direction of prestrain have reduced yield strengths in tension just as if they had been longitudinal specimens tested in compression. This effect is analogous to the Bauschinger effect and will be referred to as such, but in quotation marks to differentiate it from the difference in behavior between tension and compression. Both phenomena are believed to have the same causes. Commercial isotropic copper and 100-percent cubically alined copper sheet were both examined for the existence of this "Bauschinger effect" and to determine if the extent to which it was exhibited differed for the two materials. The cubically alined copper is similar to a single crystal in that all the grains have the same orientation, thus removing the possibility of residual intergranular stresses due to differences in orientation. Thus, if this material exhibits the "Bauschinger effect" to the same degree as isotropic copper, it will have been demonstrated that the residual stresses exist on a scale intragranular rather than intergranular.

EXPERIMENTAL PROCEDURE

The experiments performed fall under three headings: (1) The variation of Bauschinger effect with prestrain, (2) the effect of heat treatment and composition upon the Bauschinger effect, and (3) the "Bauschinger effect" in cubically alined copper sheet.

Variation of Bauschinger effect with prestrain. - For this phase of the investigation, specimens were cut from a 3/4-inch cold-rolled bar of electrolytic tough pitch copper (99.90 percent Cu). The button-head type of specimen employed is illustrated in figure 1. The reduced section in the center provided by the 2-inch radius served two purposes. It restricted the maximum stress and strain to the center of the specimen where all strain readings were taken and it allowed higher strains to be reached in compression without buckling. It has been shown that the effect of such a large radius on the stress state can be neglected (fig. 19 of reference 8).

All specimens were annealed at 1000° F for 45 minutes after machining. Tension and compression tests were carried out on a 120,000 pound hydraulic tensile machine. Axiality of loading in tension testing was achieved through the use of a specially designed fixture similar to one used by Sachs (reference 9). This fixture insured that at the beginning of the test the load axis was not more than 0.0005 inch removed from the specimen axis. Strains were computed from change of diameter readings obtained with a mechanical

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radial gage illustrated in figure 2. A minimum diameter change of 0.00025 inch could be determined over a total range of 0.024 inch. This change corresponds to a minimum longitudinal strain δ of 0.0017 and a maximum longitudinal strain δ of 0.17 in tension for a specimen having an original diameter of 0.300 inch. Strains greater than this value were measured with point micrometers.

Data were plotted in the form of true stress-natural strain curves. The true stress σ was computed as the load divided by the instantaneous area and the natural strain δ as $2 \log_e \frac{d_0}{d}$ where d_0 is the original area and d is the instantaneous area. Stress-strain curves were obtained for the annealed material in tension and in compression.

Specimens were prestrained in tension various amounts and then tested in compression to examine the effect of tensile prestrain on the flow properties in compression. For tensile prestrains greater than $\delta = 0.16$, the height-to-diameter ratio of the prestrained specimen was such that buckling would have occurred early in the subsequent compression test. For this reason a section with height-to-diameter ratio of about 2 was cut out of the prestrained specimen for compression testing.

The effect of heat treatment and composition on Bauschinger effect. - The effect of stress relief annealing after tensile prestrain on the stress-strain curves in tension and compression was investigated. The desideratum in this case was to anneal at a temperature and for a period of time that would relieve the stresses responsible for the Bauschinger effect but would cause no recrystallization. For this reason the tensile prestrain was kept small, 1 percent, so that the recrystallization temperature would be relatively high. Actually, complete stress relief and no recrystallization is impossible to obtain; a treatment was selected that most closely approximated this condition. It was felt that the separation in temperature ranges between stress relief and recrystallization would be greater for alloys than for relatively pure materials. For this reason and to determine the effect of alloying elements on the Bauschinger effect, three different brass alloys, 70-30 (Cartridge brass), 70-30 (leaded), and 60-40 (Muntz metal), were investigated in addition to the electrolytic copper. This series of alloys gave a range in structures from the relatively pure copper, to the solid solutions of zinc in copper with and without a dispersed soft second phase of lead, to the two phased $\alpha + \beta'$ 60-40 Muntz metal.

The leaded 70-30 brass and the Muntz metal specimens were cut from 3/4-inch-diameter cold-rolled bars and annealed at 1000° F for 3/4 hour after machining. The Cartridge brass specimens were machined from slugs cut from an annealed 11/16-inch-thick plate with the longitudinal axis of the specimen in the rolling direction.

For this phase of the investigation, it was desirable to use a more sensitive strain-measuring device than the mechanical radial gage (fig. 2). Two different gages were employed, the Huggenberger gage for the experiments on copper and for the experiments on the brasses, an extensometer of the O. S. Peters type using a selsyn system to draw autographic load-elongation curves. The Huggenberger gage measures elongations to a sensitivity of 50×10^{-6} inch in a 1-inch gage length. Four times this sensitivity can easily be obtained by estimating between gage marks. The sensitivity of the Peters gage was 80×10^{-6} inch in a 1-inch gage length.

The specimens used for these experiments were cylindrical to allow the use of the extensometers described. Analogous dimensions were the same as those illustrated in figure 1 except for the diameter of the gage section, which for copper specimens was 0.550 inch and for brass specimens was 0.250 inch.

For each of the four materials investigated a series of at least four specimens were prestrained 1 percent in tension. Of the four specimens, one was immediately retested in tension, one in compression, and the other two were stress relief annealed after which one was tested in tension and one in compression. The series of four curves obtained indicated the effect of the stress relief anneal on the tension and compression curves. The brasses were stress relief annealed at 480° F for 7 hours and the copper at 500° F for 10 hours. For the latter, the effect of extending the annealing time to $15\frac{1}{2}$ hours was also investigated.

Investigation of "Bauschinger effect" in cubically alined copper. - As was pointed out previously, it was desired to throw further light on the subject of the Bauschinger effect in single crystals. The 0.032-inch-thick, annealed, 100-percent cubically alined copper sheet used in this phase of the investigation is comparable to a single crystal in that all the crystals have a (100) plane parallel to the rolling plane and a [001] axis parallel to the rolling direction. The behavior of this sheet was compared to the behavior of ordinary commercial copper sheet 0.034-inch thick in order to determine the difference in "Bauschinger effect."

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The specimens employed were 3 inches long and 0.5 inch wide with no reduced section. Gripping was accomplished with Templin sheet grips.

Autographic load-elongation curves were obtained with a gage, similar to the Peters gage discussed in the preceding section, sensitive to 125×10^{-6} inch in 1-inch gage length. The gage was mounted on the edge of the specimen. Strains greater than 12 percent were read with dividers and a scale to an accuracy of 0.01 inch.

The virgin longitudinal and transverse tensile curves were obtained for the cubically alined and for the isotropic copper sheet. Following this, an 18-inch by 3-inch strip of each was pulled 10 percent. From these prestrained sheets, 3-inch by 0.5-inch specimens were cut in longitudinal and transverse directions and tested in tension.

RESULTS AND DISCUSSION

Variation of Bauschinger effect with prestrain. - True stress-natural strain curves for the annealed copper in tension and compression are plotted in figure 3. (Also shown is a corrected compression curve, which will be discussed later.) The curves are average curves of several tension and compression tests. It can be seen that the compression curve lies slightly higher than the tension curve up to a strain of about $\delta = 0.175$ but that the position is reversed above this strain.

The fact that the compression curve for copper is higher than the tension curve has been previously reported (work done by Ludwik and Scheu, and Taylor and Quinney referred to on p. 69 of reference 10). This work also showed that the relationship is reversed if the strain becomes sufficiently large, and this reversal was attributed to the strengthening effect of necking. The present investigation, however, reveals clearly that the two curves cross each other at a strain of roughly 17 percent, considerably below the necking strain, which is about 40 percent for copper.

At very small strains the stress-strain curve in compression lies approximately 5 percent higher than the tension curve, but the strain hardening in compression becomes gradually less than that in tension. It could be expected that the strain hardening should decrease faster with strain in compression than in tension because of the following considerations: The individual crystals in a polycrystalline specimen rotate during deformation thus causing strengthening by raising the net stress on the cross section necessary to reach the critical resolved shear stress on the slip plane. This rotation is responsible for the preferred orientation assumed by crystals in deformed metals, which is called texture. The texture obtained in compression is different from that obtained in tension and consequently the contribution of the rotation to the strengthening is different in the two cases. The evidence for the foregoing ideas is presented in the following paragraphs.

For polycrystalline copper Ono has shown that the grains approach a texture in tension where primarily the [111] - direction of the crystal lattice gradually becomes coincident with the direction of tension, whereas the texture in compression consists of a [110] - direction being parallel to the direction of compression. This relationship probably applies to all face-centered cubic metals and has been demonstrated for aluminum by Sachs and Schiebold (reference 11) and for brass by Hermann and Sachs (reference 12). The referenced work on copper and aluminum has been summarized by Sachs (reference 13).

Furthermore, experiments on face-centered cubic single crystals, primarily for aluminum (reference 14) but also extended to brass (references 15 and 16) and copper (reference 17), have definitely shown that the yield strength of crystals in terms of the critical resolved shear stress is a constant value. Consequently, the tensile yield strength varies depending on the angle between the slip system and the direction of the applied stress or on the orientation of the crystal. In particular, it is found that the [111] - orientation requires close to 50-percent more applied stress to produce slip than the [110] - orientation. The general relationships found for orientation dependence of properties of single crystals also apply to polycrystalline copper, as demonstrated for sheet with a highly preferred orientation (work done by Fahrenhorst, Matthaes, and Schmid referenced on p. 317 of reference 18, Czochralski's work referenced on pp. 129-130 of reference 18, and reference 19).

Thus, the amount of strain hardening produced by deformation of a polycrystalline metal should depend on the texture developed. If this preferred orientation possesses a comparatively high yield strength, then the stress required to produce plastic flow in a given polycrystalline metal depends on the strain hardening and on the deformation texture developed. If rates of strain hardening are considered equal, the stress-strain curve will be steeper for the stronger texture. It is believed that this is the explanation for the appearances of the tension and compression curves presented in figure 3.

As a measure of the Bauschinger effect, a ratio can be formed of the yield strength in compression after tensile prestrain to the flow stress at the same strain in compression assuming that the prestrain had also been in compression. For the denominator of this ratio it would be incorrect to use the actually observed compression curve inasmuch as the prestrain of the actual specimen was in tension and had therefore a higher degree of strengthening due to rotation of the slip directions into the stress axis. For this reason, a corrected compression curve having the same amount of strengthening as tension due to slip direction rotation was determined. At small strains (0.005 to 0.01), where the rotation is negligible, the compression curve is higher than the tension curve by about 4.1 percent. This amount was assumed to be the percentage by which the compression curve should lie higher than the tension curve if there were no difference in deformation texture between tension and compression. A corrected compression curve was thus determined which was always higher than the tension curve by this 4.1 percent. This curve is also shown in figure 3.

Stress-strain curves for specimens tested in tension and in compression after a tensile prestrain of $\delta = 0.046$ are shown in figure 4. The curves illustrate the Bauschinger effect, the yield strength in compression being considerably lower than that in tension. Also shown is the portion of the corrected virgin compression curve beginning at a strain of $\delta = 0.046$. In the present investigation the Bauschinger effect at any arbitrary plastic strain is defined in the following fashion: An elastic modulus line is drawn at an offset equal to the arbitrary strain in question. The ratio of the stresses at the intersections of this line with the subsequent compression curve and the virgin corrected compression curve is the Bauschinger effect at this strain. Referring to figure 4, the Bauschinger effect at 0.001 plastic strain is the ratio of the stress at the point A to the stress at the point B. Points A and B are the intersections of the subsequent compression test and the corrected virgin compression curve with the elastic modulus line drawn at an offset of $\delta = 0.001$. This line has a slope of 11.2×10^6, which is the transverse modulus corresponding to a longitudinal modulus of 17×10^6 and Poisson's ratio of 0.33, which values were taken from the literature. It should be noted that the lower this ratio, the greater the Bauschinger effect.

It can be seen from figure 4 that the tension and compression curves after tensile prestrain converge after a strain of $\delta = 0.01$ indicating that the residual stresses responsible for the Bauschinger effect (or, as discussed previously, the largest part of the Bauschinger effect, which is due to residual stresses) do not affect the flow properties beyond this amount of strain. This effect is further illustrated in figure 5 where the Bauschinger effect is plotted against natural plastic strain in the subsequent compression test for different values of tensile prestrain. It is evident from this plot that for any prestrain the above ratio reaches a nearly constant value near unity after the strain in the subsequent compression test reaches approximately $\delta = 0.01$. The attainment of this constant value is an indication that, as expected, the Bauschinger effect is no longer influencing the flow characteristics. A value of unity for the ordinate of this plot would indicate coincidence of the flow stresses in the actual subsequent compression test with the corrected virgin compression curve. It should be noted that as the prestrain increases, the limiting value of the ordinate reached decreases. This effect will be discussed in more detail later in the report. 2161

The variation of Bauschinger effect at 0.001 plastic strain with prestrain is plotted in figure 6. It can be seen that the ratio expressing the magnitude of the Bauschinger effect, which must be unity for 0 prestrain, drops to a value of about 0.74 at very small prestrains, under $\delta = 0.005$, and remains nearly constant even to strains beyond necking.

A simple model that explains the appearance of the tension and compression curves after tensile prestrain is presented in figure 7. Assume a specimen made up of crystals exhibiting no strain hardening which have two different yield strengths, their individual stress-strain curves in tension being OBC and OAK. (Although it will be demonstrated later in the report that the stresses responsible for the Bauschinger effect are intragranular, the concept of strong and weak crystals is a convenient analog for use in this model.) It is assumed that the flow curves in virgin compression and tension are identical. The average stress-strain curve for the specimen will then be OAEZ. The tension and compression curves for a specimen loaded in tension to the point D and unloaded are now considered. At this point the strong crystals will have undergone no plastic flow whereas the weak crystals will have flowed plastically an amount AJ. The former will unload along the line SO and the latter along the line JN. In the unloaded condition or at average 0 stress, the strong crystals will now have a residual tensile stress of LM and the weak crystals a residual compressive stress of MN. If the specimen is now reloaded in tension further plastic flow will occur at the point D in the weak crystals and the point E in the strong crystals. The resultant curve will be MDEZ. The curve that will be obtained in compression is now examined. The specimen will load along the line MP with the strong crystals loading along the line LQ. The weak crystals will flow plastically when their stress reaches the point T or at an average stress of P and the strong crystals when their stress reaches the point U or at an average stress R. The resulting curve will be MPR or, transposed to the tension quadrant for comparison with the tension curve, MHJFZ. Thus, the yield point is lower in compression than in tension by the difference in stresses at D and H and the curves converge at the point F exactly like the experimentally determined curves in figure 4.

If the prestrain is increased from D to V then the curves obtained in subsequent tension and compression are YXVZ and YXGZ, respectively. In this case the Bauschinger effect is larger than for the smaller prestrain. The magnitude of the Bauschinger effect is a function of the length of the line SJ, which determines the magnitude of the residual stresses after unloading. The length of SJ increases as the prestrain increases to the point E after which its length is constant. This point occurs at very small prestrains, namely, as soon as all the crystals are flowing plastically. The variation of Bauschinger effect with prestrain observed in figure 6 is in conformity with the behavior deduced from the model.

It should be noted that it is not necessary to assume ideal plasticity for the model to explain the experimentally observed effects. It is only necessary that the stress values for the strong and the weak crystals differ by the same percentage at any strain after plastic yielding for the magnitude of the residual stresses to be constant with prestrain after unloading.

The relationship of the flow curve in subsequent compression after various tensile prestrains to the virgin corrected compression curve is illustrated in figure 8. Several interesting observations can be made from this plot. The effect of prior tensile strain weakens the material in subsequent compression as compared to the stress which it would be expected to sustain for the same strain in virgin compression. This effect increases with increasing prestrain. In order to determine the magnitude of the effect a plot (fig. 9) was made showing flow curves having stress values 0.98, 0.96, 0.94, 0.92, and 0.90 of the corrected compression curve. This plot was laid over a plot like figure 8 and the compression curve from figure 9 which was tangent to the actual compression curve after prestrain was determined. For example, the actual compression curve obtained after a tensile prestrain of $\delta = 0.24$ is plotted in figure 9. The reduced corrected compression curve tangent to the curve for the prestrained specimen has a value of 0.91. These values, which are arbitrarily called tangency factors, are plotted against prestrain in figure 10.

It can be seen that the tensile prestrain influences the subsequent compression flow curve in this respect at a rate which decreases with increasing prestrain. For prestrains greater than $\delta = 0.30$ the tangency factor remains practically constant.

Observations can be made from figure 8 also concerning the influence of tensile prestrain on the rate of strain hardening in subsequent compression. At prestrains less than $\delta = 0.15$ the subsequent compression curves have the same general shape as virgin curves. For prestrains exceeding 0.15 the initial part of the stress-strain curve has a region of low slope. The slope rises progressively with further strain and eventually becomes approximately parallel to the virgin compression curve. This initial nearly horizontal portion of the stress-strain curves is similar to the "yield point effect" observed in mild steel.

<u>The effect of heat treatment and composition on Bauschinger effect.</u> - The results of the experiments to determine the effect of stress relief annealing and composition on the Bauschinger effect after a tensile prestrain of $\delta = 0.01$ are presented in idealized form in figure 11 and as experimentally determined in figures 12(a), 12(b), 12(c), and 12(d). In the following analysis it has been assumed that the orientation effect mentioned previously is negligible at the small prestrains. For the ideal case where there is complete stress relief and no recrystallization, strain aging, or other extraneous effects, behavior such as depicted in curve E of figure 11 might be expected. The tension and compression curves after stress relief annealing would be coincident and lie midway between the unannealed tension and compression curves. Any residual stress not removed by the heat treatment would cause a proportionate upward displacement of the tension curve and a downward displacement of the compression curve from this midway position (curves C and F of fig. 11). This is the behavior exhibited by the copper (fig. 12(a)). A heat treatment of 10 hours at 500° F has raised the compression curve and lowered the tension curve from the curves of the unheat-treated specimens approximately equal amounts. Unfortunately, the use of higher temperatures or longer times to eliminate more of the residual stress would result in structural changes other than stress relief because these processes are concurrent. It can be seen from this figure that extending the annealing time to $15\frac{1}{2}$ hours lowered the tension curve at higher strains. This effect is probably due to structural changes other than stress relief which occurred in this time.

The behavior of the brass alloys was somewhat different from the copper. If strain aging has occurred during the stress relief

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annealing then the positions of both the tension and compression curves for the stress relief annealed specimens will have been raised as shown in figure 11. It is assumed in the schematic representation of figure 11 that the strain aging is of such small magnitude that only the early part of the stress-strain curve is affected. Examination of figures 12(b), 12(c), and 12(d) reveals that the behavior of the brasses conforms with the conceptions presented in figure 11. These figures show that the stress to cause yielding is nearly the same for the tension specimens and for the specimens stress relief annealed followed by tension or compression. The residual stresses were almost completely eliminated by the stress relief anneal; the amount of stress remaining in each case is indicated by the difference between curves C and D. The amount of strain aging is represented by the difference between the average of curves C and D and the average of curves A and B. Strain aging has probably influenced all previously published data on the Bauschinger effect in brass. The behavior of all the brass alloys is similar, indicating little effect of composition within the range studied. Whatever differences were observed were probably due to experimental scatter and to differences in amount of strain aging.

Investigation of Bauschinger effect in cubically alined copper. - Stress-strain curves for isotropic and cubically alined copper sheets in the annealed condition are presented in figures 13(a) and 13(b). Curves were obtained for specimens cut longitudinal and transverse to the rolling direction. It can be seen that there is practically no difference in the stress-strain relation between the two directions.

It will be recalled that the object of this phase of the investigation was to determine if isotropic and cubically alined copper possessed the same amount of "Bauschinger effect," which in this case is the difference in longitudinal and transverse yield strength for longitudinally prestrained specimens. Plotted in figures 14(a) and 14(b) are the curves obtained for longitudinal and transverse specimens cut from isotropic and cubically alined copper sheets which had been prestrained 10 percent. It can be seen that for both materials the "Bauschinger effect" is exhibited to about the same degree, the curve for the longitudinal specimen being higher than that for the transverse specimen by approximately the same amount for the isotropic as for the cubically alined material. Inasmuch as the orientation of all the grains in the cubically alined material is the same, there can be no residual stresses built up between them because of mismatch in orientation between adjacent grains. Because it is assumed that the "Bauschinger effect" is a residual stress phenomenon, the residual stresses must exist between different portions of the individual grains, just as Zener (reference 5) has contended.

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SUMMARY OF RESULTS

1. Compression testing of copper prestrained in tension various amounts yielded the following results:

(a) The Bauschinger effect developed at very small prestrains, less than $\delta = 0.005$, and remained essentially constant in magnitude up to a prestrain of $\delta = 0.65$, which exceeded the necking strain.

(b) The Bauschinger effect disappeared after the strain in the subsequent compression test exceeded $\delta = 0.01$. A model that qualitatively explains the above phenomena was presented.

(c) Tensile prestrain weakened the material in subsequent compression. The degree of weakening increased with prestrain up to a prestrain of about $\delta = 0.30$ above which the effect was constant.

(d) The shape of the stress-strain curve in compression after tensile prestrain was a function of prestrain. For prestrains under $\delta = 0.15$, the form of the curve was similar to that for an annealed specimen. Above this prestrain the curve exhibited a region of low slope immediately after initial yielding. The slope of this initial part, in turn, decreased with increasing prestrain until it became practically horizontal at a prestrain of $\delta = 0.24$. This behavior was similar to the "yield point effect" in mild steel. Once the initial region of low slope was exceeded the slope of the compression curve was essentially parallel to the actual virgin compression curve.

2. An examination of the effect of stress relief annealing and composition on the Bauschinger effect in copper, Muntz metal, and leaded and unleaded 70-30 brass all prestrained in tension $\delta = 0.01$ yielded the following results:

(a) For copper the effect of stress relief annealing (10 hr at 500° F) on the tension and compression yield strengths was to raise the compression yield strength and lower the tension yield strength approximately equal amounts.

(b) Stress relief annealing (7 hr at 480° F) Muntz metal and leaded and unleaded 70-30 brass changed the tension yield strength little and raised the compression yield strength to the extent that it almost equaled the tension yield strength. It is believed that strain aging in the brasses during stress relief annealing raised both the tension and compression yield strengths.

(c) There was practically no difference in behavior in the three brass alloys studied.

3. An effect analogous to the Bauschinger effect was noticed in approximately equal magnitude for both cubically alined and isotropic copper sheets. Thus, it appears that the residual stresses responsible for the Bauschinger effect are intragranular.

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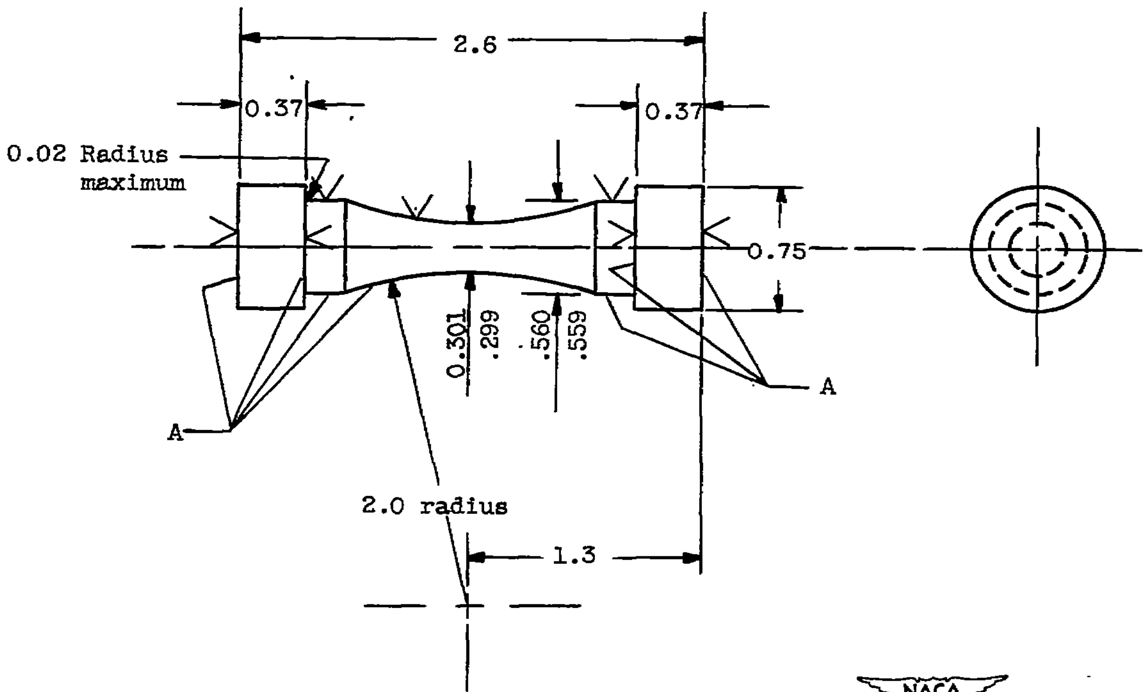

A Surfaces must be concentric, parallel, flat, square, and true (as applicable) to each other within 0.0005 inch full indicator reading unless otherwise specified.

Figure 1. - Buttonhead tensile specimen.

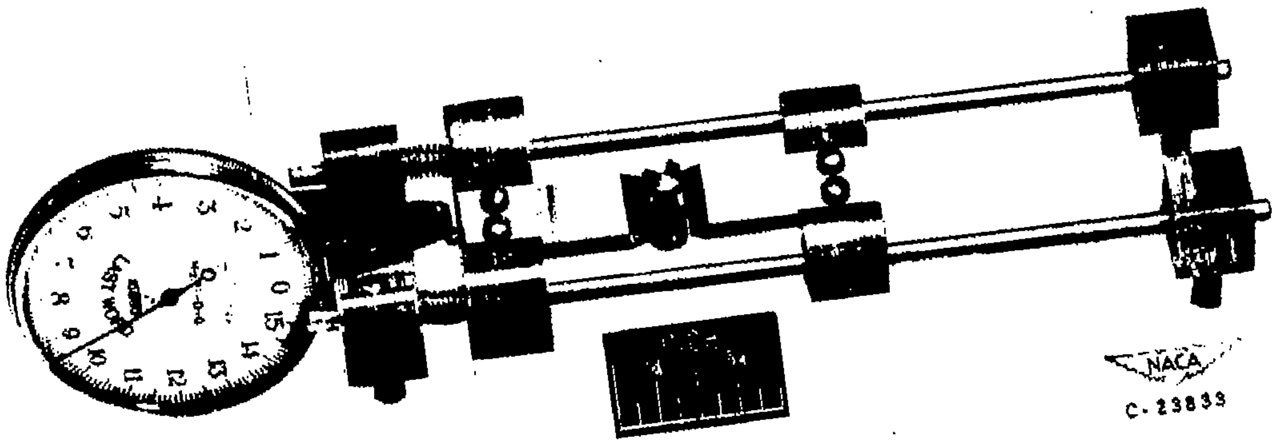

Figure 2. - Mechanical radial gage.

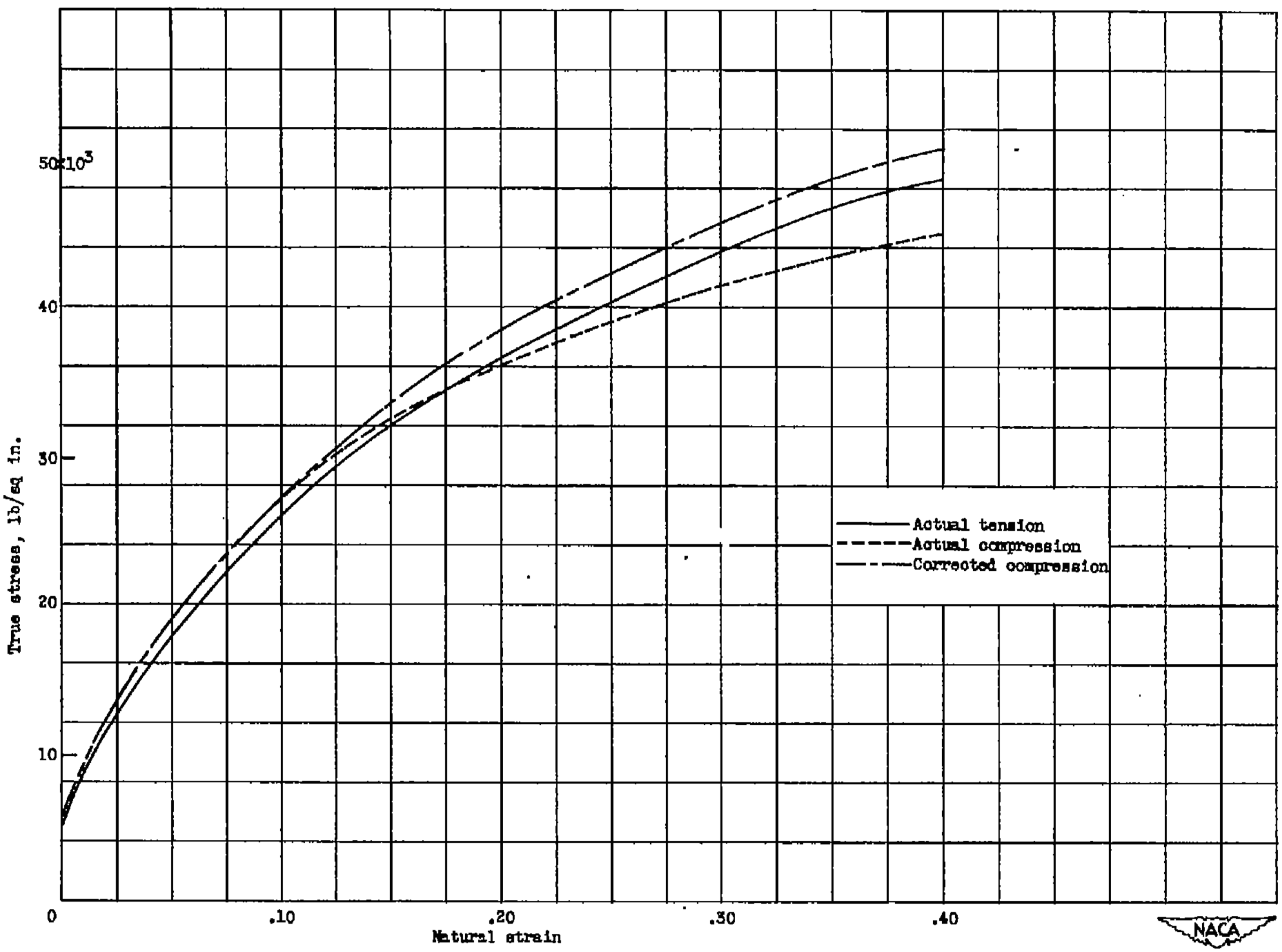

Figure 3. - True stress-natural strain tension and compression curves for annealed copper.

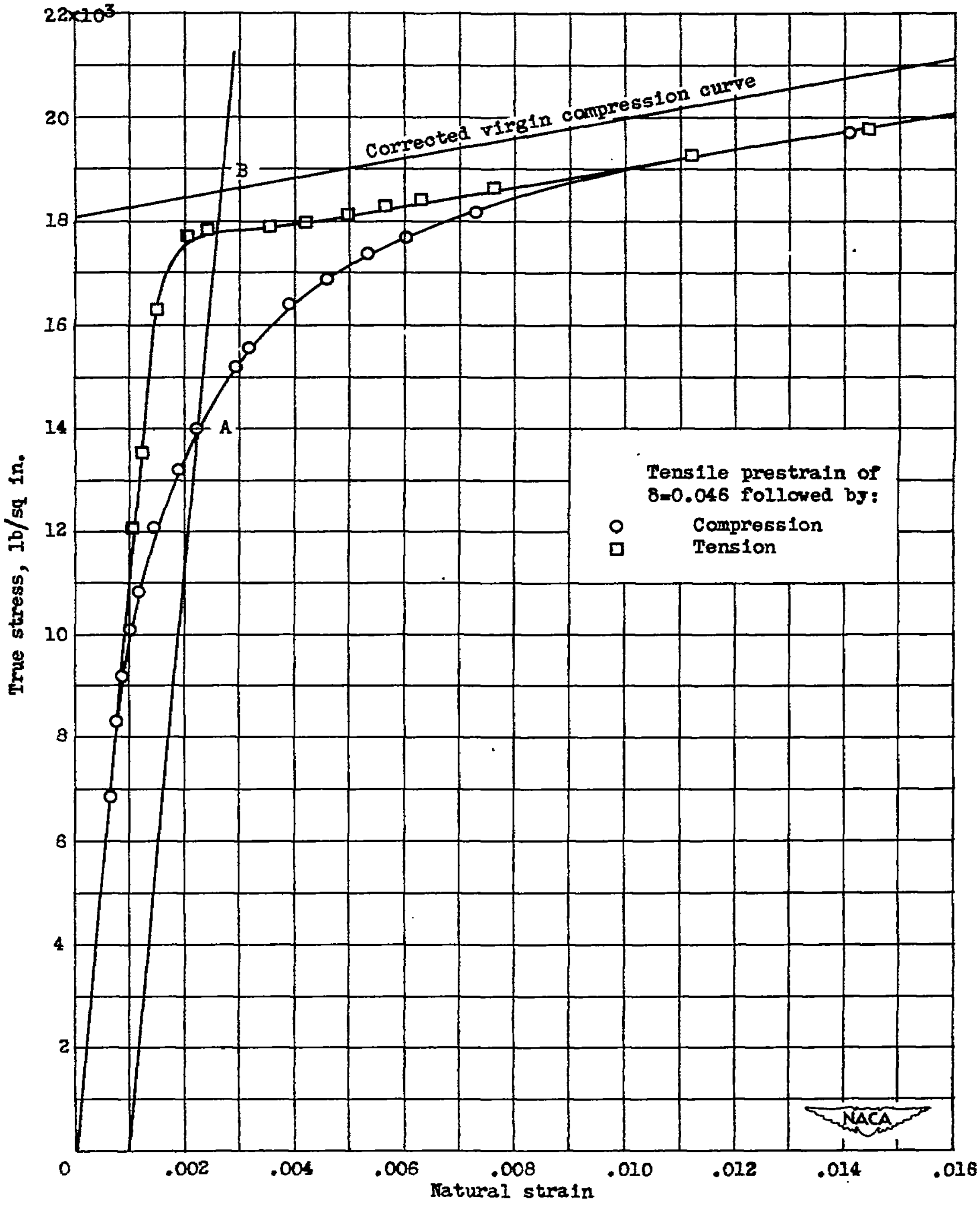

Figure 4. - True stress-natural strain curves in tension and compression for specimens prestrained in tension.

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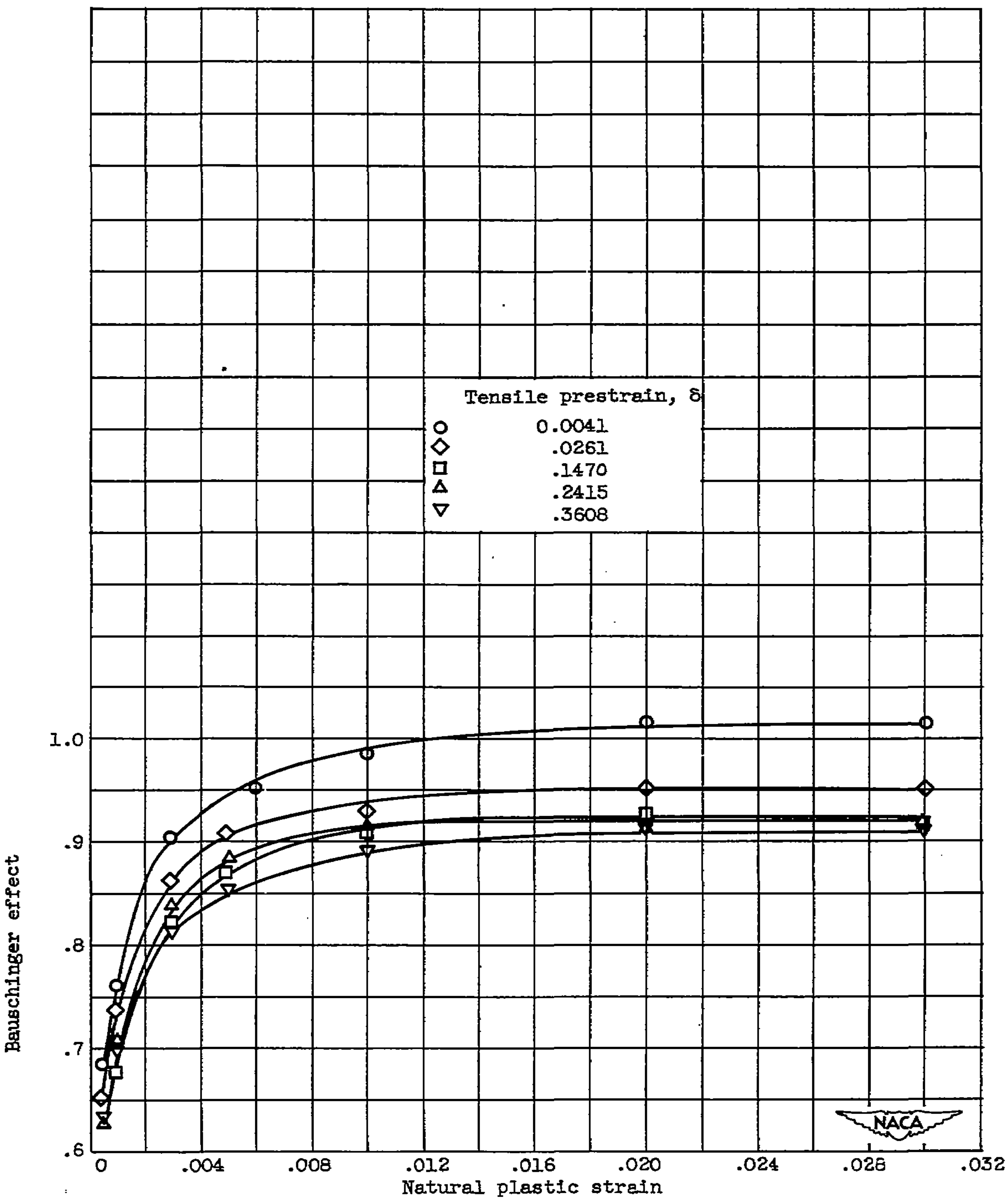

Figure 5. - Bauschinger effect against natural plastic strain for different values of tensile prestrain.

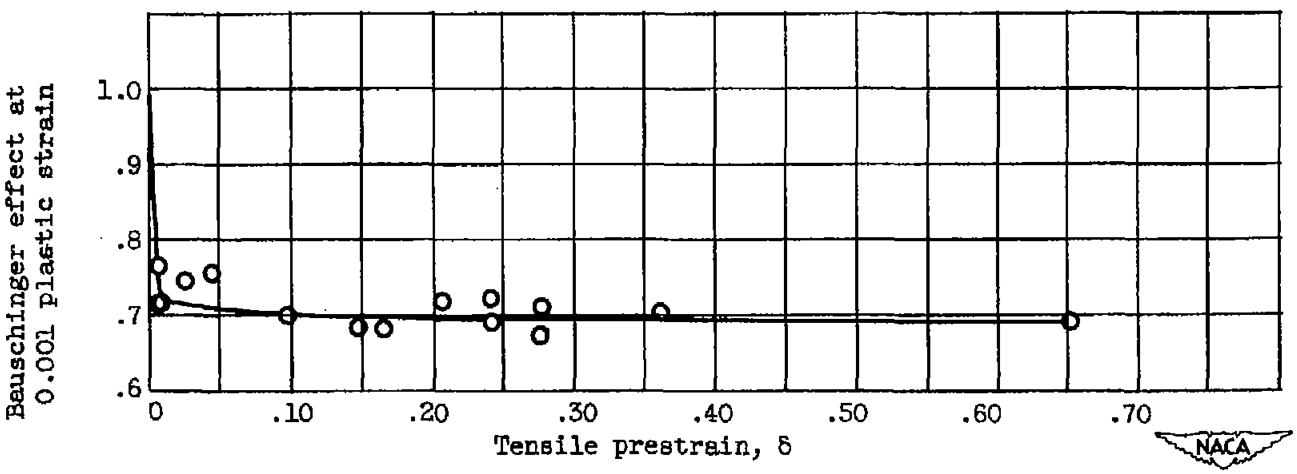

Figure 6. - Variation of Bauschinger effect at 0.001 plastic strain with tensile prestrain.

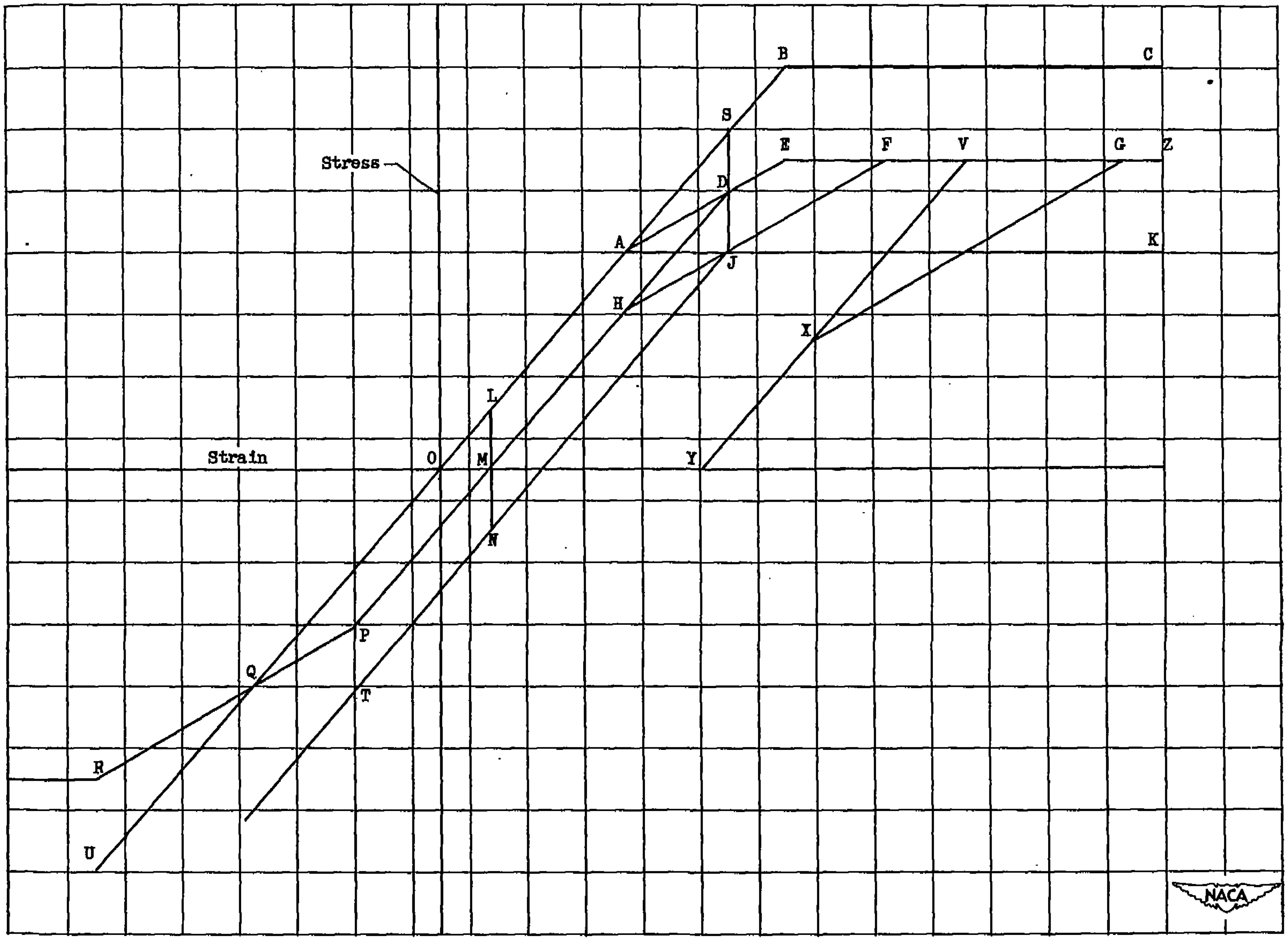

Figure 7. - Model used to qualitatively explain Bauschinger effect.

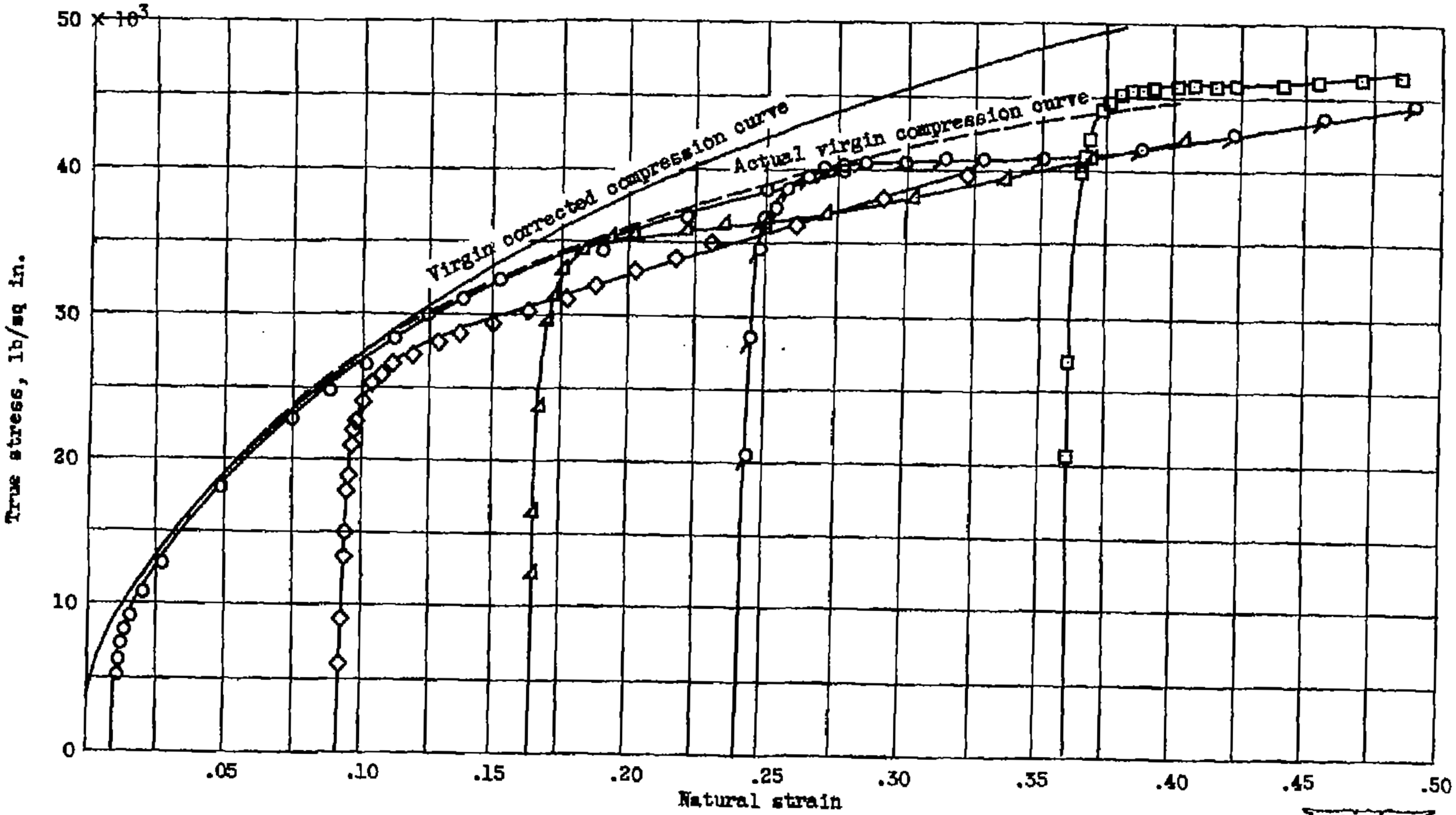

Figure 8. - Stress-strain curves in compression for copper specimens not prestrained and for specimens prestrained various amounts in tension.

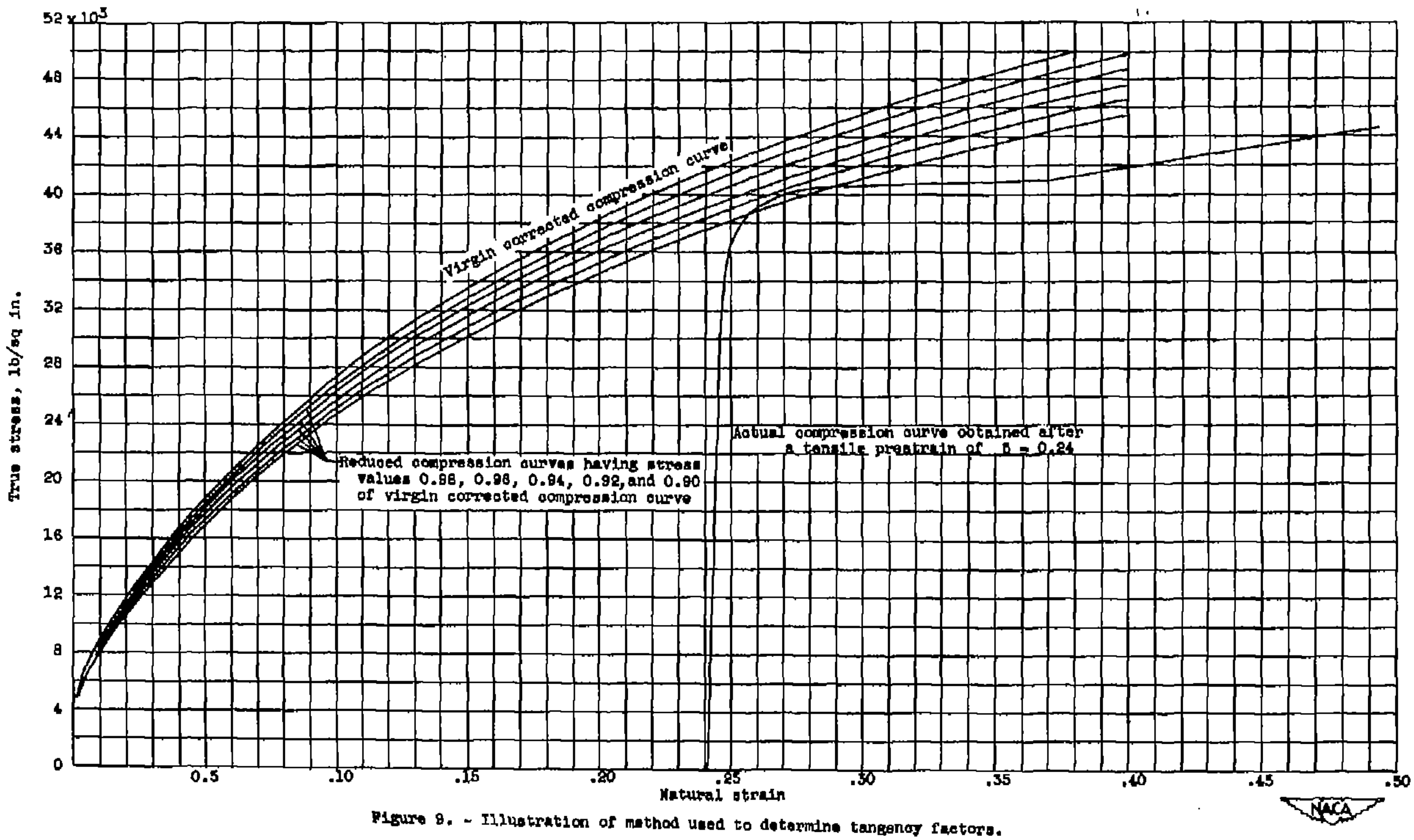

Figure 9. - Illustration of method used to determine tangency factors.

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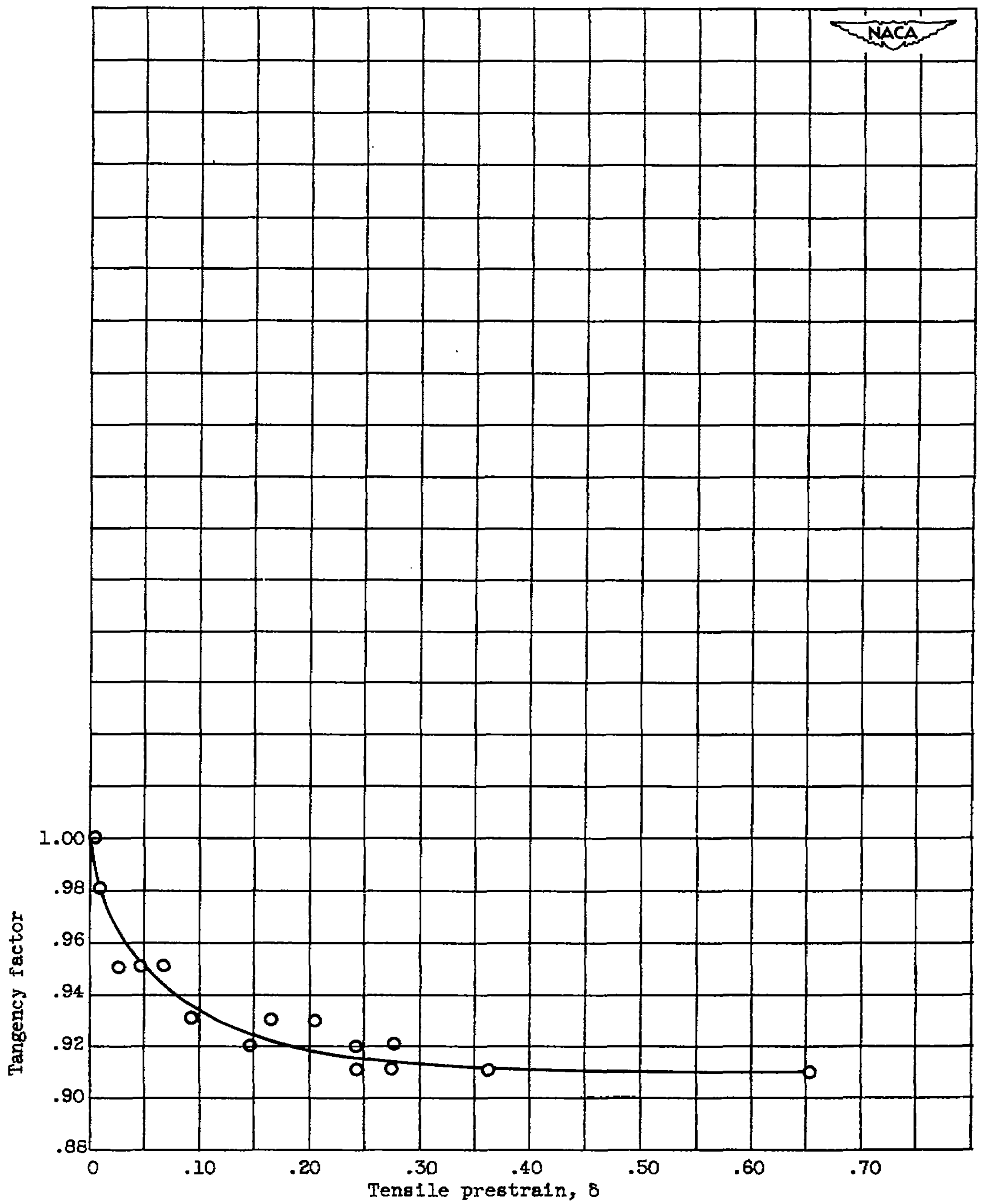


Figure 10. - Variation of tangency factor with tensile prestrain.

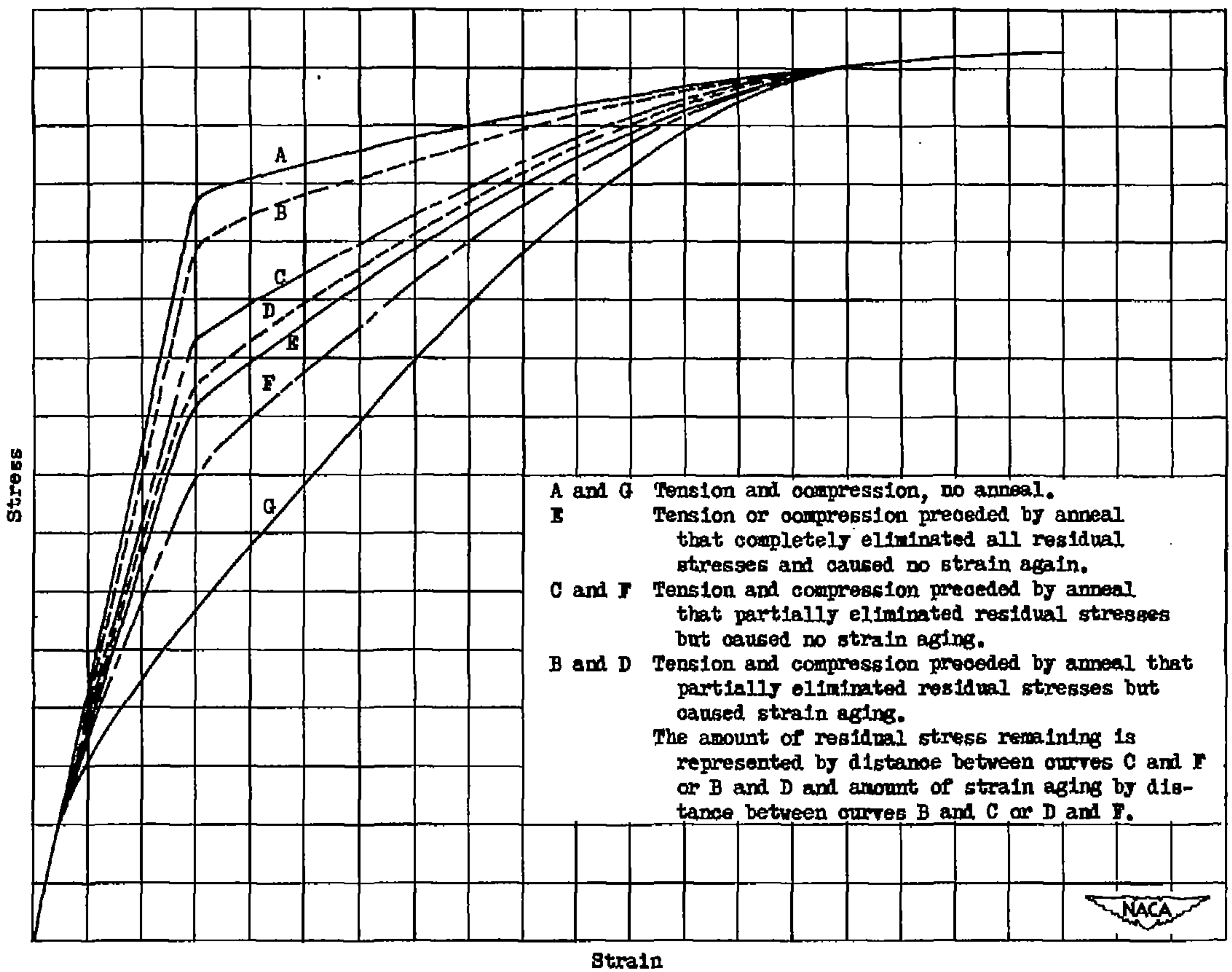
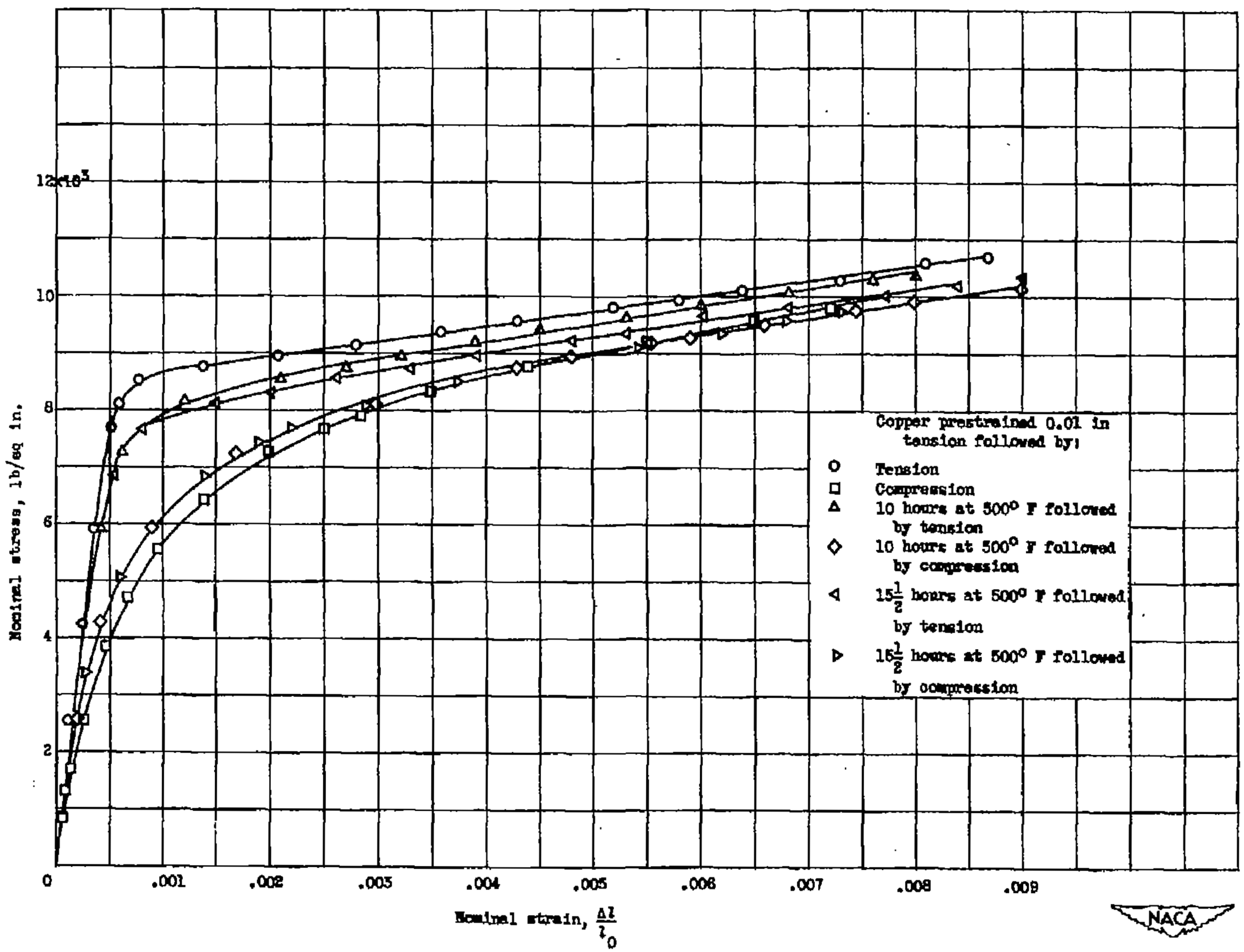
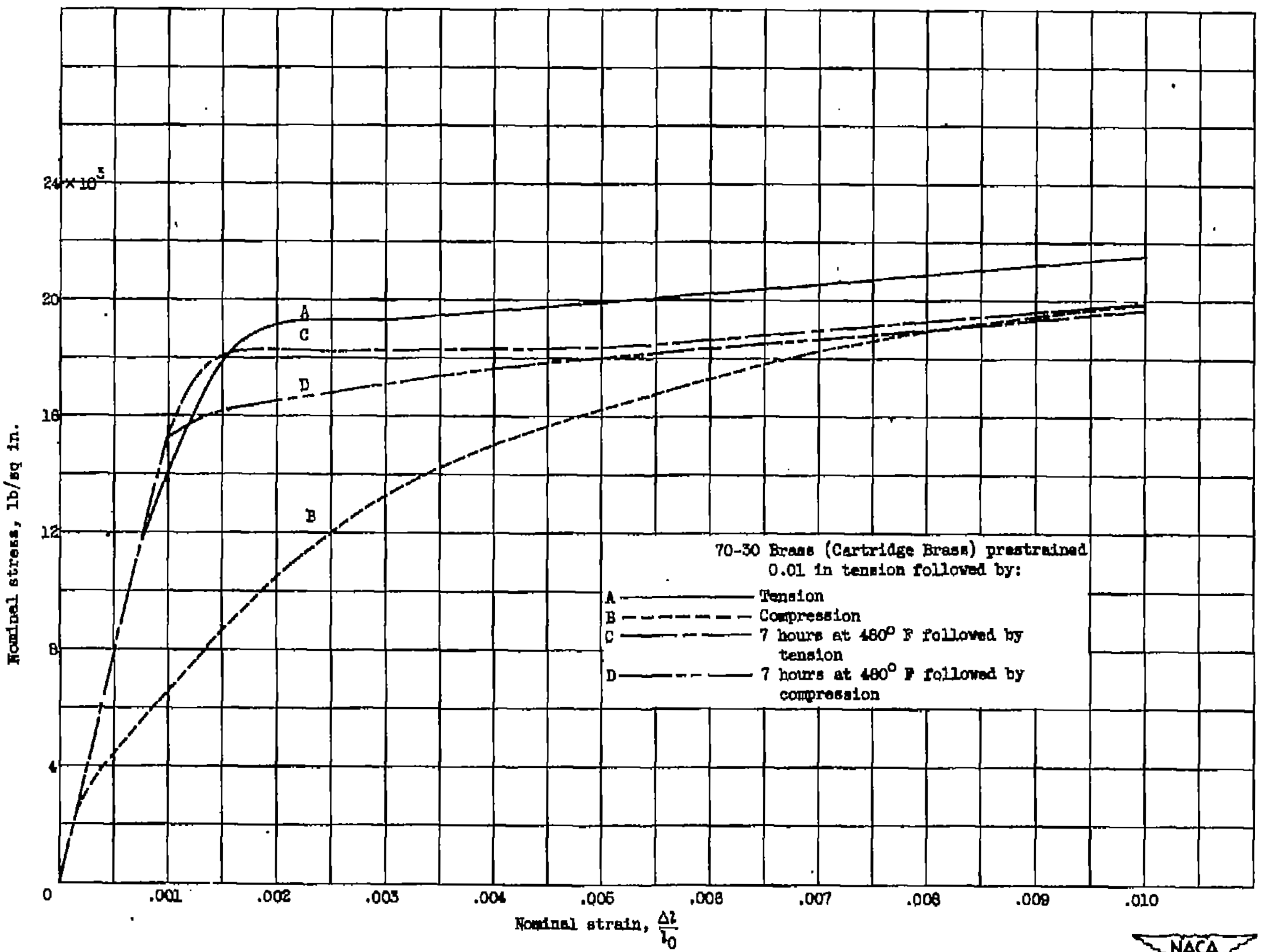


Figure 11. - Idealized stress-strain curves for material prestrained in tension and tested in tension or compression with or without an intermediate stress relief anneal.



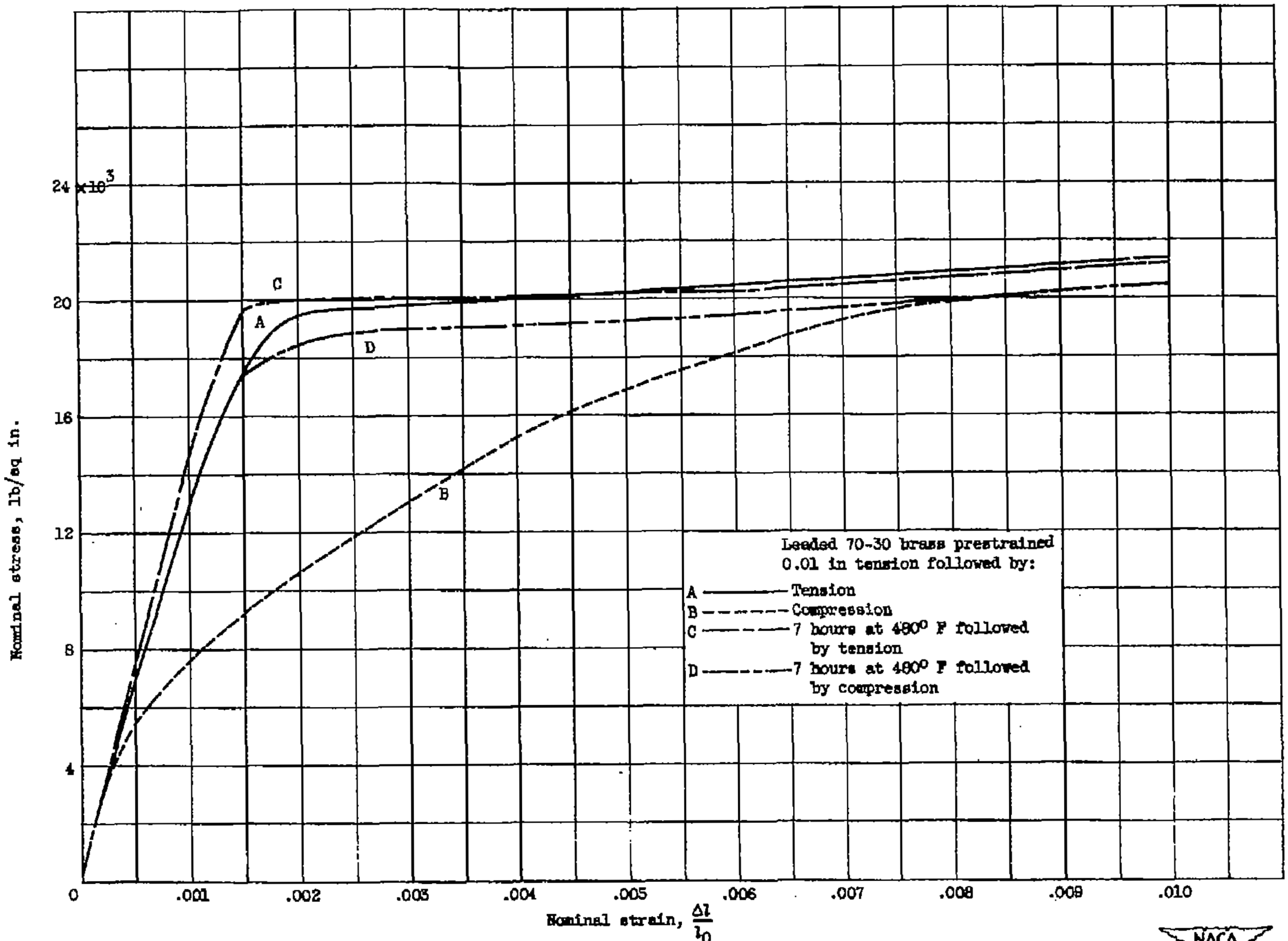
(a) Copper.

Figure 12. - Tension and compression stress-strain curves for tensile prestrained copper and brass specimens with and without intermediate anneals.



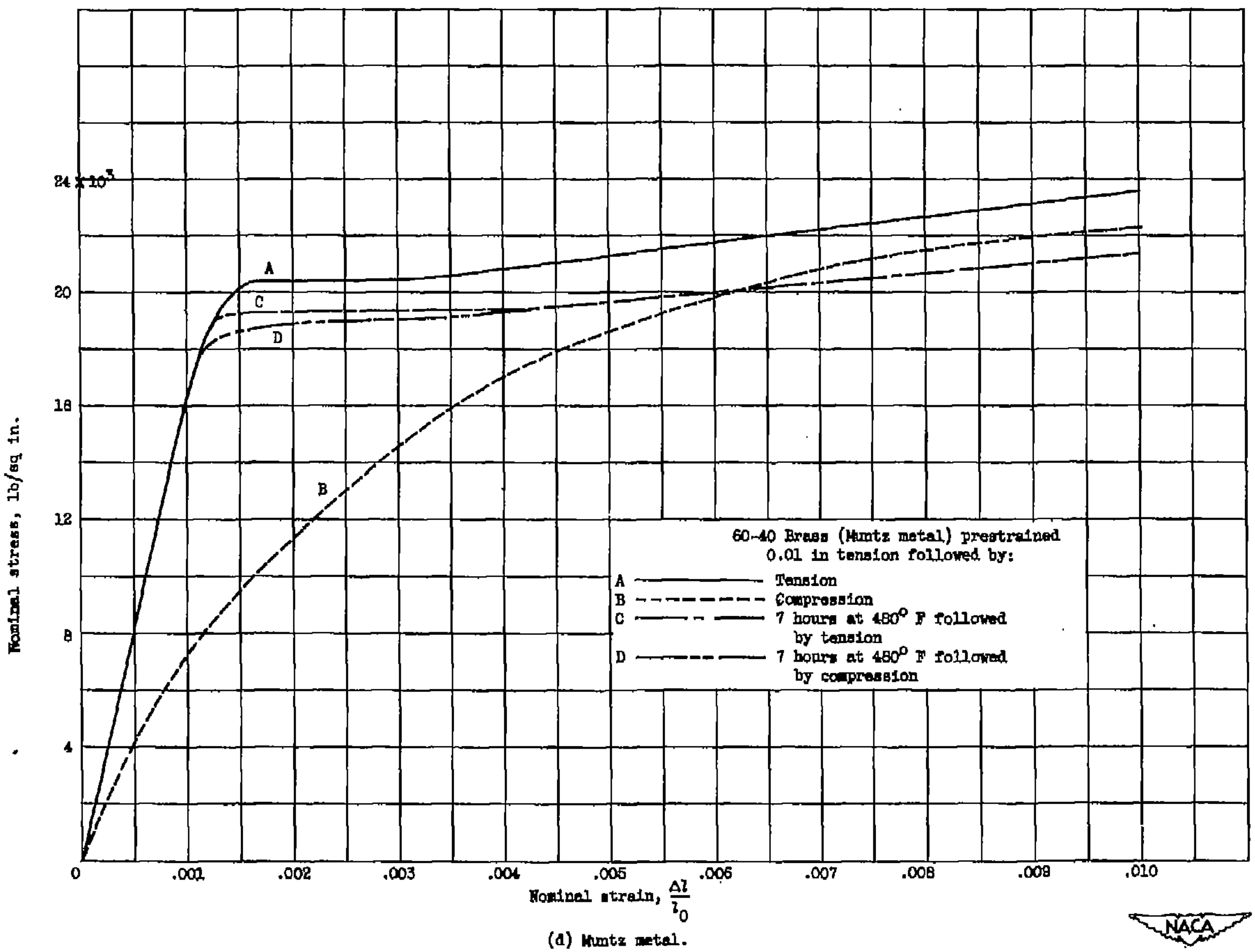
(b) Cartridge brass.

Figure 12. - Continued. Tension and compression stress-strain curves for tensile prestrained copper and brass specimens with and without intermediate anneals.



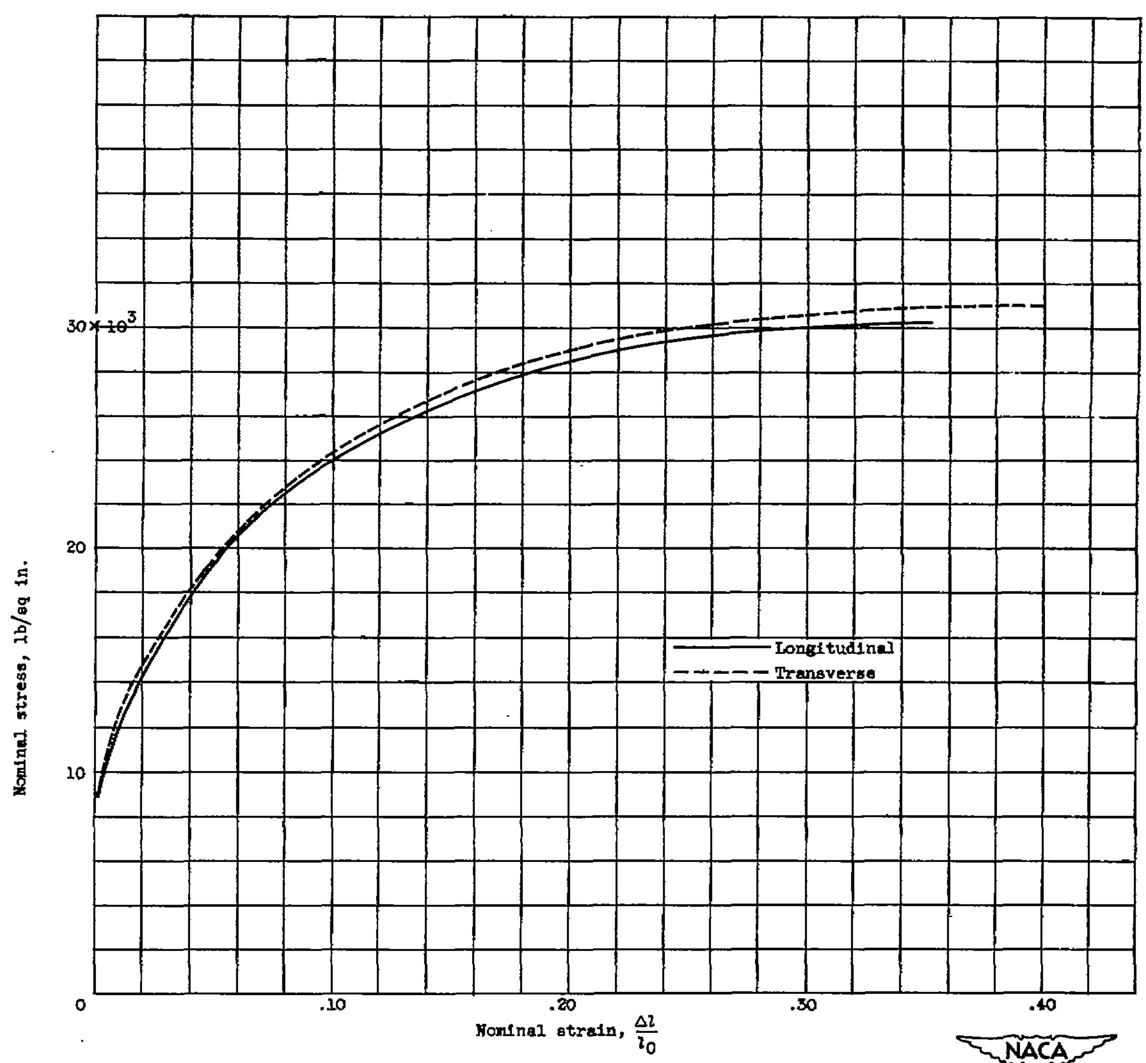
(c) Leaded 70-30 brass.

Figure 12. - Continued. Tension and compression stress-strain curves for tensile prestrained copper and brass specimens with and without intermediate anneals.



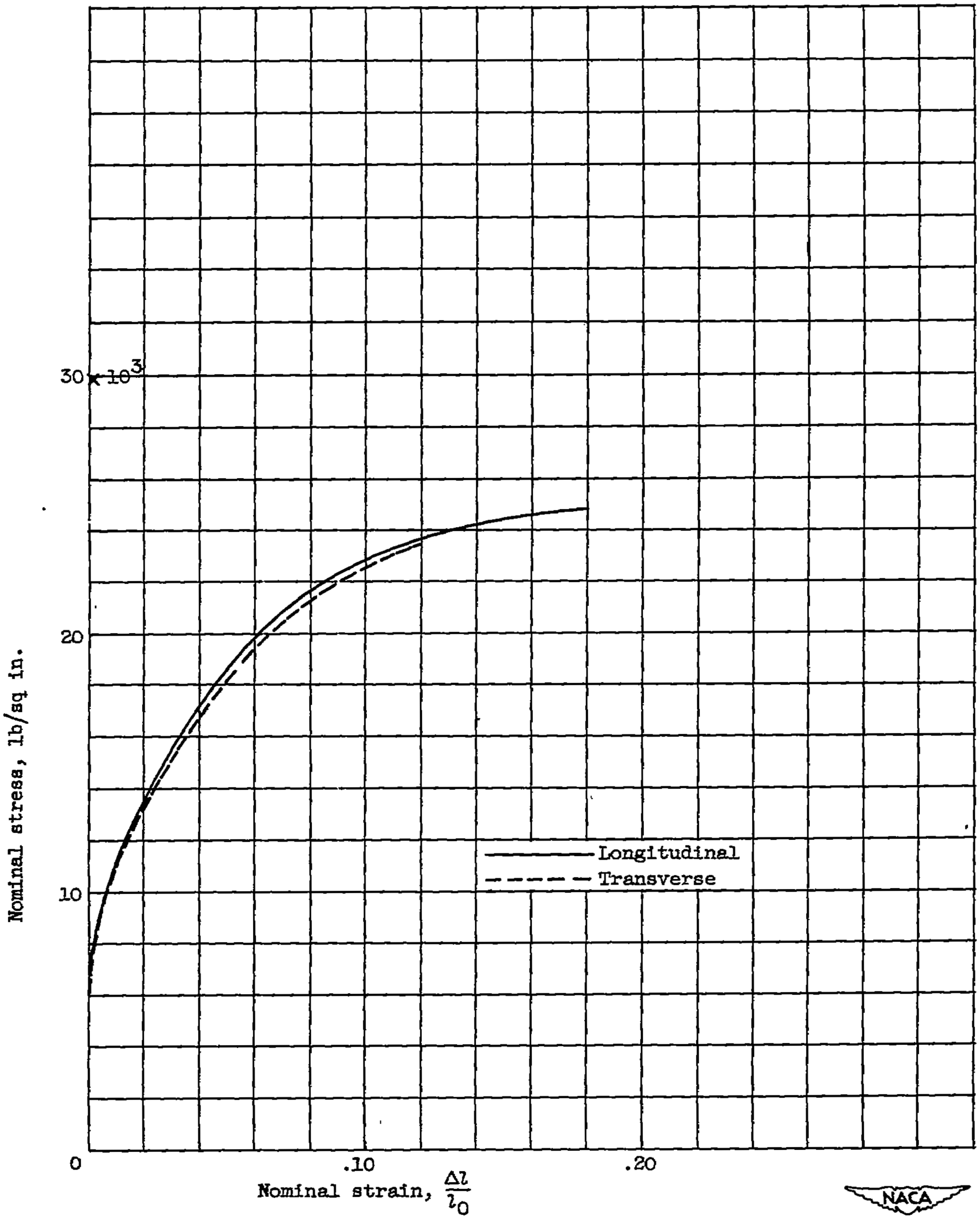
(d) Muntz metal.

Figure 12. - Concluded. Tension and compression stress-strain curves for tensile prestrained copper and brass and specimens with and without intermediate anneals.



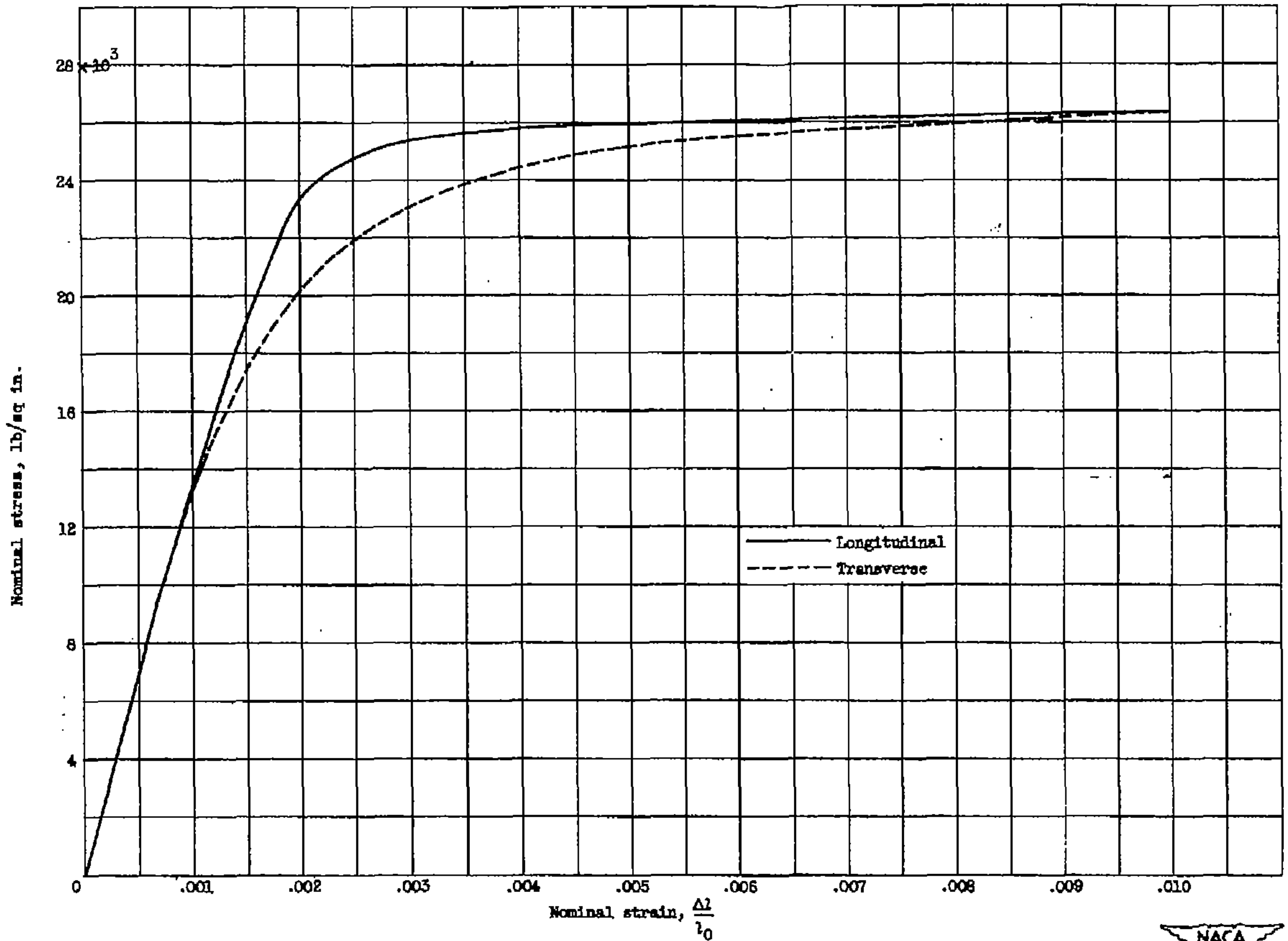
(a) Isotropic copper.

Figure 13. - Longitudinal and transverse stress-strain curves for isotropic and cubically alined copper sheet.



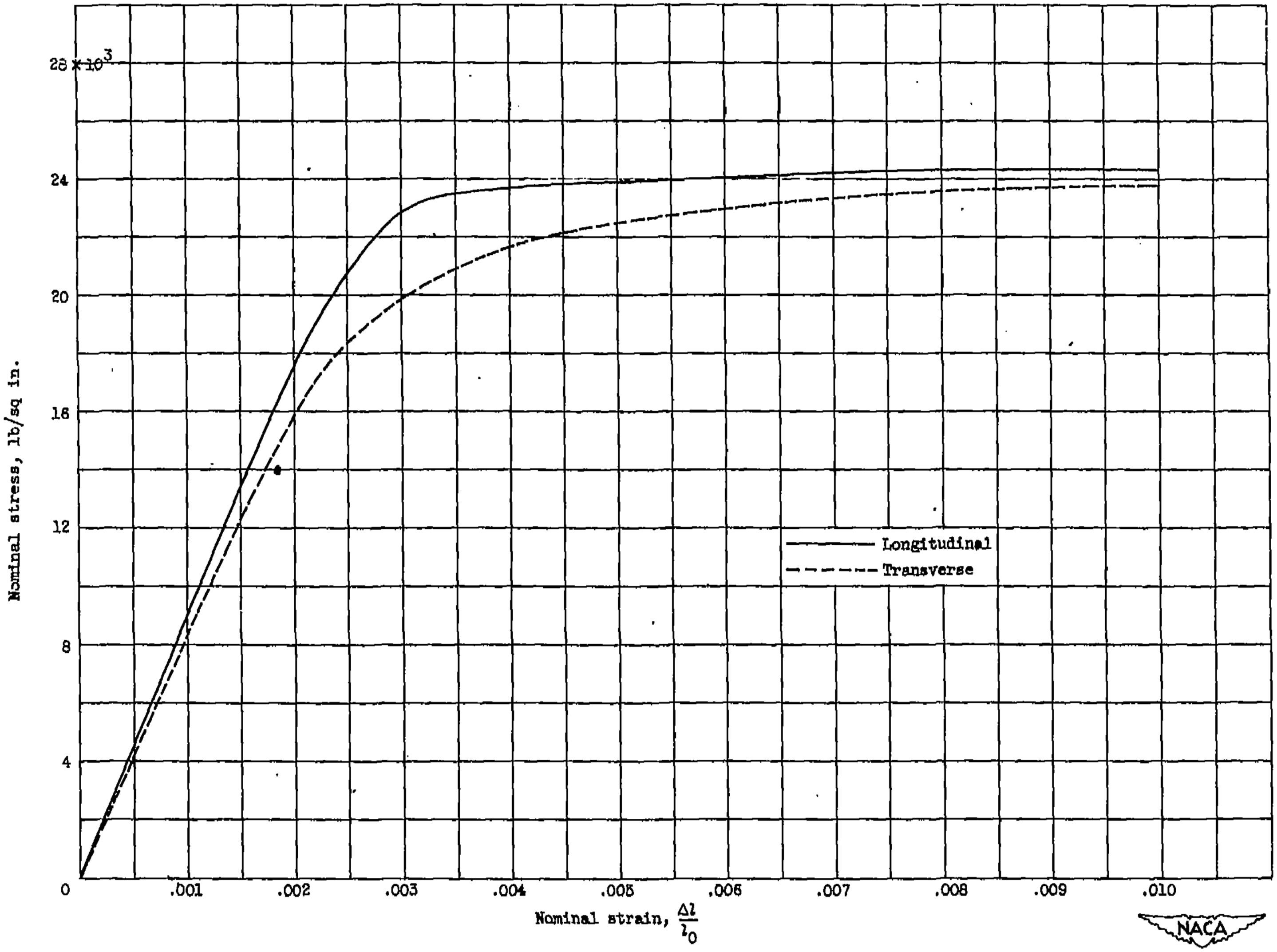
(b) Cubically alined copper.

Figure 13. - Concluded. Longitudinal and transverse stress-strain curves for isotropic and cubically alined copper sheet.



(a) Isotropic.

Figure 14. - Longitudinal and transverse tension stress-strain curves for specimens cut from isotropic and cubically alined copper sheet prestrained 10 percent in tension.



(b) Cubically alined.

Figure 14. - Concluded. Longitudinal and transverse tension stress-strain curves for specimens cut from isotropic and cubically alined copper sheet prestrained 10 percent in tension.

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