NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 967

SHEAR ELASTIC PROPERTIES OF SOME HIGH STRENGTH NONFERROUS METALS AS AFFECTED BY PLASTIC DEFORMATION AND BY HEAT TREATMENT

By R. W. Mebs and D. J. McAdam, Jr.
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SUMMARY

A study was made of the shear elastic properties of monel, nickel, Inconel, and aluminum-monel tubing, as influenced by extension of annealed specimens, by cold reduction during manufacture, and by stress-relief annealing of cold-reduced materials. The properties studied were the shear proof stresses and the shear modulus of elasticity and its variation with stress.

The factors which determine the variation of the shear elastic properties of these metals with plastic deformation and annealing temperature are shown to be (a) internal stress, (b) work-hardening or lattice expansion, and (c) crystal reorientation.

With slight extension of annealed tubing, the shear proof stresses generally decrease, owing to induced internal stress. Subsequent extension, or cold reduction, causes a rise of shear proof stress, due to the dominant influence of the work-hardening factor. A small increase of proof stress is obtained upon cold-reduced monel, Inconel, and aluminum-monel tubing by annealing at fairly low temperatures, owing to the relief of internal stress. With further increase of annealing temperature, there is a continuous decrease of shear proof stress for monel, nickel, and Inconel tubing, due to relief of work-hardening effects and recrystallization. For aluminum-monel, there is obtained a marked increase in proof stress by holding at temperature immediately below the recrystallization range. This rise is due to precipitation-hardening.

A rise of the shear modulus of elasticity is obtained with moderate cold reduction of monel and nickel tubing, but

not with extension of the annealed tubing. Evidence is given that this difference probably is due to the directional influence of internal stress induced during prior deformation upon subsequently measured elastic moduli; that is, such directional influence is believed to be more prominent for extended annealed tubing than for cold-reduced tubing. The internal stress induced during prior extension probably has little effect on the shear modulus as subsequently measured; it would more greatly affect tensile modulus measurements. The effect of internal stress induced during cold reduction would affect tensile and shear moduli more nearly alike.

A decrease of the shear modulus of elasticity is observed with extension of monel and aluminum-monel tubing. It is also observed over at least a portion of the range of cold reduction of all the metals tested. This decrease is believed to be due to the combined dominant influence of the work-hardening factor and preferred crystal orientation. The relative influence of each of these two factors, however, is not established.

With increase of annealing temperature for cold-reduced Inconel and aluminum-monel, a rise of the shear modulus is observed. This rise is accredited to the combined influence of relief of the work-hardening effects and recrystallization.

INTRODUCTION

The demand for more detailed information about the deformation of metals under applied stress, within the useful working stress range, has resulted in numerous investigations of significant elastic properties of metals. In a project sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics at the National Bureau of Standards, a series of reports (references 1, 2, 3, 4, and 5) has been presented upon the tensile and shear elastic properties of high strength aircraft metals. The elastic properties investigated were (a) the proof stresses producing selected proof sets, (b) the tensile and shear moduli of elasticity and their variation with applied stress, and (c) Poisson's ratio and its variation with stress. The influence of cold work and of heat treatment upon these properties was also studied. These indices were derived from correlated stress-strain and stress-set curves, as described in the earlier reports (references 1, 2, 3, 4, and 5).

These earlier reports discussed tensile-elastic properties for a large number of metals (references 1, 2, and 3) and torsional-elastic properties for 18:8 chromium-nickel steel (references 4 and 5). The present report, which is the sixth of the series, discusses the shear elastic properties of monel, nickel, Inconel, and aluminum-monel. The shear properties, as in previously described investigations, were determined by means of torsion tests of tubing.

MATERIALS AND TESTS

The material used in this investigation was obtained from The International Nickel Company through the cooperation of Dr. W. A. Mudge, Assistant Director of the Technical Service Section; it was supplied in the form of seamless tubing of 1-inch outside diameter and 0.085-inch wall thickness, nominal size. Each material was supplied in several hardness grades, as obtained by cold reduction without intermediate anneal; Inconel and aluminum-monel were also supplied in a soft annealed condition. There was also supplied, of each material, tubing which had been severely cold-reduced and then normalized or stress-relief-annealed at 500° F. All hardness grades of a single material were from the same heat. Chemical compositions are listed in table I. Mechanical and thermal treatments of individual specimens are listed in table II.

Cold deformation in manufacture was applied to these tubular materials by "cold-drawing" or by the "tube-reducer" method. The method applied to each material is indicated in table II. Cold-drawing consists in drawing the tubing between an ordinary drawing die and a mandrel. The tube-reducer method consists in kneading the tubing over a mandrel with the aid of rolls. Both processes will be referred to in this report as cold reduction, in order to differentiate from the cold deformation obtained by tensile extension of specimens soft-annealed in this laboratory.

Specimens from each of the cold-reduced and of the annealed materials were prepared for torsion testing in the as-received condition. The normalized, cold-reduced material was softened by further annealing at a higher temperature. Individual laboratory-annealed specimens were then extended varying amounts in a tension testing machine before testing in torsion.

The method of preparing and measuring torsion specimens was described in an earlier report (reference 4). The torsion tests were made in a manually operated, pendulum-type torsion testing machine of 13,000 inch-pound capacity. The optical torsion meter employed was the same as that used in the earlier investigation (reference 4). Shear stress-strain and stress-set curves were measured simultaneously on each specimen by methods explained previously (references 1, 2, 3, and 4). From these were derived the various shear elastic indices.

Stress-deviation and stress-set curves and the derived stress-modulus curves are not given in this report. Such curves are illustrated, however, in earlier reports (references 1, 2, 3, and 4). The relationship between the forms of such curves and the values of the derived indices are also given in the earlier reports.

THE INFLUENCE OF PLASTIC DEFORMATION AND HEAT TREATMENT UPON THE SHEAR ELASTIC PROPERTIES OF MONEL TUBING

Influence of Prior Plastic Extension and Cold Reduction upon the Shear Elastic Strength of Monel

Monel tubing (TGE) which had been cold-reduced 75 to 80 percent in area of cross section and normalized at 500° F during manufacture was soft-annealed at 1400° F. Individual annealed specimens were then extended 0.46, 1.11, 1.92, 2.83, 4.67, and 10.13 percent, respectively. Shear proof stress values derived from torsion stress-set curves measured upon these specimens are plotted in figure 1A. The amount of extension expressed as equivalent reduction of area is plotted as abscissa. The shear proof stresses are plotted upon offset scales in order to separate the values corresponding to the various proof sets indicated: namely, 0.001, 0.003, 0.01, 0.03, and 0.1 percent. The experimentally derived points are connected by straight lines. A smooth curve drawn through the experimentally derived points would not deviate greatly from these lines. With increasing plastic deformation (fig. 1A), the various proof stresses exhibit an initial sharp decrease, followed by a slower rise. The initial decrease is most pronounced for the lower proof sets, and the subsequent increase is more rapid at the higher proof sets. The 0.001

and 0.003-percent proof stresses do not reach during 10.13-percent extension (9.2-percent reduction of area) the values obtained at zero reduction (fig. 1A).

In figure 1B are plotted shear proof stresses obtained with monel tubing cold-reduced 10, 20, 30, and 40 percent during manufacture. The amount of cold reduction in cross section is plotted as abscissa. Symbols denoting the various cold-reduced grades are marked on the diagram along corresponding abscissa. Proof stress values for the fully annealed monel specimens are plotted at zero equivalent reduction in both figures 1A and 1B.

With increasing cold reduction (fig. 1B) all the proof stresses rise. This rise is greatest between zero and 10-percent reduction. Values of proof stress for the annealed metal and monel cold-reduced 10 percent are connected by broken straight lines; the exact course of these curves is not known.

In earlier reports (references 2 to 6) were discussed the various factors which influence the variation of proof stress. These factors are (1) macroscopic internal stress and microstructural stress, hereafter referred to as internal stress, and (2) the work-hardening or lattice expansion factor. The initial decrease in proof stress with extension of the annealed metal (fig. 1A) is probably due to an increase of internal stress. (See references 2, 4, and 6.) The subsequent rise of proof stress with extension (fig. 1A) and the rise with cold reduction (fig. 1B) may be attributed to the influence of the second factor, work-hardening (references 2, 4, and 6).

It should be noted that the shear proof stresses corresponding to 9.2 percent equivalent reduction (fig. 1A), especially those corresponding to the smaller proof sets, are somewhat lower than the shear proof stresses obtained with monel tubing cold-reduced 10 percent (fig. 1B). This difference may be attributed either to a more deleterious influence of internal stress induced by the extension process than by cold reduction, or possibly because cold reduction during manufacture may have been imparted to hot-rolled tubing, rather than to annealed tubing.

Influence of Prior Plastic Extension and Cold Reduction upon the Shear Modulus of Elasticity of Monel Tubing

The variation of the shear modulus of elasticity with extension of annealed monel and with cold reduction of monel is shown in figures 2A and 2B, respectively. Values obtained for the fully annealed metal are plotted at zero equivalent reduction in both figures. The method of derivation of the modulus was described in earlier reports (references 1, 2, 4, and 6).

Because the stress-strain lines for monel, and for many other metals, are curved in form, it becomes desirable to specify the stress at which the modulus was measured.* In earlier reports (references 1, 2, 3, and 6), the tensile modulus was selected at zero stress and generally at 25,000 and 50,000 psi. Nadai (reference 7) has suggested that the stress-strain curve for a metal in pure shear can be derived from its stress-strain curve in tension, by multiplying stresses by $1/\sqrt{3}$ and strains by 1.5. This relationship will hold accurately only for isotropic metals, provided some questionable assumptions employed in its derivation are valid. As a first approximation, however, it may be applied to all metals. Therefore, shear modulus values were obtained at zero stress, and where possible at 14,450 and 28,900 psi. These modulus values are to be utilized in a later report (to be published) in calculating Poisson's ratio.

With prior extension of the annealed metal, G_o and $G_{14.45}$ are both found to decrease (fig. 2A); G_o, $G_{14.45}$, and $G_{28.9}$ rise with increase of cold reduction (fig. 2B) from 10 to 20 percent, and decrease continuously with further cold reduction to values below that obtained for the annealed metal. After 10.13-percent extension (9.2-percent reduction in fig. 2A), however, the values of G_o, $G_{14.45}$, and $G_{28.9}$ (the latter point indicated by the lowest of the three points plotted at this reduction) are somewhat lower than the values obtained by 40-percent cold reduction (fig. 2B).

With increasing extension (fig. 2A), the linear stress coefficient, C_o, rises to a maximum at about 2-percent

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*In this report, as in earlier reports (references 1, 2, 3, 4, and 6), the modulus is given as the ratio of the stress to the elastic strain (the total strain corrected for permanent set).

equivalent reduction, decreasing rapidly thereafter to zero. With cold reduction (fig. 2B), a zero value of C_o is obtained, except for the tubing cold-reduced 40 percent; the indicated variation of the shear modulus with stress, however, signifies that for some of the tubes the modulus does not vary linearly with stress.

It is apparent that the influence upon the shear modulus of extension differs from that of cold reduction. The decrease of the modulus during prior extension probably can be attributed to the predominating influence of the work-hardening or lattice-expansion factor. The internal stress induced during prior extension does not greatly affect the shear modulus values, as has been explained in an earlier report (reference 5). As stated there, maximum shear occurs along different planes during prior extension than during torsion testing. The internal stress set up during extension would have appreciably less influence upon subsequent torsion measurements than it would if the planes of maximum shear were the same during prior deformation and during testing. As previously stated (reference 5), residual stress produced during extension is anisotropic in its influence upon some of the subsequently measured elastic properties.

With cold reduction of monel, the initial rise of the shear modulus indicates that the work-hardening factor does not predominate. It is known that during cold reduction, the most active slip planes will not have the same orientations throughout the cross section of the tube. The internal stresses produced during such reduction will therefore be more nearly isotropic in their influence upon subsequently measured elastic properties than during extension. It is probable that such internal stress will therefore predominate in causing a rise of shear modulus for cold reductions up to 20 percent. The decrease of the shear modulus for reductions greater than 20 percent (fig. 2B) may be attributed to the combined influence of lattice expansion, and to another factor, crystal reorientation. The influence of this latter factor, which will be discussed in more detail later, may also be effective in causing the decrease of the shear modulus with extension of annealed monel (fig. 2A).

The causes for variation of the linear stress coefficient of the modulus C_o are not so evident; the value of C_o is difficult to evaluate accurately and is generally small.

The Influence of Annealing Temperature on the Shear Elastic Properties of Monel Tubing

There is shown in figure 9A the variation of the shear proof stresses with annealing temperature. These values were derived from tests on a series of cold-reduced monel tubes TGD, annealed at 300°, 500°, 700°, 900°, 1000°, 1100°, and 1200° F, respectively. Proof stress values obtained upon an unannealed specimen TGD are plotted at 100° F, and the values obtained upon a soft-annealed specimen TGE are replotted from figure 1 at 1400° F.

With increase of annealing temperature, all proof stresses rise, reaching a maximum at 300° F for 0.1 percent proof set and at 500° F for the remaining proof sets. With further increase all proof stresses decrease; this decrease is most rapid for the 0.1 percent proof set. All proof stresses decrease at their maximum rate for annealing temperatures between 1200° and 1400° F. The initial rise may be attributed to relief of deleterious internal stress; the subsequent decrease to the removal of work-hardening effects and to recrystallization.

In figure 10 are plotted values of the shear modulus and its linear stress coefficient C_0, obtained on these same annealed specimens. With increase of annealing temperature, the several modulus curves rise slowly to maxima at about 900° F. The linear stress coefficient of the modulus, C_0, likewise reaches a maximum at 900° F, decreasing to zero for an annealing temperature of 1400° F. The actual variation of the shear modulus curves is small; this would indicate that no single factor predominates in its influence upon this property during annealing of monel. The absolute values of C_0 are quite small; no great significance can be attached to their variation.

THE SHEAR ELASTIC PROPERTIES OF NICKEL, INCONEL, AND ALUMINUM-MONEL TUBING

Influence of Plastic Deformation on the Shear Elastic Strength

The variation of shear proof stress with extension of soft-annealed nickel (TRF), Inconel (TLD), and aluminum-monel

(THD) tubing are shown in figures 3A, 5A, and 7A, respectively. With extension of annealed nickel (fig. 3A), the 0.1- and 0.03-percent shear proof stresses show a slight initial rise. The lower proof stresses for annealed nickel, as well as all proof stresses for annealed Inconel (fig. 5A) and aluminum-monel (fig. 7A), exhibit an initial decrease. This decrease is most marked at the lower proof stresses. At greater extensions, proof stresses for all metals rise; this rise is most rapid at the greater values of set. Similar proof stress extension curves were obtained with annealed monel tubing (fig. 1A).

With increase of cold reduction of nickel (fig. 3B), Inconel (fig. 5B) and aluminum-monel (fig. 7B), all proof stresses exhibit a rise. Values for the laboratory-annealed tubing, as well as for the factory-annealed Inconel (fig. 5B) and aluminum-monel (fig. 7B), are plotted at zero reduction of area; broken lines connect these points with the points representing the smallest cold reductions. The actual variation of proof stresses in this range may deviate appreciably from such a linear relationship. Solid lines connecting the points representing the various cold reductions would correspond more nearly to the actual variation of these proof stresses.

The initial decrease of proof stress with extension for these metals is probably due to the dominant influence of induced internal stress. The subsequent rise of proof stress, as well as the rise exhibited for cold-reduced tubing, may be attributed to the dominant influence of the work-hardening or lattice-expansion factor.

Influence of Plastic Deformation on the Shear Modulus of Elasticity and its Linear-Stress Coefficient

With extension of annealed nickel (TRF) (fig. 4A), the shear modulus of elasticity, G_o, exhibits a sharp initial rise; at greater extensions, little variation of the shear modulus is noted. With extension of annealed aluminum-monel (THD) (fig. 8A), little variation is likewise obtained. With extension of annealed Inconel tubing (TLD) (fig. 6A), however, there is a general decrease of shear modulus similar to that obtained with annealed monel (fig. 2A).

With increase of cold reduction, nickel tubing (fig. 4B) exhibits an initial increase of the shear modulus, G, followed by a decrease. This is similar to the variation obtained with monel tubing (fig. 2B). Inconel (fig. 6B) and aluminum-monel (fig. 8B), however, exhibit a continuous decrease of G with increase of cold reduction.

The decrease of the shear modulus with extension of annealed Inconel (fig. 6A) may be attributed to the dominant influence of either work-hardening or crystal orientation. The horizontal position of the shear modulus curves for extended annealed nickel (fig. 4A) and aluminum-monel (fig. 8A), however, suggests that no single factor has a dominant influence on the shear modulus in this range.

Little significance can be attached to the sharp rise of the shear modulus during initial extension of annealed nickel (fig. 4A). Owing to the extremely small stress range over which strain is measured, as indicated by the 0.1-percent proof stress value in figure 3A, the determination of the shear modulus may be subject to considerable error. With subsequent extension, however, the stress range is greater, increasing the accuracy of determining the shear modulus.

With increase of cold reduction of nickel (fig. 4B), the initial rise of the shear modulus may be attributed to the predominant influence of internal stress. The decrease of the shear modulus, with subsequent cold reduction of nickel (fig. 4B), and throughout the cold-reduction range of Inconel (fig. 6B) and aluminum-monel (fig. 8B), may be attributed to the combined dominant influence of the lattice expansion and crystal reorientation factors. A discussion of the relative influence of these factors will be given later.

With extension of annealed nickel (fig. 4A), the linear stress coefficient of the modulus C_0 has a zero value over nearly the whole range. For extended annealed Inconel (fig. 6A), a maximum value of C_0 is reached at about 3-percent equivalent cold reduction; whereas, for extended annealed aluminum-monel (fig. 8A), C_0 is still rising after 9.1-percent reduction.

With 30-percent cold reduction of nickel (fig. 4B), C_0 reaches a maximum; it decreases continuously with cold reduction of Inconel (fig. 6B). The variation of C_0 with cold reduction for these latter two metals is qualitatively similar to the variation of their shear modulus G. A maximum value of C_0 is reached at 40-percent cold reduction of aluminum-monel (fig. 8B). The magnitude of the values of C_0 attained with extension of annealed nickel, and with cold reduction of both nickel and aluminum-monel, however, is generally small.

The rise of C_0, with extension of annealed Inconel and annealed aluminum-monel, and with cold reduction of nickel and aluminum-monel, may be attributed to the dominant influence of induced internal stress. The subsequent decrease of some of these curves may be attributed to the dominant influence of the lattice-expansion factor and probably to some extent to crystal reorientation.

The large value of C_0 for the factory-annealed Inconel (fig. 6B) is commensurate with large values of G and small values of proof stress (fig. 5B) obtained on this metal. It is believed probable that this material was straightened, following factory annealing, thereby inducing internal stress.

Influence of Annealing Temperature on the Shear Elastic Strength

In figure 9B is shown the variation of the shear proof stresses with annealing temperature for cold-reduced nickel, TRE. With increase of annealing temperature, there is a continuous decrease of shear proof stress; this decrease is most rapid between 1100° and 1200° F. With increase of annealing temperature the shear proof stresses for cold-reduced Inconel TLC (fig. 12A) rise to maxima between 700° and 800° F and decrease continuously at higher temperatures; the most rapid decrease occurs between 1100° and 1300° F. For cold-reduced aluminum-monel, THC (fig.12B), there are two maxima in the proof stress-annealing temperature curves. The first occurs at about 500° F, the second and much higher maxima at 1075° F. The aluminum-monel specimen annealed at 1075° F was held at temperature for 10 hours. Proof-stress values obtained upon soft annealed specimens and plotted in figures 3A (TRF), 5A (TLD), and 7A(THD) are replotted in figures 9B, 12A, and 12B, respectively.

The initial rise of proof stress with temperature for Inconel (fig. 12A) and aluminum-monel (fig. 12B) tubing is probably due to the dominant influence of relief of internal stress. The second maximum in proof stress for the aluminum-monel may be attributed to precipitation hardening of this alloy. Such precipitation hardening is additive to previous hardening by cold work. The decrease of proof stress obtained subsequently on Inconel (fig. 12A) and aluminum-monel (fig. 12B), and throughout the temperature range for nickel (fig. 9B), may be attributed to the combined dominant influence of relief of work-hardening effects and recrystallization.

Influence of Annealing Temperature on the Shear Modulus of Elasticity and Its Linear Stress Coefficient

With increase of the temperature of annealing of cold-reduced nickel (fig. 11A), the shear modulus G shows little variation except for a sharp rise at 1200° F followed by an abrupt drop at 1450° F. The stress range over which strain was measured on these latter two specimens is so small (see 0.1-percent proof stress, fig. 9B) that an accurate calculation of the modulus was not possible. The shear modulus of Inconel (fig. 11B) and of aluminum-monel (fig. 13) rises continuously with increase of annealing temperature. The highest value of G for Inconel is obtained with the factory-annealed tubing.

The rise of the shear modulus with annealing temperature, for Inconel and aluminum-monel, may be attributed to the influence of relief of work-hardening and to recrystallization. With increase of annealing temperature of nickel, however, no single factor appears to have a dominant influence on the shear modulus.

With increase of annealing temperature upon nickel (fig. 11A) or Inconel (fig. 11B), there is no regular variation of the linear stress coefficient of the shear modulus, C_0; the magnitude of C_0 is generally small. As was noted before (fig. 6B), the value of C_0 for factory-annealed Inconel is large; C_0 for aluminum-monel (fig. 13) tends to decrease with increase of annealing temperature; its magnitude, however, is small.

THE INFLUENCE OF VARIOUS FACTORS UPON THE SHEAR ELASTIC PROPERTIES OF NONFERROUS METALS

In earlier reports (references 1 to 6) much attention has been given to the influence of several fundamental factors upon the tensile and shear elastic strength and the elastic modulus of metals, as influenced by plastic deformation and heat treatment. These factors are (1) the internal stress, (2) the work-hardening or lattice-expansion factor, and (3) preferred crystal orientation.

The introduction of internal stress tends to lower the shear proof stress, as is evident after slight extension of annealed metals (figs. 1A, 3A, 5A, and 7A). The influence of internal stress upon the shear modulus, however, is apparently dependent upon the relative positions of the planes on which maximum slip occurs during cold working and during subsequent testing. Its influence upon the shear modulus is not evident during shear testing of previously extended annealed tubing (reference 5). Since the planes upon which slip occurs during cold reduction, however, are apparently not so selective as during tensile extension, there is evidence during moderate cold reduction of monel and nickel tubing of induced internal stress. This causes a rise of the shear modulus G (figs. 2B and 4B). Such induced internal stress may cause the lowering of proof stresses and increase of shear modulus obtained with factory-annealed Inconel tubing TIA, owing to a possible post-annealing straightening operation (figs. 6B and 11B).

The influence of the lattice-expansion factor is evident in the increase of proof stress and the lowering of the shear modulus of elasticity. With increase of cold deformation, as produced by extension or by cold reduction, a sharp rise of proof stress is produced, owing to the predominance of this factor (figs. 1, 3, 5, and 7). The limit of work-hardening is evidently obtained, for the nickel, Inconel, and aluminum-monel tubing, after about 40-percent cold reduction in area. The lowering of the shear modulus by the influence of the work-hardening factor is most evident in the extension of monel and Inconel tubing (figs. 2A and 6A) and in the cold reduction of Inconel and aluminum-monel tubing (figs. 6B and 8B). There is little evidence that the work-hardening factor has a significant effect upon the shear modulus of nickel (reference 6 and fig. 4).

All of the metals tested are of the face-centered cubic type. After cold deformation, such metals tend to assume a duplex crystal orientation along the specimen axis - namely, cubic [100] and octahedral [111]. The proportion of each orientation produced will greatly affect the value of the shear modulus of elasticity. Earlier work (references 2 and 6) tends to indicate that the orientation textures produced in monel and nickel are predominantly octahedral [111]; such a texture might also be expected to be found in severely cold-deformed aluminum-monel. A predominantly octahedral orientation would tend to give a lower value of the shear modulus than obtained if the orientation were randomly distributed (references 2 and 6).

Although preferred orientation is generally observed in metals by X-ray measurements only after severe plastic deformation, the limiting deformation cannot be established at which preferred orientation first exerts a dominant influence upon the shear modulus. The relative influence of lattice-expansion and of preferred crystal reorientation, in causing a lowering of the shear modulus during deformation, therefore, is not apparent. In earlier measurements of the tensile modulus (references 2 and 6), however, there was scattered evidence that the influence of preferred crystal orientation was dominant even at small deformations.

It was noted in earlier reports (references 2 and 6) that preferred crystal orientation influences tensile and shear moduli in an opposite manner. There is evidence that internal stress will tend to cause an increase of both the shear and tensile moduli. The relative influence of such internal stress is dependent, however, upon the directions of slip planes during prior deformation and during strain measurements. It is likewise believed that lattice expansion will tend to decrease both tensile and shear moduli. Comparison of the variation of tensile and shear moduli of metals, as influenced by plastic deformation and heat treatment, should provide valuable information of the relative influence of the various factors.

Measurements are now being made of the tensile elastic properties upon a series of tubular specimens similar to those tested in torsion for this investigation. A comparison of these values with values given in the present report will be published shortly.

CONCLUSIONS

The effects of plastic deformation and of heat treatment on the shear elastic properties of monel, nickel, Inconel, and aluminum-monel tubing were studied. The variation of these properties is influenced by three important factors - namely, (a) internal stress, (b) the work-hardening or lattice-expansion factor, and (c) crystal orientation. In the following summation, the relative influence of these three factors will be discussed. These conclusions apply to all of the metals tested except as indicated.

1. With plastic extension of annealed tubing, the shear proof stresses exhibit an initial decrease or a slight rise, followed by a more rapid rise. Induced internal stress is evident after slight extensions; whereas the work-hardening factor dominates following large deformations.

2. Moderate cold reduction, as produced either by cold-drawing or by the "tube-reducer" method, causes a large increase of shear proof stress. The work-hardening factor evidently dominates in causing this rise. Severe cold reduction does not produce an appreciable rise in proof stress above that obtained at 40-percent reduction, for the size of tubing tested.

3. Annealing of cold-reduced monel, Inconel, and aluminum-monel tubing at intermediate temperatures leads to a noticeable increase in all shear proof stresses. This is taken as evidence for the relief of internal stress. A marked increase in all proof stresses is obtained with aluminum-monel metal after holding at higher temperatures, within the precipitation hardening range; a fairly long holding time at temperature is required to obtain a maximum rise in proof stress. With increase of annealing temperatures above those required to obtain these maxima, the proof stresses for these metals decrease. The proof stresses for nickel tubing decrease continuously with increase of annealing temperature. The most rapid decrease of proof stress for all metals occurs for annealing temperatures in the vicinity of 1200° F. The decrease in proof stress with rise of annealing temperature is due to the dominant influence of relief of work-hardening and to recrystallization.

4. With extension of annealed monel and Inconel tubing, there occurs a lowering of the shear modulus of elasticity due to the dominant influence of the work-hardening factor and perhaps to some extent to preferred crystal orientation. No significant variation of the shear modulus of nickel and of aluminum-monel tubing occurs with such extension.

5. With increase of cold reduction of monel and nickel tubing the shear modulus of elasticity rises first to a maximum, followed by a decrease at greater reductions; internal stress probably predominates during early cold reduction. For Inconel and aluminum-monel the shear modulus decreases continuously with increase of cold reduction. The decrease

of the shear modulus with cold reduction of all metals is probably due to the combined dominant influence of the work-hardening factor and the production of preferred orientation of grains as obtained with cold reduction. The relative influence of these two factors has not been established.

6. With increase of annealing temperature, the shear modulus of elasticity of Inconel and aluminum-monel tubing rises continuously. This rise is evidently due to the dominant influence of relief of work-hardening effects and recrystallization. No significant variation of the shear modulus of elasticity of monel and nickel tubing with change of annealing temperature is observed. The shear modulus of elasticity of factory-annealed Inconel tubing is somewhat greater than that obtained for the laboratory annealed tubing.

7. Although considerable fluctuation is observed of the linear stress coefficient of the shear modulus, C_0, with plastic deformation and variation of annealing temperature, the magnitude of these fluctuations is generally not significant. The decrease of the shear modulus with stress, obtained in tests of some specimens for which the value of C_0 is zero, indicates that the variation of the shear modulus with stress is of quadratic or higher order. The variation of the shear modulus with stress, however, is generally not proportionally as great as was obtained earlier from tensile tests on tensile bars of similar materials.

Although the conclusions drawn apply specifically to the tubular materials tested, it appears probable that they are applicable qualitatively to many other metals.

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Washington, D. C., July 1944.

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TABLE I.- CHEMICAL COMPOSITION OF TUBING *

Metal	Designation	Carbon (percent)	Iron (percent)	Nickel (percent)	Copper (percent)	Chromium (percent)	Manganese (percent)	Aluminum (percent)	Sulphur (percent)	Silicon (percent)
Monel	TG	0.13	1.49	67.64	29.70	--------	0.98	--------	0.005	0.05
Nickel	TR	.04	.05	99.53	.04	--------	.28	--------	.005	.03
Inconel	TL	.08	6.40	79.33	.15	13.64	.20	--------	.011	.17
Aluminum-monel	TH	.16	.33	66.42	29.68	--------	.25	2.80	.005	.33

*Mill analyses

TABLE II.- DETAILS OF THERMAL AND MECHANICAL TREATMENTS OF METAL TUBING

Metal	Treatment as received	Specimen designation	Annealing temperature (deg F)	Time held (hr)	Cooled in	Mechanical treatment following heat treatment
Monel	Cold drawn 10 percent	TGA	----------	As received	--------	------------
	Cold drawn 20 percent	TGB	----------	As received	--------	------------
	Cold drawn 30 percent	TGC	----------	As received	--------	------------
	Cold drawn 40 percent	TGD	----------	As received	--------	------------
		TGD-3	300	1	Air	------------
		TGD-5	500			
		TGD-7	700			
		TGD-9	900			
		TGD-10	1000			
		TGD-11	1100			
		TGD-12	1200			
	Tube reducer 75 to 80 percent, normalized at 500° F	TGE-14	1400	1	Air	As annealed
		TGD-14R-0.5				Extended 0.45 percent
		TGE-14R-1.0				Extended 1.10 percent
		TGE-14R-2.0				Extended 1.89 percent
		TGE-14R-3.0				Extended 2.75 percent
		TGE-14R-5.0				Extended 4.46 percent
		TGE-14R-10.0				Extended 9.20 percent
Nickel	Cold drawn 10 percent	TRA	--------	As received		
	Cold drawn 20 percent	TRB	--------	As received		
	Cold drawn 30 percent	TRC	--------	As received		
	Cold drawn 40 percent	TRD	--------	As received		
	Tube reducer 75 to 80 percent	TRE	--------	As received		
		TRE-3	300	1	Air	------------
		TRE-5	500			
		TRE-7	700			
		TRE-9	900			
		TRE-10	1000			
		TRE-11	1100			
		TRE-12	1200			
	Tube reducer 75 to 80 percent, normalized at 1500° F	TRF-14.5	1450	1	Air	As annealed
		TRF-14.5R-0.5				Extended 0.53 percent
		TRF-14.5R-1.0				Extended 1.11 percent
		TRF-14.5R-2.0				Extended 2.0 percent
		TRF-14.5R-3.0				Extended 3.0 percent
		TRF-14.5R-5.0				Extended 5.0 percent
		TRF-14.5R-10.0				Extended 10.0 percent
Inconel	Annealed	TLA	--------------	As received		
	Cold drawn 50 percent	TLB	--------------	As received		
	Tube reducer 75 to 80 percent	TLC	--------------	As received		
		TLC-3	300	1	Air	------------
		TLC-5	500			
		TLC-7	700			
		TLC-9	900			
		TLC-11	1100			
		TLC-13	1300			
		TLC-15	1500			
	Tube reducer 75 to 80 percent, normalized at 500° F	TLD-17.5	1750	1	Air	As annealed
		TLD-17.5R-0.5				Extended 0.48 percent
		TLD-17.5R-1.0				Extended 1.07 percent
		TLD-17.5R-2.0				Extended 1.92 percent
		TLD-17.5R-3.0				Extended 3.0 percent
		TLD-17.5R-5.0				Extended 4.5 percent
		TLD-17.5R-10.0				Extended 10.17 percent
		TLD-17.5R-17.25				Extended 17.25 percent
Aluminum-monel	Annealed	THA	---------------	As received		
	Cold drawn 40 percent	THB	---------------	As received		
	Tube reducer 60 percent	THC	---------------	As received		
		THC-3	300	1	Air	
		THC-5	500			
		THC-7	700			
		THC-9	900			
		THC-10	1000			
		THC-10.75	1075	10	Furnace	
	Tube reducer 60 percent, normalized at 500° F	THD-15.5	1550	1	Oil	As annealed
		THD-15.5R-0.5				Extended 0.47 percent
		THD-15.5R-2.0				Extended 1.98 percent
		THD-15.5R-3.0				Extended 2.75 percent
		THD-15.5R-5.0				Extended 4.38 percent
		THD-15.5R-10.0				Extended 10.0 percent

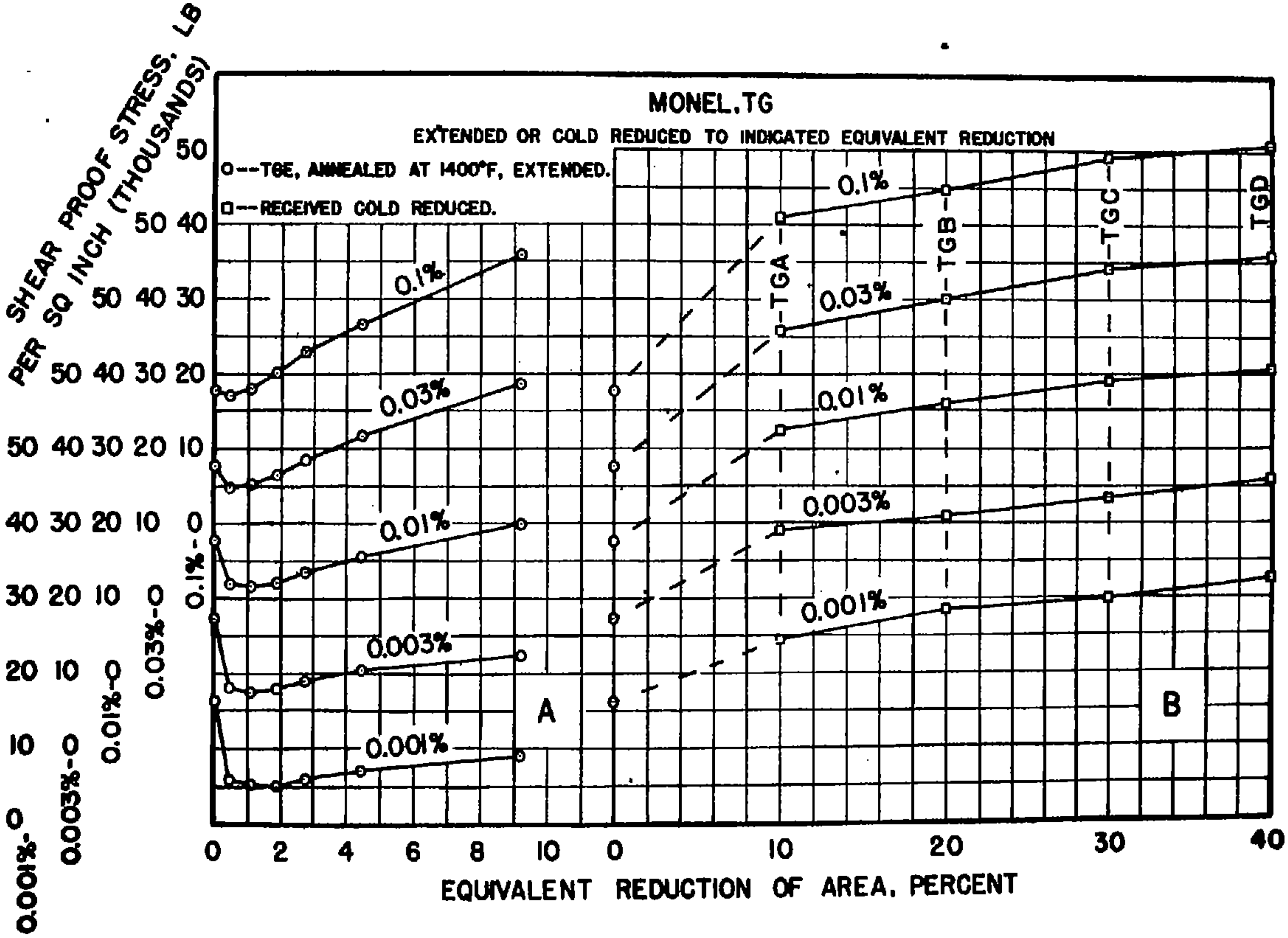

Figure 1.- Variation of shear proof stresses with prior deformation for monel tubing TG. A, monel TGE, annealed and extended; B, cold-reduced monel.

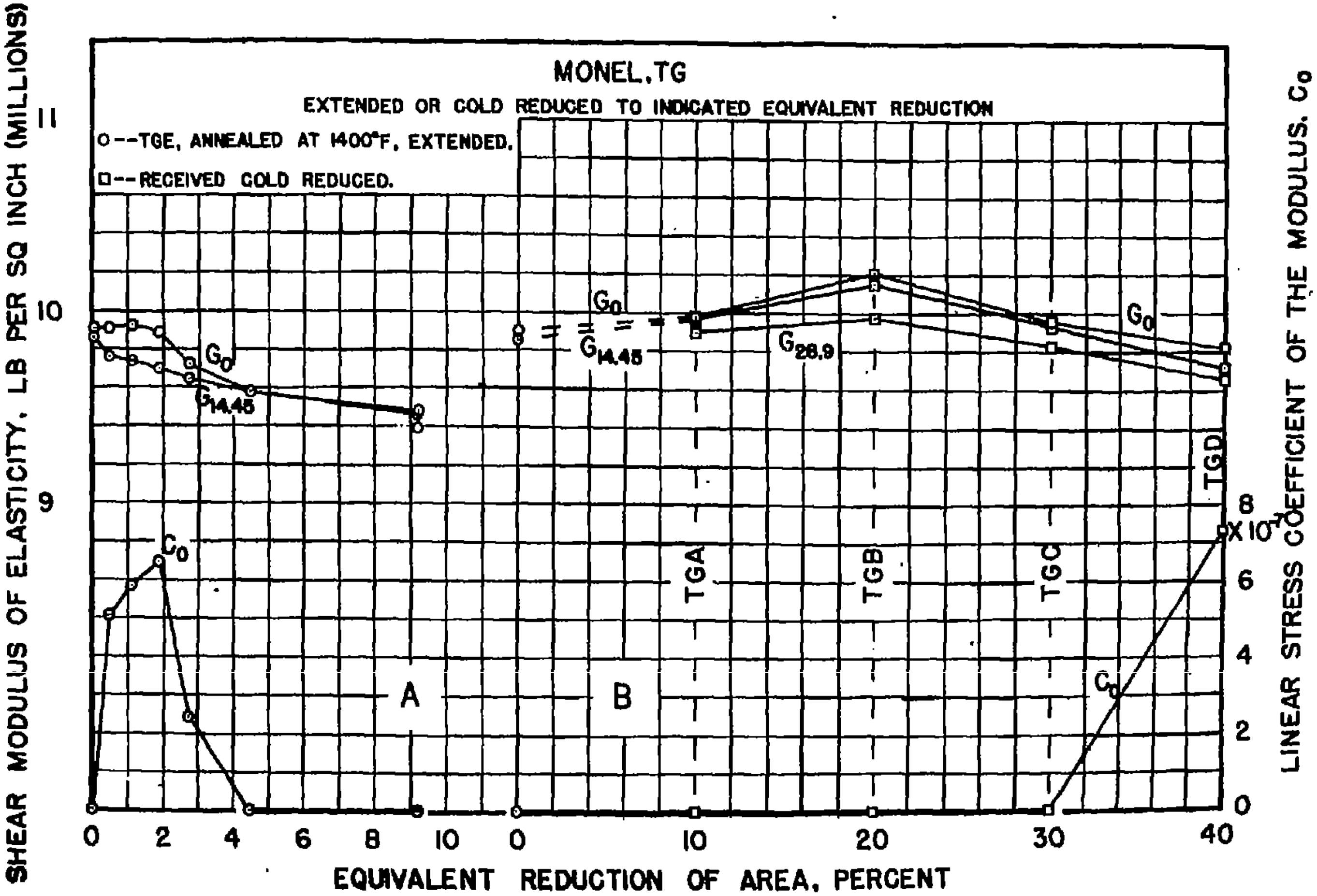

Figure 2.- Variation of shear modulus of elasticity and its linear stress coefficient with prior deformation for monel tubing TG. A, monel TGE, annealed and extended; B, cold-reduced monel.

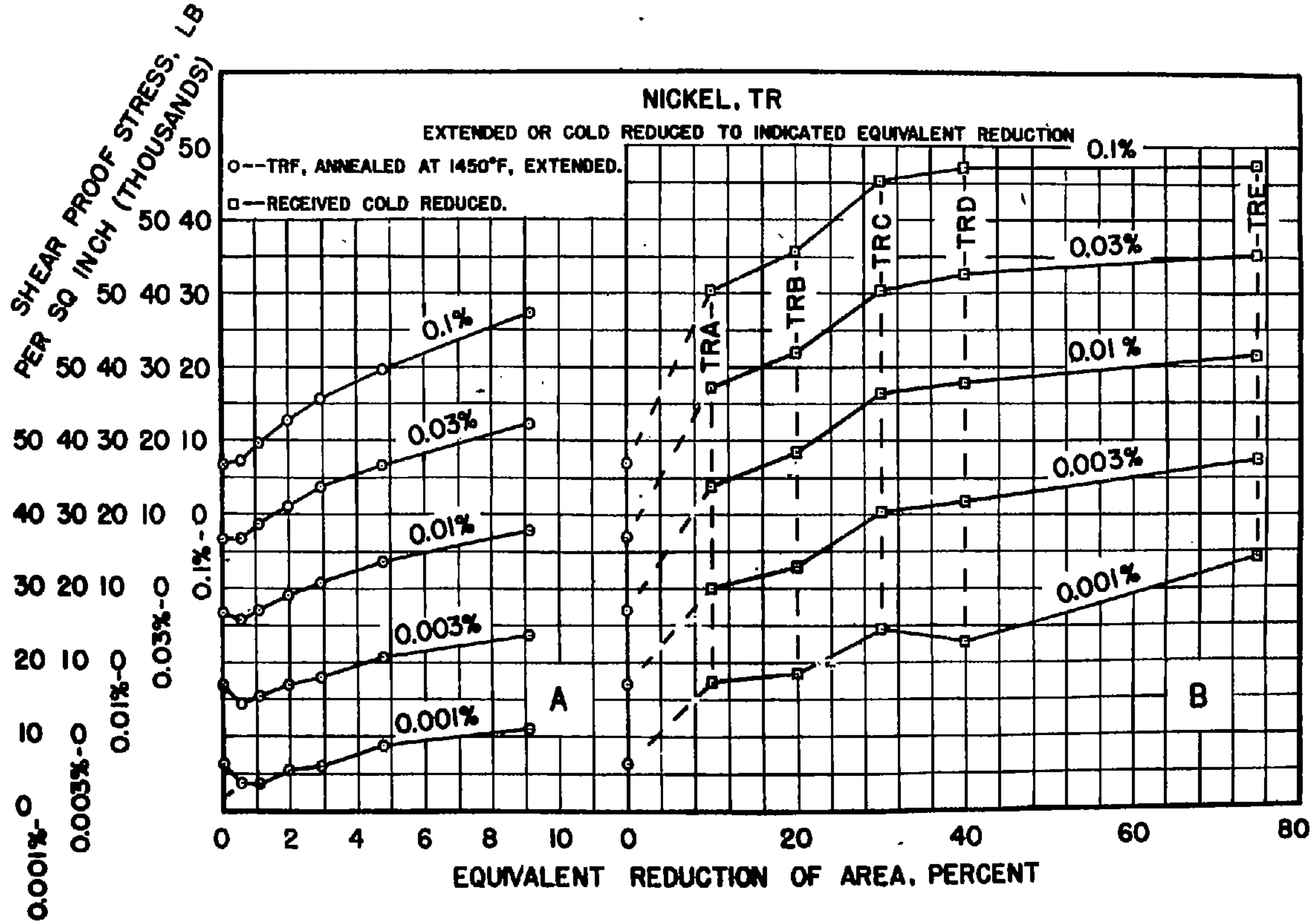

Figure 3.- Variation of shear proof stresses with prior deformation for nickel tubing TR. A, nickel TRF, annealed and extended; B, cold-reduced nickel.

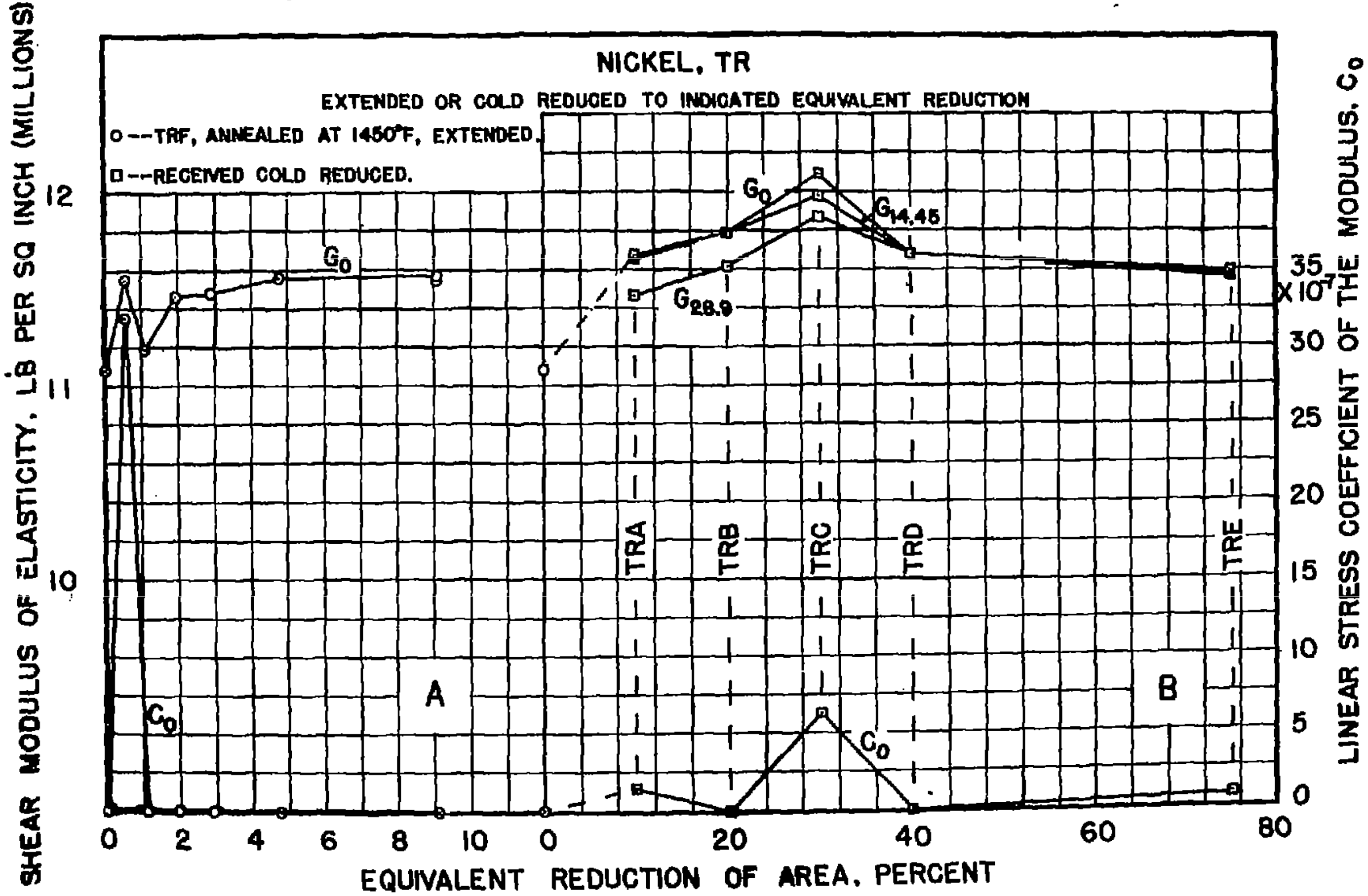

Figure 4.- Variation of shear modulus elasticity and its linear stress coefficient with prior deformation for nickel tubing TR. A, nickel TRF, annealed and extended; B, cold-reduced nickel.

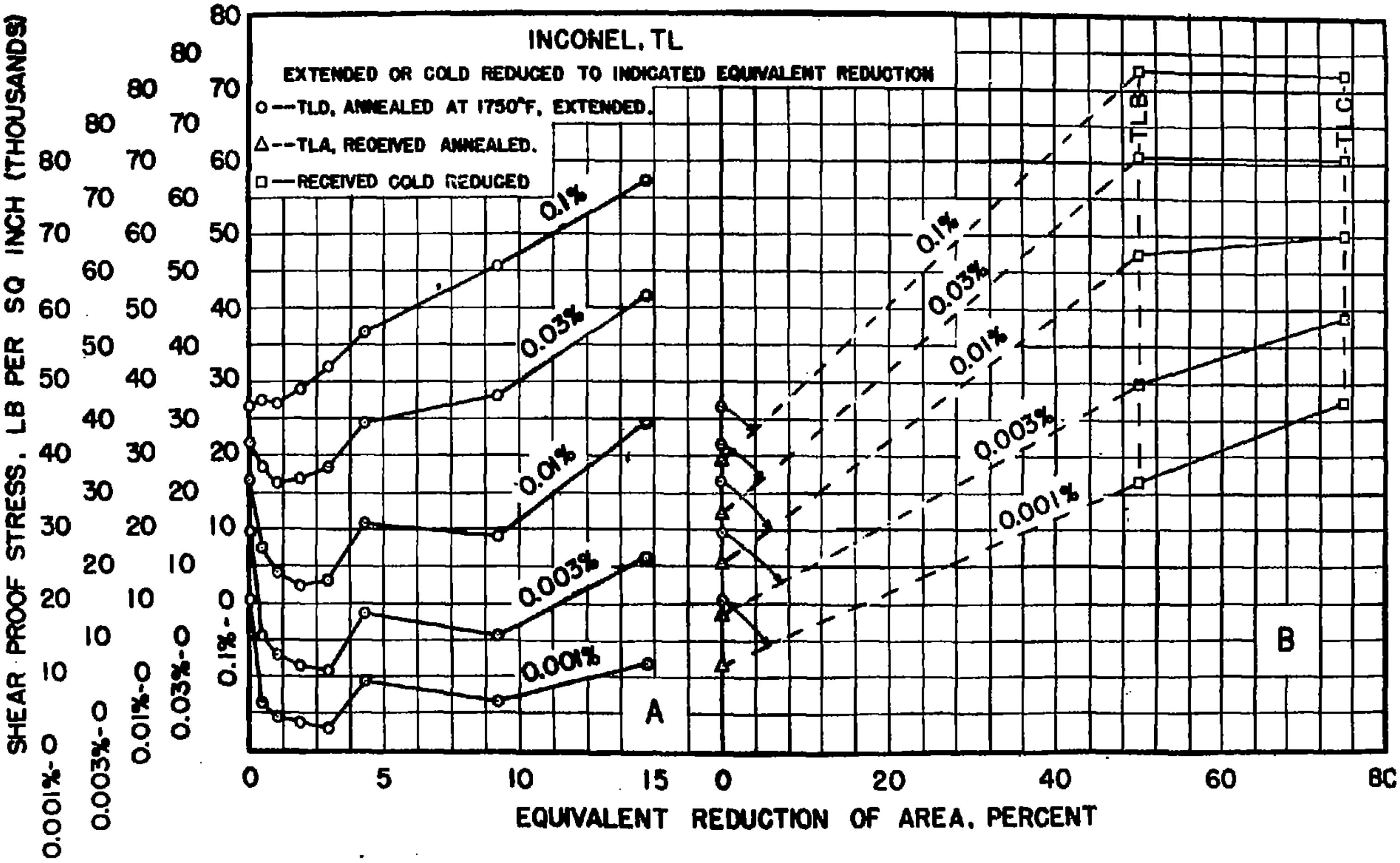

Figure 5.- Variation of shear proof stresses with prior deformation for Inconel tubing TL. A, Inconel TLD, annealed and extended; B, cold-reduced Inconel.

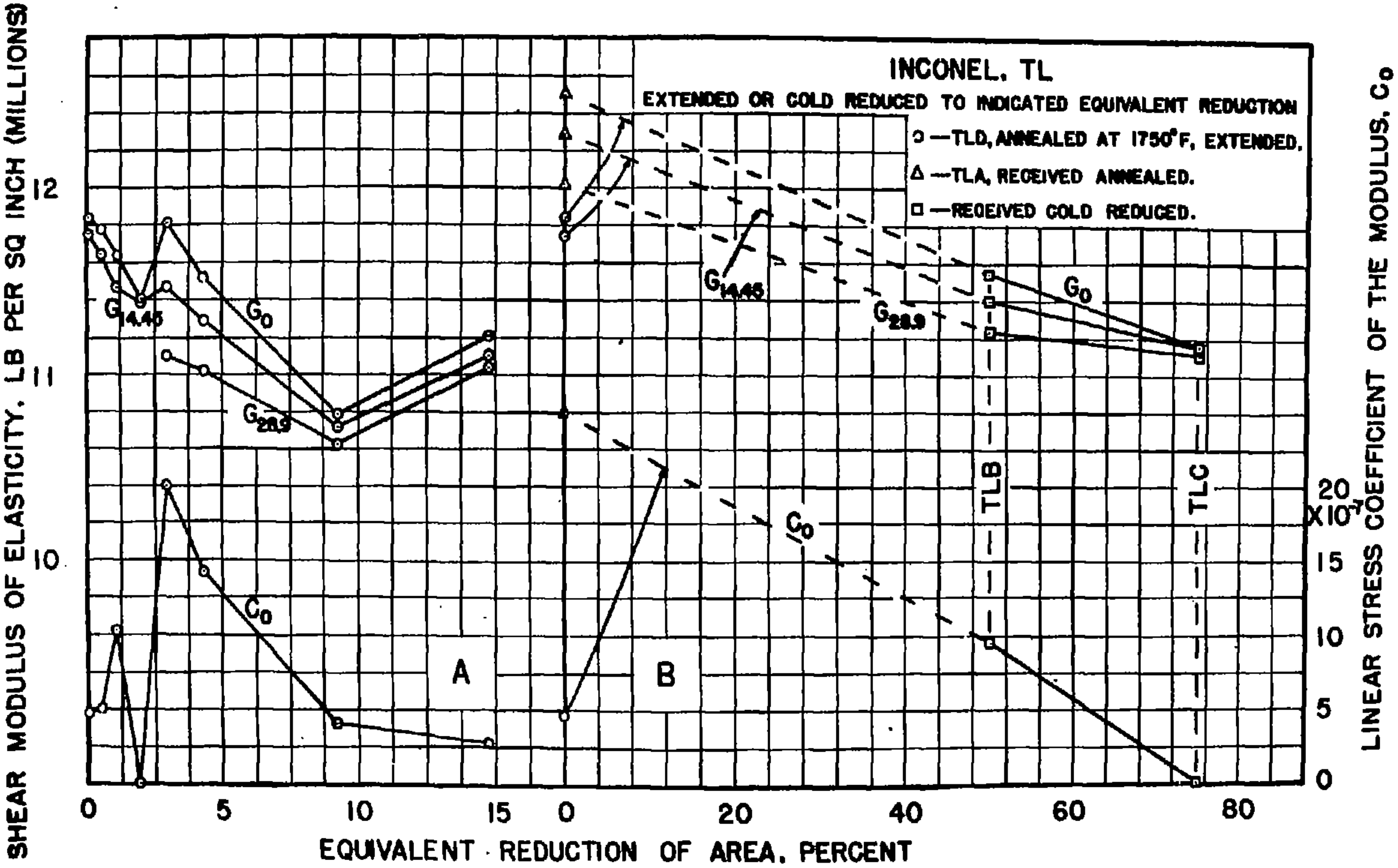

Figure 6.- Variation of shear modulus of elasticity and its linear stress coefficient with prior deformation for Inconel tubing TL.
A, Inconel TLD, annealed and extended; B, cold-reduced Inconel.

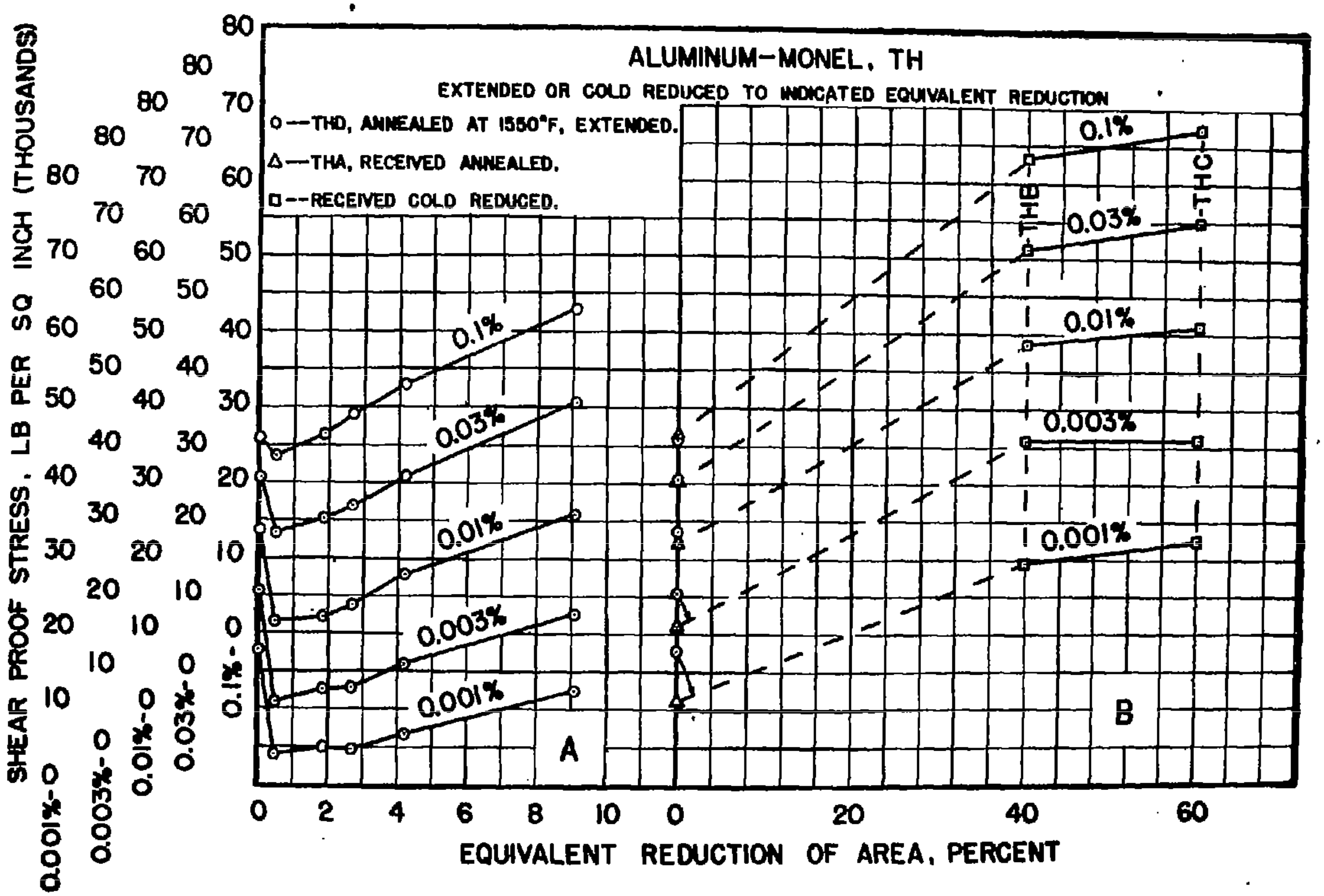

Figure 7.- Variation of shear proof stresses with prior deformation for aluminum-monel tubing TH. A, aluminum-monel THD, annealed and extended; B, cold-reduced aluminum-monel.

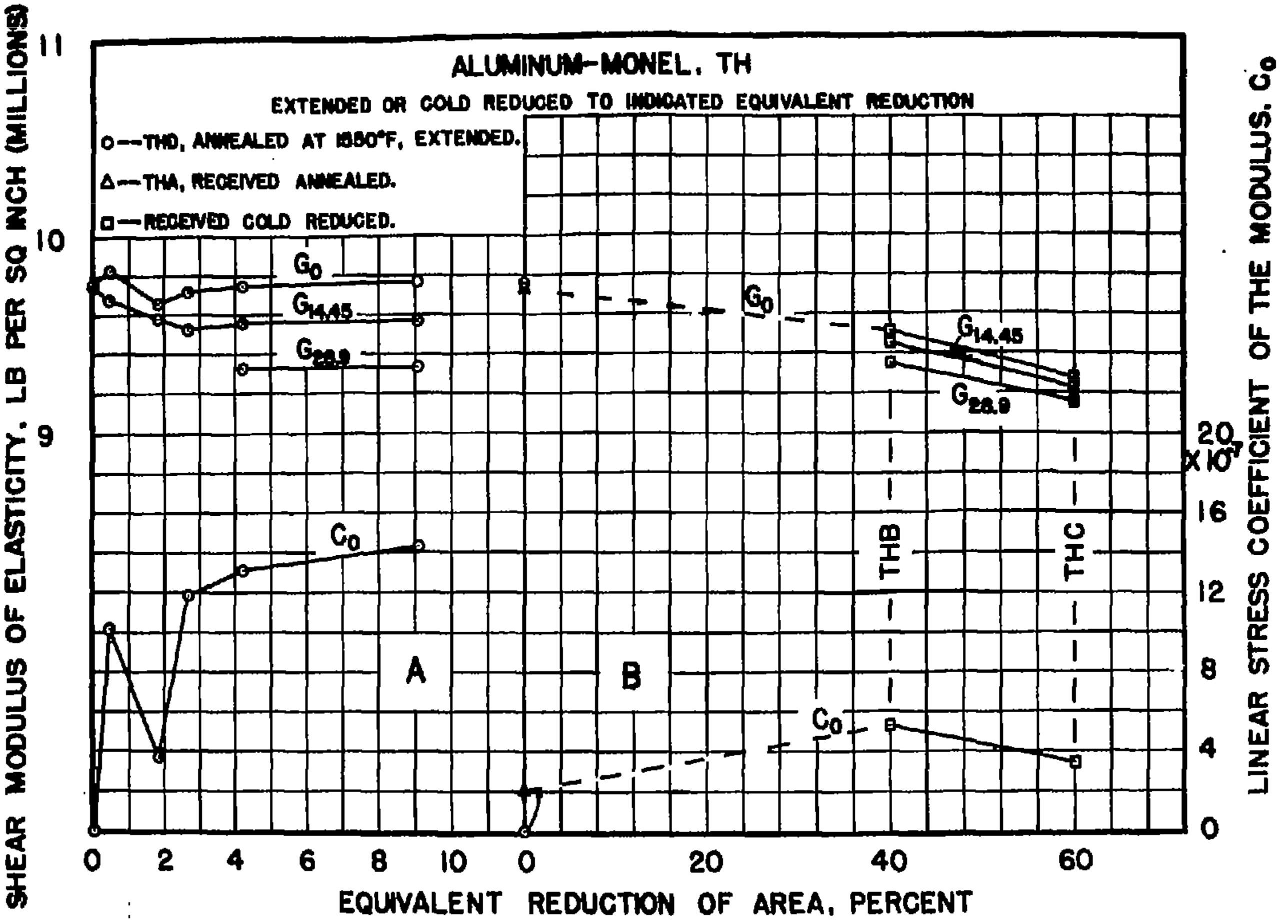

Figure 8.- Variation of shear modulus of elasticity and its linear stress coefficient with prior deformation for aluminum-monel tubing TH. A, aluminum-monel THD, annealed and extended; B, cold-reduced aluminum-monel.

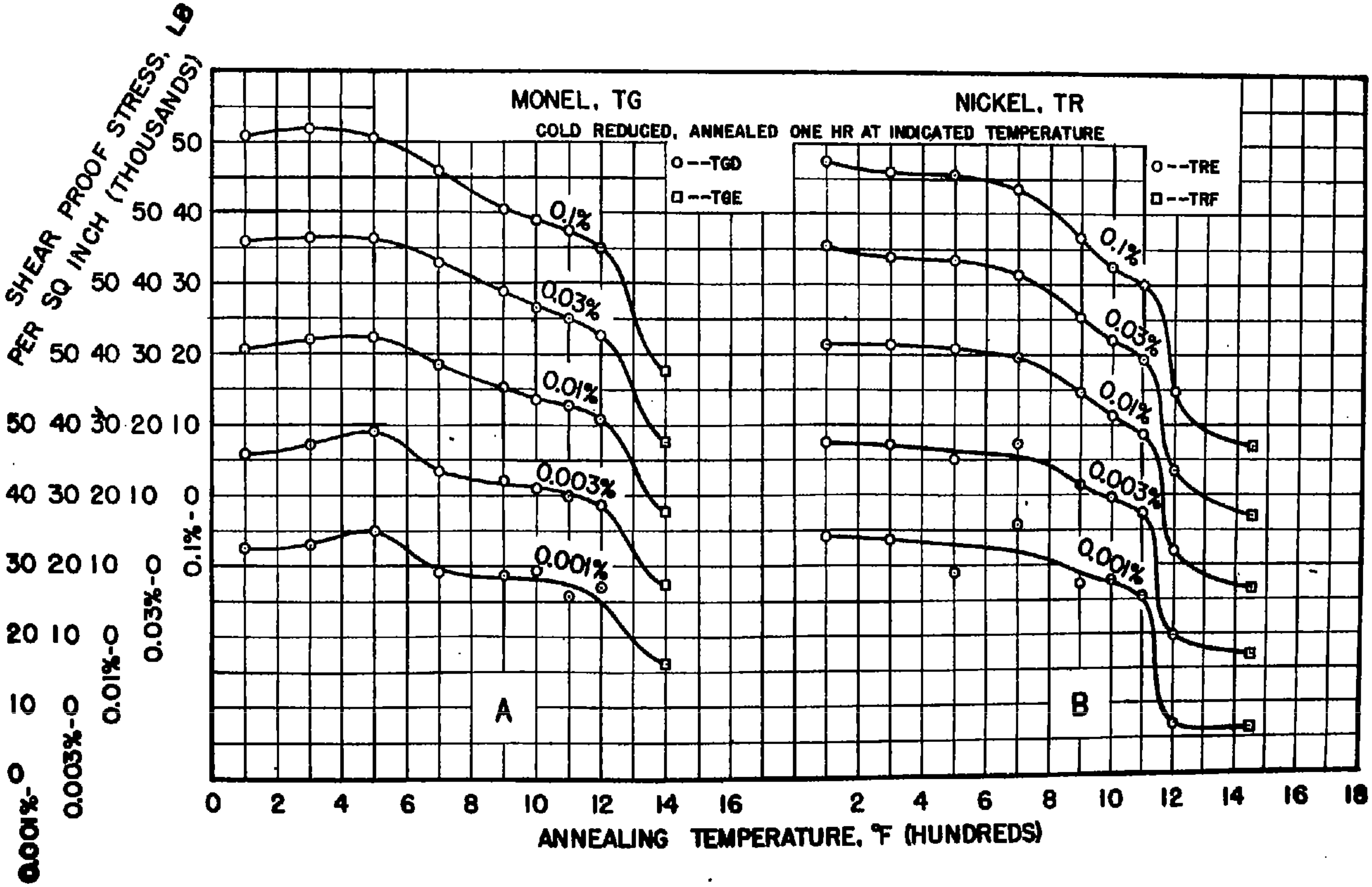

Figure 9.- Variation of shear proof stresses with annealing temperature. A, monel tubing TG; B, nickel tubing TR.

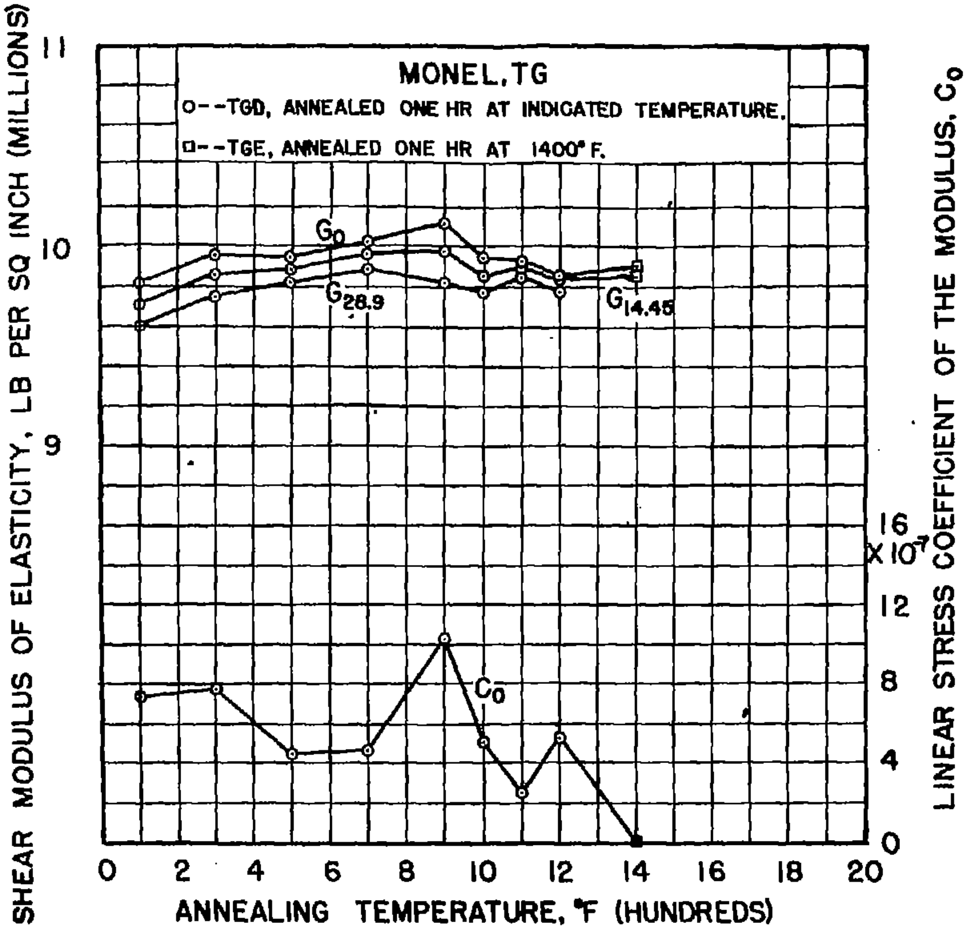

Figure 10.- Variation of shear modulus of elasticity and its linear stress coefficient with annealing temperature for monel tubing TG.

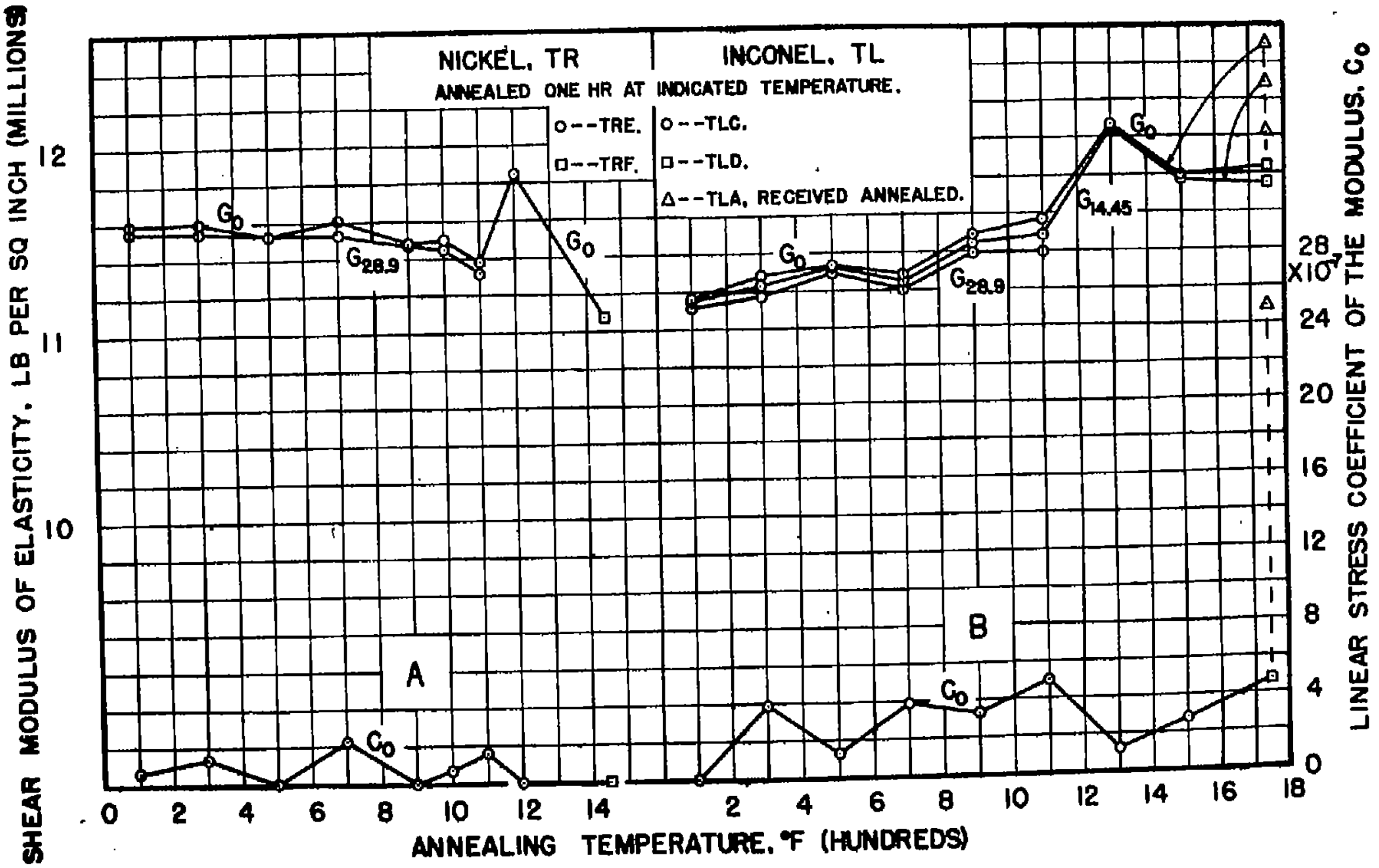

Figure 11.- Variation of shear modulus of elasticity and its linear stress coefficient with annealing temperature. A, nickel tubing TR; B, Inconel tubing TL.

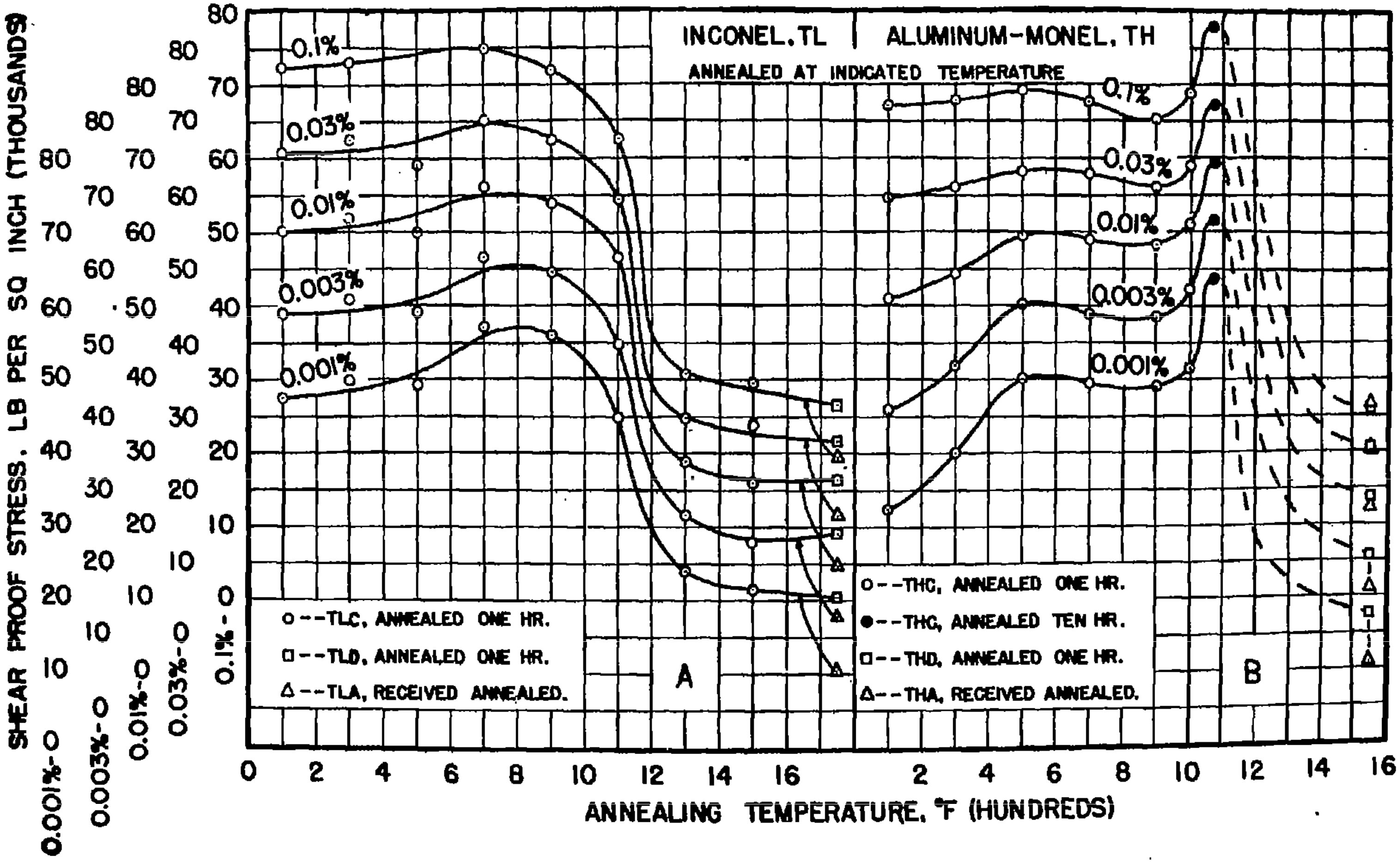

Figure 12.- Variation of shear proof stresses with annealing temperature. A, Inconel tubing TL; B, aluminum-monel tubing TH.

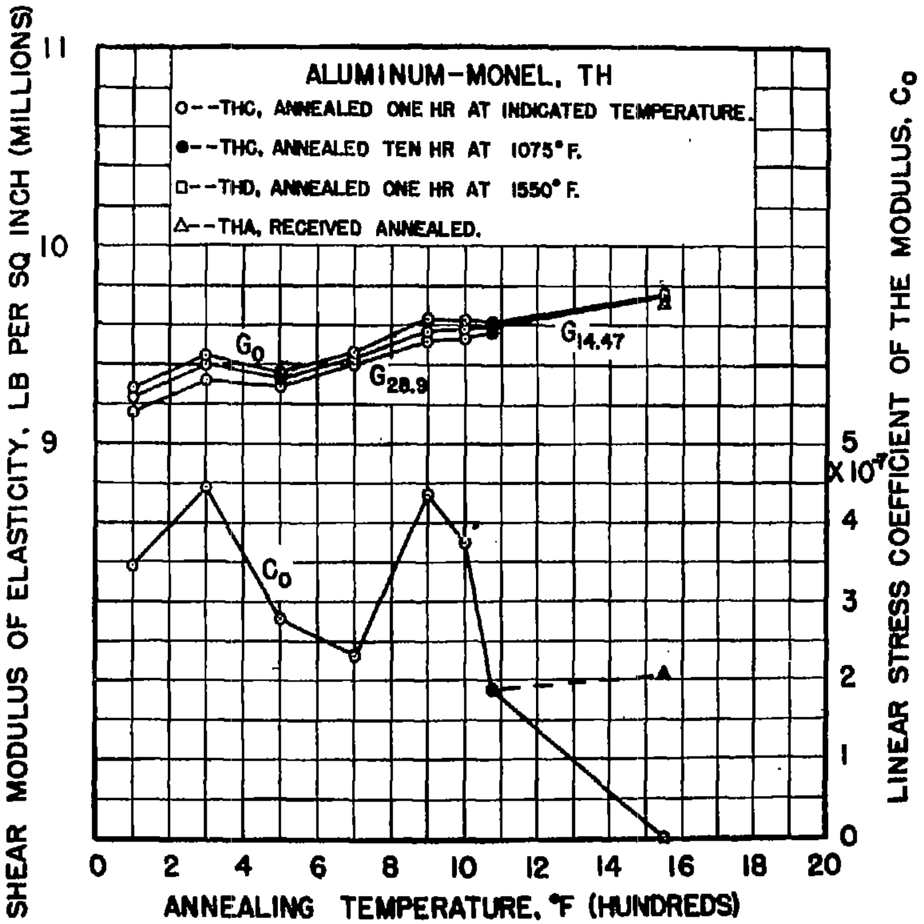

Figure 13.- Variation of shear modulus of elasticity and its linear stress coefficient with annealing temperature for aluminum-monel tubing TH.