NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3842

CREEP BEHAVIOR OF STRUCTURAL JOINTS OF AIRCRAFT MATERIALS UNDER CONSTANT LOADS AND TEMPERATURES

By Leonard Mordfin and Alvin C. Legate

National Bureau of Standards

Washington
January 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3842

CREEP BEHAVIOR OF STRUCTURAL JOINTS OF AIRCRAFT MATERIALS UNDER CONSTANT LOADS AND TEMPERATURES

By Leonard Mordfin and Alvin C. Legate

SUMMARY

The results of 55 creep and creep-rupture tests on structural joints are presented. Methods are described by which the time to rupture, the mode of rupture, and the deformation of joints in creep may be predicted. These methods utilize creep data on the materials of the joint in tension, bearing, and shear. The accuracy of these methods is within the scatter of the materials creep data.

INTRODUCTION

Aerodynamic heating effects require that aircraft structures for high-speed flight be designed so that excessive creep deformation and creep rupture will not occur during the design lifetime of the structure. In order to execute properly such designs, an understanding of the creep behavior of structures is necessary.

A limited study by the Aluminum Company of America of the creep of riveted joints, which involved the testing of only four specimens, reference 1, showed that the creep of a joint can be considerably greater than the tensile creep of an unriveted sheet. This study aroused the interest of the various aircraft establishments in this country in the need for obtaining a more thorough understanding of the creep of structural joints. To fill this need, the National Advisory Committee for Aeronautics sponsored a more comprehensive investigation of the creep of structural joints at the National Bureau of Standards, reference 2. This investigation corroborated the Alcoa result that the creep of a joint can be considerably greater than the tensile creep of an unriveted sheet. Furthermore, no correlation between the creep of a joint and the tensile creep of an unriveted sheet was found. Several empirical design criteria were proposed, but the number of different joint designs investigated was insufficient to verify completely these criteria.

The purpose of this report is to describe an investigation which was undertaken as an extension of that reported in reference 2. The present investigation was conducted at the NBS under the sponsorship and with the financial assistance of the NACA. It involved the testing of additional joint designs, with the aim of establishing design criteria for structural joints in creep.

Acknowledgment is due the Ryan Aeronautical Company for their assistance in the fabrication of spot-welded specimens and the Watertown Arsenal for supplying the RC-130A titanium alloy used in this investigation. The authors thank Mr. E. L. Horne of the Wright Air Development Center for furnishing much of the materials creep data used in this report.

SYMBOLS

d	rivet diameter, in.
e	edge distance, in.
h	sheet thickness, in.
n	number of rivets
P	test load, lb
T	temperature, °R
t	time, hr
t_r	time to rupture, hr
τ	shear stress

SPECIMENS

Design

Six designs of joints were investigated, four fabricated from 2024-T3 clad aluminum-alloy sheet and two fabricated from RC-130A titanium-alloy sheet. The six designs were designated as D, E, F, G, T, and U. The nominal dimensions of the six designs and the materials and fasteners from which the specimens were fabricated are shown in figures 1(a) to (c) and in table 1. The axial direction of the specimens was in the direction of rolling of the sheet materials.

NACA TN 3842

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3842

CREEP BEHAVIOR OF STRUCTURAL JOINTS OF AIRCRAFT MATERIALS UNDER CONSTANT LOADS AND TEMPERATURES

By Leonard Mordfin and Alvin C. Legate

National Bureau of Standards

NACA
Washington
January 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3842

CREEP BEHAVIOR OF STRUCTURAL JOINTS OF AIRCRAFT MATERIALS UNDER CONSTANT LOADS AND TEMPERATURES

By Leonard Mordfin and Alvin C. Legate

SUMMARY

The results of 55 creep and creep-rupture tests on structural joints are presented. Methods are described by which the time to rupture, the mode of rupture, and the deformation of joints in creep may be predicted. These methods utilize creep data on the materials of the joint in tension, bearing, and shear. The accuracy of these methods is within the scatter of the materials creep data.

INTRODUCTION

Aerodynamic heating effects require that aircraft structures for high-speed flight be designed so that excessive creep deformation and creep rupture will not occur during the design lifetime of the structure. In order to execute properly such designs, an understanding of the creep behavior of structures is necessary.

A limited study by the Aluminum Company of America of the creep of riveted joints, which involved the testing of only four specimens, reference 1, showed that the creep of a joint can be considerably greater than the tensile creep of an unriveted sheet. This study aroused the interest of the various aircraft establishments in this country in the need for obtaining a more thorough understanding of the creep of structural joints. To fill this need, the National Advisory Committee for Aeronautics sponsored a more comprehensive investigation of the creep of structural joints at the National Bureau of Standards, reference 2. This investigation corroborated the Alcoa result that the creep of a joint can be considerably greater than the tensile creep of an unriveted sheet. Furthermore, no correlation between the creep of a joint and the tensile creep of an unriveted sheet was found. Several empirical design criteria were proposed, but the number of different joint designs investigated was insufficient to verify completely these criteria.

The purpose of this report is to describe an investigation which was undertaken as an extension of that reported in reference 2. The present investigation was conducted at the NBS under the sponsorship and with the financial assistance of the NACA. It involved the testing of additional joint designs, with the aim of establishing design criteria for structural joints in creep.

Acknowledgment is due the Ryan Aeronautical Company for their assistance in the fabrication of spot-welded specimens and the Watertown Arsenal for supplying the RC-130A titanium alloy used in this investigation. The authors thank Mr. E. L. Horne of the Wright Air Development Center for furnishing much of the materials creep data used in this report.

SYMBOLS

d	rivet diameter, in.
e	edge distance, in.
h	sheet thickness, in.
n	number of rivets
P	test load, lb
T	temperature, $^{\circ}$R
t	time, hr
t_r	time to rupture, hr
τ	shear stress

SPECIMENS

Design

Six designs of joints were investigated, four fabricated from 2024-T3 clad aluminum-alloy sheet and two fabricated from RC-130A titanium-alloy sheet. The six designs were designated as D, E, F, G, T, and U. The nominal dimensions of the six designs and the materials and fasteners from which the specimens were fabricated are shown in figures 1(a) to (c) and in table 1. The axial direction of the specimens was in the direction of rolling of the sheet materials.

It will be noted from figure 1 that the gage length of each specimen included two identical joints in tandem. The extensions of the joints under load were obtained by dividing the extensions of the gage length by two. This quantity is used throughout this report wherever reference is made to the extension of a joint. The time to rupture was, conservatively, the time for the weaker of the two joints to rupture. The extensions and the rupture times, when obtained in this manner, have statistical advantages over data obtained from specimens containing a single joint. These statistical advantages are outlined in reference 2 and are described more fully in reference 3.

Relatively thick doublers were used, figure 1, so that all of the creep would be effectively restricted to the sheet materials and the fasteners, thus simplifying the interpretation and the application of the results. Furthermore, the use of a heavy doubler served to make the test joints approximate actual aircraft construction more closely, with the sheet representing a wing skin and the doubler simulating a spar cap or rib.

The specimens were fabricated at this laboratory. The riveting was done by a laboratory mechanic having considerable experience in the riveting of various types of aircraft structures. The spot-welding was done by the Ryan Aeronautical Company.

Each specimen was given a designation such as, for example, 5E-48, where the first digit represents the nominal test temperature in hundreds of degrees Fahrenheit, the letter specifies the specimen group in accordance with table 1, and the last figures represent the nominal test load in hundreds of pounds. The example given, then, refers to a specimen of group E, tested at 500° F with a load of 4,800 pounds.

Several joints of each group were tested in static tension to determine the maximum loads at room temperature and at three elevated temperatures. The results are listed in table 2. These tests were performed with a crosshead speed of about 0.1 inch per minute.

Mechanical Properties of Specimen Materials

Room-temperature properties.- Static tensile tests at room temperature were performed on three coupons of each sheet material. The average mechanical properties thus determined are given in table 3.

The shear strengths of the rivets and bolts used are listed in table 4. Each value represents the average result of four tests at room temperature.

Creep properties.- The creep properties of the specimen materials were obtained from the literature and are plotted in figures 2 through 9 in terms of the Larson-Miller parameter, reference 4. These data were obtained from references 5 through 19.

The joints of groups D, E, F, and G were fabricated with 2024-T3 clad aluminum-alloy sheet, table 1. Master curves for creep rupture and 0.5-percent total deformation of this material in tension are given in figures 2 and 3, respectively. (The term "total deformation" as used in this report means initial extension plus extension due to creep.)

Figure 4 gives the master rupture curve for 2024-T3 bare aluminum-alloy sheet in bearing creep. Figure 5 is the master curve for a bearing-creep deformation equal to 5 percent of the diameter of the pin used to load the sheet in bearing. Both figures are for an edge distance of 2 diameters. Similar data are not available for the clad material.

The master curves for bare 2024-T3 aluminum-alloy pins in shear creep are given in figures 6 and 7. Figure 6 is the rupture curve and figure 7 is for a deformation of 8 percent of pin diameter.

The group F joints were fabricated with Monel rivets, table 1. A master rupture curve for Monel pins in shear creep is given in figure 8.

The group G joints were spot-welded. Data are not available on the creep of spot-welds in shear. It is shown in reference 20 that the creep properties of spot-welds are different from those of the parent material.

RC-130A titanium alloy was used as the sheet material for the joints of groups T and U, table 1. All available creep-rupture data for this material in tension are given in figure 9. It will be noted that considerable differences exist between the results of different laboratories. While these differences may be due to differences in experimental technique, it is felt that they are more likely due to differences in composition or condition of the alloy. Regardless of the real cause, however, it is clear that the creep properties of RC-130A titanium alloy are not yet well defined.

The group T joints were fastened with K-Monel rivets, and the group U joints with aircraft bolts. Shear creep data are not available for either of these.

CREEP AND CREEP-RUPTURE TESTS OF JOINTS

The equipment and procedure used for the creep tests were essentially the same as those described in reference 2, with a few minor exceptions.

The specimens were heated to test temperature in 1 to $1\frac{1}{2}$ hours. They were then kept at test temperature for a similar length of time before the test load was applied at a crosshead speed of 0.1 inch per minute. The time at which the full test load was reached was considered time zero for the test.

Thermal expansion measurements were not made, since in reference 2 it is shown that this quantity for joints is equal to that for materials.

The specimens tested in this investigation were reasonably straight and flat in the unloaded condition, so that it was not necessary to apply straightening loads before "zero" extension readings were made.

The extensometers used were similar to those described in reference 2 except that the parallel extension arms were replaced by concentric rods and tubes.

Temperature measurements were made with three thermocouples which were attached near each end and near the center of each joint. The thermocouples were attached to the aluminum-alloy specimens by peening them into very small holes drilled in the doubler. For the titanium-alloy specimens, the thermocouples were attached by spot-welding. Test temperatures were maintained constant and uniform within 5° F of the average test temperature.

Fifty-five creep tests were made, most of which were continued to rupture. The loads and temperatures at which the tests were made are listed in table 5.

The creep curves obtained are shown in figures 10 through 15. The extensions plotted are the sum of the initial and the creep extensions, but do not include the thermal expansions. The letter R on these curves indicates that the test was carried to rupture; the letter D indicates that the test was discontinued before rupture.

GENERAL PROCEDURE OF ANALYSIS

In reference 2 an attempt was made to find a correlation between the creep of a joint and the creep of its component materials. The attempt was unsuccessful because creep data were not available for the joint materials in shear and in bearing. Such data are available now, however, and it has been found that correlations do exist between the creep properties of a joint and the creep properties of its component materials.

By means of these correlations, both the creep rupture and the creep deformation of structural joints may be predicted from the creep properties of the materials of the joint. The exact nature of these correlations and the ways in which they may be used to predict the creep properties of joints are described by means of examples in succeeding sections.

CREEP RUPTURE OF JOINTS

2024-T3 Clad Aluminum-Alloy Riveted Joints

Method of analysis.- A riveted joint may rupture in one of four different ways: tearing (tension) of the sheet, bearing, shearing of the fasteners, and shearing of the sheet. The stresses tending to produce each of these types of failure can be computed and the time to rupture for each mode of rupture can then be found from the appropriate master rupture curve. The predicted time to rupture is, then, the least of the various times to rupture obtained. The predicted mode of rupture is that corresponding to the predicted time to rupture.

Some explanation may be in order here regarding joint failure by shearing of the sheet, since this mode of rupture is not usually covered in standard texts on strength of materials. In this type of failure the element of sheet material lying between a rivet and the edge of the sheet is sheared out. The appearance of this failure is very similar to that of a bearing failure, except that in the latter case the material which is pushed out ahead of the rivet exhibits definite evidences of crushing and wrinkling.

As an example, consider joint 3D-112. Using the dimensions of the joint as shown in figure 1(a), the minimum net tearing area of the sheet is found to be

$$0.125\left\{2\left[\frac{3}{8}+\sqrt{\left(\frac{5}{8}\right)^2+\left(\frac{9}{32}\right)^2}\right]-3\left(\frac{3}{16}\right)\right\} = 0.195 \text{ sq in.}$$

(This value checks well with the effective cross-sectional area of the joint as determined from the room-temperature strength, table 2, and the ultimate strength of the material, table 3.) Hence, the average tensile stress on the minimum cross-sectional area is

$$\frac{11,200}{0.195} = 57,400 \text{ lb/sq in.}$$

as listed in table 5. If this stress is introduced into the tensile rupture curve for 2024-T3 clad aluminum-alloy sheet, figure 2, together with the test temperature, 301° F ($T = 761^\circ$ R), a time to rupture t_r of 0.023 hour is obtained.

The bearing area of the joint is

$$(11)(0.125)\left(\frac{3}{16}\right) = 0.258 \text{ sq in.}$$

The average bearing stress is therefore

$$\frac{11,200}{0.258} = 43,400 \text{ lb/sq in.}$$

as listed in table 5. By using figure 4, the bearing rupture curve, the time to rupture in bearing creep is found to be 1.4×10^6 hours.

The cross-sectional area of the rivets is

$$(11)\left(\frac{\pi}{4}\right)\left(\frac{3}{16}\right)^2 = 0.304 \text{ sq in.}$$

and, hence, the average shear stress on the rivets is

$$\frac{11,200}{0.304} = 36,800 \text{ lb/sq in.}$$

as listed in table 5. With this stress and figure 6, a time to rupture of 3.3 hours in shear creep is obtained.

Rupture by shearing of the sheet is effectively ruled out by the design of the joint and need not be considered at this point.

The predicted time to rupture is the least of the times to rupture obtained, 0.023 hour, and the predicted mode of rupture is obviously tearing of the sheet.

This method was applied to all of the joints of groups D, E, and F, except that: (a) For the group E joints, the countersunk rivet heads had to be accounted for in the computation of the tearing and bearing areas and (b) for the group F joints, which had Monel rivets, the time to rupture by shearing of the fasteners was obtained from figure 8.

Table 6 lists the predicted and the actual times to rupture and the predicted and the actual modes of rupture. It is worth noting that the actual mode of rupture was correctly predicted in all but one case.

In reference 2 data are presented for four types of joints tested in creep. These were designated as groups A, B, C, and S. The group A joints ruptured by shearing rivets for which shear creep data are not available and, therefore, cannot be analyzed by the method described herein. Similarly, the group S joints were not tested to rupture and cannot be analyzed here. The group B and the group C joints were analyzed by the method described. These joints were fabricated from 2024-T3 clad aluminum-alloy sheet and 2024-T31 aluminum-alloy rivets and had a single row of three rivets in the transverse direction, with edge distances of 2 and 2.5 rivet diameters. In addition to consideration of tearing, bearing, and rivet shear ruptures, the rivet pattern for these joints requires that rupture by shearing of the sheet also be considered. The shear stresses tending to produce such rupture were computed from the relation (see ref. 21)

$$\tau = \frac{P}{2n\left(e - \frac{d}{2}\right)h} \text{ lb/sq in.} \tag{1}$$

where

P test load, lb

n number of rivets, 3

e edge distance, in.

d rivet diameter, 1/8 in.

h sheet thickness, 0.032 in.

The times to rupture in shear creep of the sheet were predicted from figure 6.

The predicted and actual times to rupture and modes of rupture for these joints are listed in table 7. Here, too, the actual mode of rupture was correctly predicted in all but one case.

A comparison of the predicted and the actual times to rupture for the aluminum-alloy riveted joints of both this investigation and that of reference 2 is given in figure 16. Of the 27 joints which ruptured by tearing the sheet or by shearing the rivets, all but 6 show a discrepancy of less than about 2:1. All but one joint have discrepancies of less than 3:1. It is worth noting that some of the data used to plot the master rupture curves, as determined by different laboratories, had scatter up to 5:1.

The discrepancies in figure 16 for the joints which failed by shearing the sheet are somewhat larger than those for the other joints. This is attributed to the fact that shear creep data for bare material were used to predict the times to rupture for clad material. The creep properties of clad and bare materials of the same alloy are not the same, reference 22.

Effect of stress concentrations.- The distribution of points in figure 16 appears to be entirely random about the line of zero discrepancy. No trends other than those already discussed were detected with respect to temperature, stress, or joint design. It is therefore inferred that no systematic error exists in the method for predicting times to rupture. This leads to the conclusion that the stress concentrations around the rivets, which were neglected in the analysis, are probably relieved in the early stages of creep and for this reason do not affect the time to rupture. Similarly, it appears that any interactions between the tensile, shear, and bearing stresses in a joint do not affect the time to rupture.

2024-T3 Clad Aluminum-Alloy Spot-Welded Joints

The group G specimens, which were spot-welded joints of 2024-T3 clad aluminum-alloy sheet, all ruptured by shearing the spot-welds. As previously mentioned, data are not available on the shear creep properties of spot-welds. Hence, these joints cannot be analyzed by the method used thus far. However, as a possible aid to designers, the data obtained from the tests of the joints were used to plot figure 17. This figure is a master rupture curve for spot-welds in 2024-T3 clad aluminum-alloy sheet in shear creep. In computing the stresses tending to produce shear failure of the spot-welds the shearing area used was

$$(4)\left(\frac{\pi}{4}\right)(0.3)^2 = 0.283 \text{ sq in.}$$

RC-130A Titanium-Alloy Joints

The joints of groups T and U were fabricated from RC-130A titanium alloy and either K-Monel rivets or steel aircraft bolts. Creep data are not available for either of these fastener materials in shear nor for RC-130A titanium alloy in bearing. The master rupture curve for RC-130A titanium alloy in tensile creep, figure 9, contains excessive scatter, as mentioned previously. Consequently, it is impossible to predict either the time to rupture or the mode of rupture for these joints.

The creep-rupture results for the joints of groups T and U are given in table 8. In figure 18 are shown the master rupture curves for RC-130A titanium alloy in tensile creep, taken from figure 9, together with points corresponding to those titanium-alloy joints which ruptured by tearing the sheet. Since the points representing the joints fall within the scatter of the data representing the sheet material, the validity of the method of analysis presented is not questioned.

CREEP DEFORMATION OF JOINTS

Initial Extension

The initial extensions of the joints tested are listed in table 9. These are the instantaneous extensions due to elastic and, sometimes, plastic deformation that occurred upon application of the test load. These extensions do not include thermal expansion, since the joints were stabilized at temperature before the load was applied. Methods of computing the initial extension of a joint would be the same as those used to compute the extension of a joint under load at room temperature, except that the high-temperature properties of the materials of the joint would have to be used. It is beyond the scope of this report to describe or develop such methods, since they are problems in statics rather than in creep. For the purposes of this report, however, it is assumed that these initial extensions can be computed.

Creep at Moderate Temperatures

The creep curves of aluminum-alloy joints at 300° F, of titanium-alloy joints at 600° F, and of stainless steel joints at 800° F, figures 10 and 13 and figures 6 and 9 of reference 2, all have one thing in common. The initial extensions are all large compared with the extensions due to creep itself. This indicates that an airplane structure which could satisfactorily withstand the relatively high initial extensions, would be unlikely to suffer serious deformation as a result of the additional creep extensions. (The expression "serious deformation" as used herein does not mean deformation which approaches the maximum deformation, but rather means deformation which destroys an aerodynamic contour or which causes dangerous redistribution of loads.) It follows, then, that for most practical purposes the design of aluminum-alloy joints at 300° F, of titanium-alloy joints at 600° F, and of stainless-steel joints at 800° F can be based solely on the initial extension and the time to rupture.

Creep at High Temperatures

A joint under load at elevated temperatures can be expected to undergo creep in tension, bearing, shear of the sheet, and shear of the fasteners. The total creep extension would thus be the sum of these various components. Examination of the joints tested in this investigation has shown, however, that, almost invariably, nearly all of the creep of a joint can be attributed to a single one of the components. This is the component which eventually produces rupture. The reason for this is obvious. Creep is an extremely stress-sensitive phenomenon. In the master rupture curve of figure 2, for example, a 10-percent change in stress near the center of the curve produces about a 2:1 change in time to rupture. At the ends of the curve, the time to rupture is even more sensitive to stress. Hence, for a given set of tensile, bearing, and shear stresses in a joint, the magnitudes of the creep resulting from each of the components will usually be widely different.

To predict the deformation of a joint in creep, then, the first step is to determine the mode of rupture by the method previously described and, then, to attribute all deformation to this mode.

Joints which creep by shearing of fasteners.- In accordance with the foregoing discussion, joints which were predicted to rupture by shearing fasteners will be considered to creep only in shear of the fasteners.

Consider joint 4D-55 which was predicted to rupture by shearing rivets, table 6. The shear stress on the rivets is 18,100 lb/sq in., table 5. If this stress and the test temperature, 861° R, are introduced into figure 7, the master curve for 8-percent shear creep deformation, a predicted time of 17 hours is obtained (table 10).

The rivets used for this joint had diameters of 3/16 inch. Eight-percent creep deformation of the rivets therefore corresponds to a joint extension of

$$0.08 \times \frac{3}{16} = 0.015 \text{ in.}$$

The initial extension of this joint, table 9, is 0.0120 inch, making the total deformation after a 0.015-inch creep extension

$$0.0120 + 0.015 = 0.027 \text{ in.}$$

From figure 11(a) it is seen that this total deformation is actually achieved at a time of 15 hours. This value compares favorably with the predicted value of 17 hours.

This method of predicting the time for 8-percent deformation of rivets was applied to all of the joints tested in this investigation and in reference 2 for which rupture by shear of rivets was predicted. A comparison of the predicted and actual times is given in table 10. It will be noted that the discrepancies between the actual and the predicted times are within the normal range of scatter for creep data.

The deformation of the group G spot-welded joints could not be predicted since creep data are not available for spot-welds. Similarly, shear creep data are not available for the fasteners used in the group T and group U joints.

<u>Joints which creep by shearing of sheet</u>.- Eleven of the joints tested in reference 2 were predicted to rupture by shearing the sheet, table 7. It is assumed that these joints creep primarily by shear of the sheet.

Consider, for example, joint 4B-5.9. The stress tending to produce shear failure of the sheet is, by equation (1),

$$\frac{590}{2(3)\left(\frac{1}{4} - \frac{1}{16}\right)(0.032)} = 16,400 \text{ lb/sq in.}$$

Introducing this stress into figure 7, the master curve for 8-percent shear creep deformation, gives a predicted time of 30 hours.

The element of sheet being sheared out is approximately rectangular in shape and has a length of $\left(e - \frac{d}{2}\right)$ or $\frac{3}{16}$ inch. Eight-percent creep deformation of this element corresponds to an extension of the joint of

$$0.08 \times \frac{3}{16} = 0.015 \text{ in.}$$

The initial extension of this joint, reference 2, is 0.0072 inch, making the total deformation after a creep extension of 0.015 inch

$$0.0072 + 0.015 = 0.022 \text{ in.}$$

From reference 2 it is found that this total deformation is actually achieved at a time of 80 hours; this is in excess of the predicted time of 30 hours.

This method was applied to six of the eleven joints which were predicted to rupture by shearing of the sheet; the other five joints were tested at 300° F, where, it was pointed out, the deformation due to creep itself is relatively unimportant. The results for the six joints are shown in table 11. Here, the agreement between the predicted and the actual times is not so good, in some cases, as might be desired. As in the case of creep rupture by shearing of the sheet, the discrepancy is attributed to the fact that shear creep data for bare material was used to predict the creep of clad material.

Joints which creep by bearing.- Only one joint, 4B-8.7 of reference 2, was predicted to rupture by bearing, table 7. This joint had a bearing stress of

$$\frac{870}{3 \times \frac{1}{8} \times 0.032} = 72{,}500 \text{ lb/sq in.}$$

With this stress and figure 5, a predicted time of 1.5 hours is obtained for a creep deformation of 5 percent of the rivet diameter.

The rivet diameter is 1/8 inch, so the corresponding creep extension of the joint is

$$0.05 \times \frac{1}{8} = 0.00625 \text{ in.}$$

The initial extension of the joint is 0.0072 inch, making the total extension

$$0.00625 + 0.0072 = 0.0134 \text{ in.}$$

From figure 7(b) of reference 2, it is found that this total extension is actually reached at a time of 1.6 hours.

The agreement between this value and the predicted value is better than expected, since joint 4B-8.7 failed by shearing of sheet and not by bearing, as predicted.

Joints which creep in tension.- In accordance with the assumptions made previously, joints which rupture by tearing the sheet may be considered to creep primarily in tension. The method of predicting the tensile creep of a riveted joint is somewhat more involved than the methods for predicting creep in shear or in bearing. There are two reasons for this: (a) The tensile stresses which produce the creep deformation vary considerably through the length of the joint, and (b) the magnitude of the creep extension of the joint depends upon the gage length under consideration.

One method of circumventing these difficulties is to find the "equivalent length" of unriveted sheet which, with a stress equal to the maximum net tensile stress on the joint, will have the same creep extensions as the joint.

As an example of the method, consider joint 4D-66, which was predicted to rupture by tearing, table 6. This joint has a maximum tensile stress at the minimum cross-sectional area of 33,800 pounds per square inch and was tested at 400° F, table 5. The length of unriveted 2024-T3 aluminum-alloy sheet at this stress and this temperature which will have the same creep resistance as the joint can be estimated by making the approximation that the creep resistances of the joint and the sheet material are proportional to their resistances to static deformation. The initial extension of the joint is 0.0175 inch, table 9. The strain of 2024-T3 aluminum-alloy sheet which is subjected to a tensile stress of 33,800 pounds per square inch after a two-hour exposure to 400° F is 0.0042 inch per inch, reference 23. The length of unriveted sheet which is equivalent to the joint is, therefore,

$$\frac{0.0175}{0.0042} = 4.17 \text{ in.}$$

From figure 3, the master curve for tensile creep, the sheet material is seen to achieve a total deformation of 0.5 percent in 0.24 hour. Thus, the joint, which is equivalent to 4.17 inches of sheet, is predicted to reach a total extension of

$$0.005 \times 4.17 = 0.0208 \text{ in.}$$

in the same time, 0.24 hour.

Actually, this joint reached a total deformation of 0.0208 inch in 0.29 hour, figure 11(a).

With the exception of those joints tested at 300° F, for which creep deformation is considered unimportant, 15 aluminum-alloy joints were predicted to rupture by tearing. The method just described was applied to these 15 joints, and the results are given in table 12. Agreement between predicted and actual values is seen to be generally good.

The method of finding the equivalent length undoubtedly accounts for many factors other than the nonuniform distribution of tensile stresses. One such factor is the effect of stress concentrations. Another is the effect of the interaction of the tensile, bearing, and shear stresses in the joint.

The creep deformation of the RC-130A titanium-alloy joints was not analyzed, since the available tensile creep data on this alloy show even greater scatter than the corresponding rupture data, figure 9.

DISCUSSION

Methods of analysis have been described which enable the prediction of the time to rupture and the deformation of a joint subjected to creep. In the design of a joint for aircraft which will be subjected to creep, there will generally be a limiting condition, either rupture or a specific allowable deformation, depending on the application. The methods described permit the prediction of the time required to produce the limiting condition. The only exception occurs in creep at moderate temperatures, where deformation is considered to be restricted primarily to the initial extension.

The accuracy of the predictions obtained is within the scatter generally observed in creep data. In many designs it is conceivable that such scatter cannot be tolerated. For these cases, it is necessary to design for a reduced stress, perhaps 10 or 20 percent lower than that determined from the analysis. Since creep is so stress sensitive, a relatively small reduction in stress gives a high degree of safety.

In order to be able to predict the creep properties of various designs of joints, it is necessary to have sufficient creep data for the materials of the joint available. It is, therefore, recommended that creep data be obtained for all aircraft structural materials in tension, bearing, and shear. The bearing data should be obtained at least for edge distances of 1.5 and 2.0 diameters. Shear creep data should be obtained, also, for spot-welds in the various materials.

CONCLUDING REMARKS

Simple methods have been described by which the time to rupture, the mode of rupture, and the deformation of structural joints in creep under constant load and temperature conditions may be predicted. These methods are based upon the creep properties of the materials of the joint in tension, shear, and bearing. The errors involved in the use of these methods are within the scatter of the materials creep data.

National Bureau of Standards,
Washington, D.C., December 12, 1955.

REFERENCES

1. Stickley, G. W., and Anderson, H. L.: Creep Resistance of Riveted Joints. Rep. 9-51-18, Aluminum Res. Lab., Aluminum Co. of Am., Dec. 4, 1951. (Not released for pub.)

2. Mordfin, Leonard: Creep and Creep-Rupture Characteristics of Some Riveted and Spot-Welded Lap Joints of Aircraft Materials. NACA TN 3412, 1955.

3. Youden, W. J.: Statistics and Planning Tests at Elevated Temperatures. Proc. Soc. Exp. Stress Analysis, vol. XI, no. 2, 1954, pp. 219-222.

4. Larson, F. R., and Miller, James: A Time-Temperature Relationship for Rupture and Creep Stresses. Trans. A.S.M.E., vol. 74, no. 5, July 1952, pp. 765-771.

5. Flanigan, A. E., Tedsen, L. F., and Dorn, J. E.: Stress Rupture and Creep Tests on Aluminum-Alloy Sheet at Elevated Temperatures. Trans. Am. Inst. Min. and Metall. Eng., vol. 171, 1947, pp. 213-244.

6. VanEcho, J. A., Page, L. C., Simmons, W. F., and Cross, H. C.: Short-Time Creep Properties of Structural Sheet Materials for Aircraft and Missiles. AF Tech Rep. 6731, pt. 1, Contract AF 33(038)-8743, WADC and Battelle Memorial Inst., Aug. 1952.

7. Shepard, Lawrence A., Starr, C. Dean, Wiseman, C. D., and Dorn, J. E.: The Creep Properties of Metals Under Intermittent Stressing and Heating Conditions - Intermittent Stressing. WADC TR 53-336, pt. 1, Sept. 1953.

8. Hanlon, F., and Guarnieri, G. J.: Intermittent Stressing and Heating of Aircraft Structural Metals (24S-T3 Clad Aluminum) Rep. KB-892-M-6, Contract AF 33(616)-2226, ARDC and Cornell Aero. Lab., Inc., Aug. 31, 1954.

9. Simmons, Ward F., and Cross, Howard C.: Constant and Cyclic-Load Creep Tests of Several Materials. Preprint 100d, A.S.T.M., 1954.

10. Guarnieri, G. J.: Intermittent Stressing and Heating Tests of Aircraft Structural Metals. WADC TR 53-24, Contract AF 33(038)-10958, pt. 1, May 1954.

11. Vawter, F. J., Derrick, G., Yerkovich, L. A., and Guarnieri, G. J.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-18, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., Apr. 1, 1955.

12. Vawter, F. J. Guarnieri, G. J., Yerkovich, L. A., and Derrick, G.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. WADC TR 54-270, Contract AF 33(616)-190, pt. 1, June 1956.

13. Vawter, F. J., Guarnieri, G. J., Yerkovich, L. A., and Derrick, G.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-11, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., Apr. 1, 1954.

14. Vawter, F. J., Guarnieri, G. J., Yerkovich, L. A., and Derrick, G.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-12, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., June 1, 1954.

15. Vawter, F. J., Yerkovich, L. A., Derrick, G., and Guarnieri, G. J.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-13, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., Aug. 1, 1954.

16. Guarnieri, G. J.: Intermittent Stressing and Heating Tests of Aircraft Structural Metals. WADC TR 53-24, Contract AF 33(038)-10958, pt. 2, Sept. 1954.

17. VanEcho, John A., Wirth, W. F., and Simmons, Ward F.: Short-Time Creep Properties of Structural Sheet Materials for Aircraft and Missiles. AF Tech. Rep. 6731, Contract AF 33(038)-8743, pt. 3, May 1955.

18. Derrick, G., Vawter, F. J., Yerkovich, L. A., and Guarnieri, G. J.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-16, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., Dec. 1, 1954.

19. Anon.: Rem-Cru Titanium Manual. Sec. VI, Rem-Cru Titanium, Inc. (Midland, Pa.), Jan. 1954, p. 12.

20. Mordfin, Leonard, and Legate, Alvin C.: Prog. Rep. on the Creep Behavior of Structural Joints of Aircraft Materials Under Constant Loads and Temperatures. Rep. 4052, Contract S55-50, NACA and Nat. Bur. Standards, Apr. 20, 1955.

21. Hilbes. W.: Riveted Joints in Thin Plates. NACA TM 590, 1930.

22. Vawter, F. J., Guarnieri, G. J., Yerkovich, L. A., and Salvaggi, J.: Investigation of the Compressive, Bearing, and Shear Creep-Rupture Properties of Aircraft Structural Metals and Joints at Elevated Temperatures. Rep. KB-831-M-3, Contract AF 33(616)-190, WADC and Cornell Aero. Lab., Inc., Feb. 1, 1953.

23. Doerr, D. D.: Determination of Physical Properties of Nonferrous Structural Sheet Materials at Elevated Temperatures. Typical Stress Vs. Strain and Stress Vs. Deformation Curves. AF Tech. Rep. 6517, pt. 1, supp. 1, Contract AF 33(038)-8681, WADC and Armour Res. Foundation, Ill. Inst. of Tech., Feb. 1953.

TABLE 1.- DESCRIPTION OF SPECIMENS

[See fig. 1]

Group	Sheet material	Fastener	Doubler material
D	0.125-in. 2024-T3 clad aluminum-alloy sheet	3/16-in. 2024-T31 aluminum-alloy universal-head rivets	0.250-in. 2024-T4 aluminum-alloy plate
E	0.125-in. 2024-T3 clad aluminum-alloy sheet	3/16-in. 2024-T31 aluminum-alloy 100° flush countersunk head rivets	0.250-in. 2024-T4 aluminum-alloy plate
F	0.125-in. 2024-T3 clad aluminum-alloy sheet	3/16-in. Monel universal-head rivets	0.250-in. 2024-T4 aluminum-alloy plate
G	0.125-in. 2024-T3 clad aluminum-alloy sheet	Spot-welds, 0.3-in. diameter	0.250-in. 2024-T4 aluminum-alloy plate
T	0.125-in. RC-130A titanium-alloy sheet	3/16-in. K-Monel universal-head rivets	0.250-in. RC-130A titanium-alloy plate
U	0.125-in. RC-130A titanium-alloy sheet	3/16-in. steel aircraft bolts	0.250-in. RC-130A titanium-alloy plate

TABLE 2.- RESULTS OF SHORT-TIME TESTS OF JOINTS

Group	Temperature, °F	Maximum load, lb	Mode of rupture (a)
D	81	12,720	T
	301	11,390	T
	397	9,740	SF
	500	6,460	SF
E	78	11,205	T
	302	10,020	T
	392	9,690	T
	503	5,820	T
F	86	12,510	T
	303	11,380	T
	397	10,570	T
	498	[b]5,860	T
G	79	10,235	SF
	300	[b]8,060	SF
	402	8,300	SF
	500	[c]6,660	SF
T	78	23,970	SF
	599	18,680	SF
	798	16,760	T
	944	9,480	T
U	81	27,910	SF
	604	18,990	T
	804	[b]8,200	T,SF
	940	7,550	T,B

[a] T = tearing of sheet; SF = shearing of fasteners; B = bearing.

[b] Average of two tests.

[c] Average of three tests.

TABLE 3.- AVERAGE TENSILE PROPERTIES OF SHEET MATERIALS AT ROOM TEMPERATURES

Material	Young's modulus, lb/sq in.	Yield strength (0.2 percent offset), lb/sq in.	Ultimate strength, lb/sq in.
2024-T3	10.7×10^6	47,800	65,500
RC-130A	15.5	121,000	138,000

TABLE 4.- SHEAR STRENGTHS OF FASTENERS AT ROOM TEMPERATURE

Fastener (a)			Ultimate shear strength, lb/sq in.
Material	Type	Head	
[b]2024-T31	Rivet	Universal	38,900
[b]2024-T31	Rivet	Countersunk	37,900
Monel	Rivet	Universal	54,200
K-Monel	Rivet	Universal	70,500
Steel	Bolt	Hexagonal	82,300

[a] For full descriptions, see table 1.

[b] Temper is actually -T4 before driving.

TABLE 5.- TEMPERATURES, LOADS, AND STRESSES FOR CREEP TESTS

Group	Specimen	Average test temperature, $^{\circ}F$	Test load, lb	Tensile stress lb/sq in. (a)	Shear stress lb/sq in. (b)	Bearing stress lb/sq in.
D	3D-112	301	11,200	57,400	36,800	43,400
	3D-92.5	300	9,250	47,400	30,400	35,900
	3D-86	299	8,600	44,100	28,300	33,300
D	4D-77	396	7,700	39,500	25,300	29,800
	4D-66	400	6,600	33,800	21,700	25,600
	4D-55	401	5,500	28,200	18,100	21,300
D	5D-45	500	4,500	23,100	14,800	17,400
	5D-35	499	3,500	17,900	11,500	13,600
	5D-25	500	2,500	12,800	8,220	9,690
	5D-20	499	2,000	10,300	6,580	7,750
E	3E-99	299	9,900	56,000	32,600	38,400
	3E-95	299	9,500	53,600	31,200	36,800
	3E-85	301	8,500	48,000	28,000	32,900
E	4E-80	396	8,000	45,200	26,300	31,000
	4E-62	401	6,200	35,000	20,400	24,000
	4E-50	389	5,000	28,200	16,400	19,400
	4E-40	399	4,000	22,600	13,200	15,500
E	5E-48-1	500	4,800	27,100	15,800	18,600
	5E-48-2	501	4,800	27,100	15,800	18,600
	5E-30	501	3,000	16,900	9,880	11,600
	5E-25	498	2,500	14,100	8,220	9,690
F	3F-109	300	10,900	54,000	43,800	51,700
	3F-99	300	9,900	49,000	39,800	46,900
	3F-83.5	300	8,350	41,300	33,500	39,600
F	4F-78	398	7,800	38,600	31,300	37,000
	4F-68	401	6,800	33,700	27,300	32,200
	4F-50	401	5,000	24,700	20,100	23,700
F	5F-45	500	4,500	22,300	18,100	21,300
	5F-35	500	3,500	17,300	14,100	16,600
G	3G-84	300	8,400	33,600	29,700	(c)
	3G-80	300	8,000	32,000	28,300	(c)
	3G-75	299	7,500	30,000	26,500	(c)
	3G-35	300	3,500	14,000	12,400	(c)
G	4G-78	399	7,800	31,200	27,600	(c)
	4G-73	400	7,300	29,200	25,800	(c)
	4G-70	400	7,000	28,000	24,700	(c)
G	5G-50	498	5,000	20,000	17,700	(c)
	5G-40	492	4,000	16,000	14,100	(c)
T	6T-180	599	18,000	92,300	59,200	69,800
	6T-170	602	17,000	87,200	55,900	65,900
T	8T-140	798	14,000	71,800	47,100	54,300
	8T-110	796	11,000	56,400	36,200	42,600
	8T-74	796	7,400	37,900	24,300	28,700
T	9.4T-60	946	6,000	30,800	19,800	23,300
	9.4T-30	946	3,000	15,400	9,870	11,600
	9.4T-10	942	1,000	5,130	3,290	3,880
U	6U-180	592	18,000	92,300	59,200	69,800
	6U-170	598	17,000	87,200	55,900	65,900
	6U-160	602	16,000	82,100	52,600	62,000
U	8U-77	797	7,700	39,500	25,300	29,800
	8U-70	799	7,000	35,900	23,000	27,100
	8U-66	796	6,600	33,900	21,700	25,600
U	9.4U-60	946	6,000	30,800	19,700	23,300
	9.4U-40	941	4,000	20,500	13,200	15,500
	9.4U-20	934	2,000	10,300	6,580	7,750

[a] Average tensile stress on minimum net area.

[b] Average shear stress on fasteners.

[c] Not applicable.

TABLE 6.- CREEP RUPTURE OF 2024-T3 CLAD ALUMINUM-ALLOY RIVETED JOINTS

Specimen	Time to rupture, hr		Mode of rupture (a)	
	Predicted	Actual	Predicted	Actual
3D-112	0.023	0.07	T	T
3D-92.5	63	31.4	T	T
3D-86	200	(b)	T	(b)
4D-77	1.6	1.6	T	T
4D-66	9.6	4.0	T	T
4D-55	23	32.8	SF	T
5D-45	.63	.60	SF	SF
5D-35	2.8	(b)	SF	(b)
5D-25	30	(b)	SF	(b)
5D-20	49	94.0	SF	SF
3E-99	.087	.05	T	T
3E-95	.85	3.9	T	T
3E-85	49	41.2	T	T
4E-80	.38	.58	T	T
4E-62	6.3	6.1	T	T
4E-50	60	46.3	T	T
4E-40	320	282	T	T
5E-48-1	.45	.55	T	T
5E-48-2	.45	.30	T	T
5E-30	7.8	(b)	T	(b)
5E-25	29	30.6	T	T
3F-109	.56	1.1	T	T
3F-99	33	13.0	T	T
3F-83.5	420	250	T	T
4F-78	2.1	2.0	T	T
4F-68	9.8	4.5	T	T
4F-50	170	90.4	T	T
5F-45	1.5	2.0	T	T
5F-35	6.5	12.5	T	T

[a] T = tearing of sheet; SF = shearing of fasteners.

[b] Test discontinued before rupture.

TABLE 7.- CREEP RUPTURE OF JOINTS

TESTED IN REFERENCE 2

Specimen	Time to rupture, hr		Mode of rupture (a)	
	Predicted	Actual	Predicted	Actual
3B-13.5	2.0	7.9	SS	SS
3B-12.5	22	17.6	SS	SS
3B-10.5	300	43.1	SS	SS
3B-10.3	330	164	SS	SS
3B-8.9	1000	(b)	SS	(b)
4B-8.7	3.6	2.2	B	SS
4B-7.1	16	12.0	SS	SS
4B-5.9	36	82.9	SS	SS
4B-3.9	560	(b)	SS	(b)
5B-5	.76	2.2	SS	SS
5B-4	4.1	(b)	SS	(b)
5B-3.4	14	31.2	SS	SS
4C-8.7	6.2	9.2	SF	SF
4C-6.8	21	51.0	SF	SF

[a] SS = shearing of sheet; SF = shearing of fasteners; B = bearing.

[b] Test discontinued before rupture.

TABLE 8.- CREEP RUPTURE OF RC-130A
TITANIUM-ALLOY JOINTS

Specimen	Time to rupture, hr	Mode of rupture (a)
6T-180	(b)	(b)
6T-170	(b)	(b)
8T-140	0.42	T
8T-110	3.6	T
8T-74	28.0	T
9.4T-60	2.1	T
9.4T-30	18.4	T
9.4T-10	(b)	(b)
6U-180	3.6	T
6U-170	1.5	SF
6U-160	(b)	(b)
8U-77	2.1	T,B
8U-70	40.1	T
8U-66	40.2	T
9.4U-60	.05	T,SF
9.4U-40	5.2	T
9.4U-20	122	T

[a] T = tearing of sheet; B = bearing; SF = shearing of fasteners.

[b] Test discontinued before rupture.

TABLE 9.- INITIAL EXTENSIONS OF JOINTS

Specimen	Initial extension, in.	Specimen	Initial extension, in.
3D-112	0.0512	3G-84	0.0142
3D-92.5	.0252	3G-80	.0138
3D-86	.0205	3G-75	.0100
		3G-35	.0048
4D-77	.0175		
4D-66	.0175	4G-78	.0138
4D-55	.0120	4G-73	.0115
		4G-70	.0080
5D-45	.0162		
5D-35	.0095	5G-50	.0098
5D-25	.0065	5G-40	.0070
5D-20	.0052		
		6T-180	.0545
3E-99	.0578	6T-170	.0392
3E-95	.0428		
3E-85	.0268	8T-140	.0392
		8T-110	.0210
4E-80	.0280	8T-74	.0140
4E-62	.0152		
4E-50	.0135	9.4T-60	.0205
4E-40	.0090	9.4T-30	.0078
		9.4T-10	.0032
5E-48-1	.0152		
5E-48-2	.0195	6U-180	.0405
5E-30	.0098	6U-170	.0375
5E-25	.0060	6U-160	.0335
3F-109	.0432	8U-77	.0178
3F-99	.0272	8U-70	.0132
3F-83.5	.0178	8U-66	.0145
4F-78	.0145	9.4U-60	.0232
4F-68	.0132	9.4U-40	.0128
4F-50	.0088	9.4U-20	.0058
5F-45	.0125		
5F-35	.0092		

TABLE 10.- CREEP DEFORMATION OF JOINTS BY SHEAR OF RIVETS

Specimen	Time for creep extension equal to 8 percent of rivet diameter, hr	
	Predicted	Actual
4D-55	[a]17	15
5D-45	.23	.43
5D-35	1.3	[a]3.7
5D-25	18	[a]8.7
5D-20	33	33
[b]4C-8.7	[a]5.1	4.7
[b]4C-6.8	[a]15	22

[a] By extrapolation.

[b] From reference 2.

TABLE 11.- CREEP DEFORMATION OF JOINTS BY SHEAR OF SHEET

Specimen (a)	Time for shear creep extension of 0.015 in., hr	
	Predicted	Actual
4B-7.1	[b]11	[b]11.
4B-5.9	[b]30	80
4B-3.9	720	[b]500
5B-5	.33	1.6
5B-4	2.0	[b]9
5B-3.4	7.9	21

[a] From reference 2.

[b] By extrapolation.

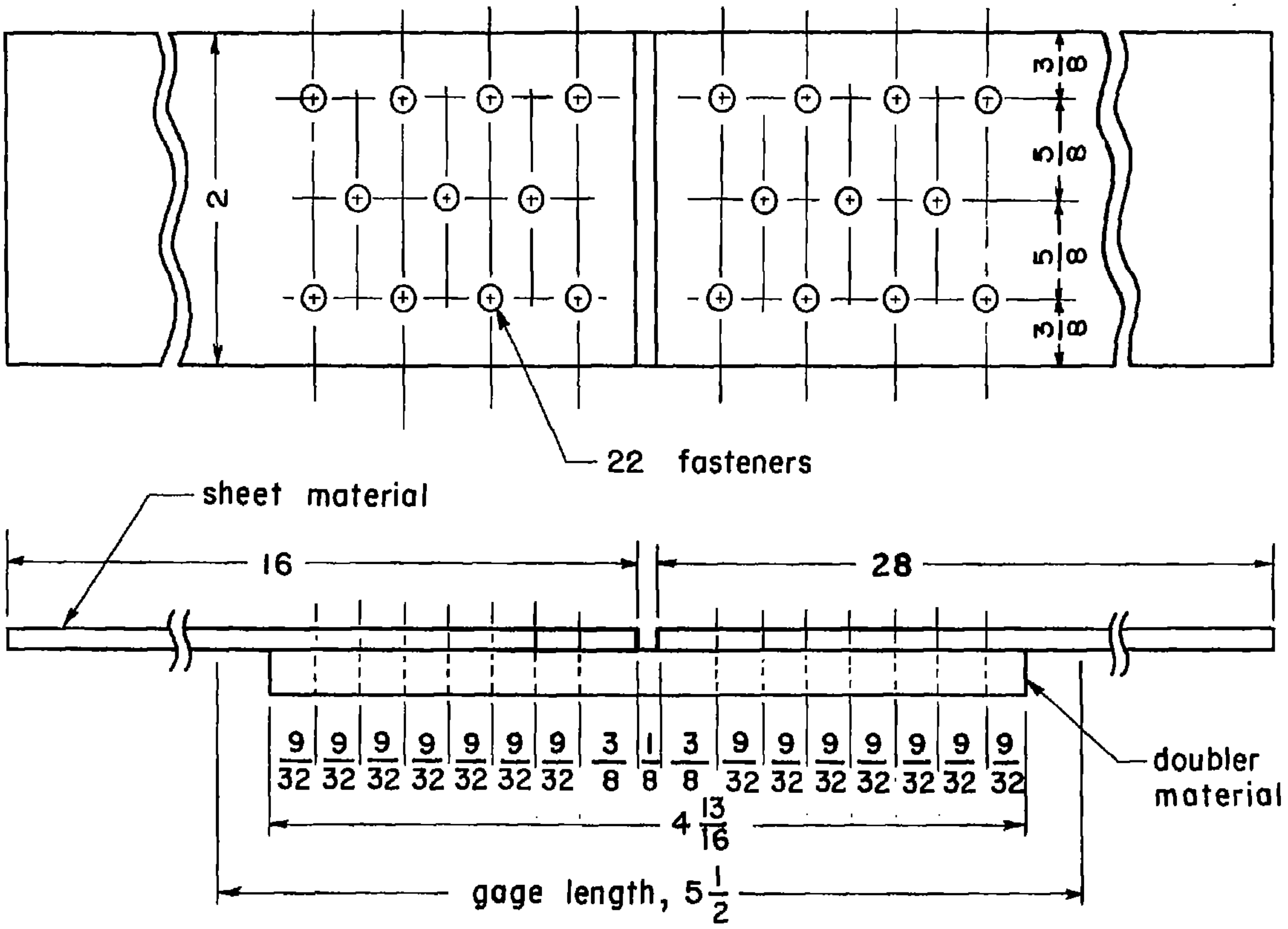
TABLE 12.- TENSILE CREEP DEFORMATION OF JOINTS

Specimen	Equivalent length, in.	Total deformation, in. (a)	Time to reach specified total deformation, hr	
			Predicted	Actual
4D-77	(b)	(b)	0.050	(b)
4D-66	4.17	0.0208	.24	0.29
4E-80	(b)	(b)	(b)	(b)
4E-62	3.24	.0162	.15	(b)
4E-50	4.82	.0241	3.5	15
4E-40	4.09	.0205	69	68
5E-48-1	3.54	.0177	.044	(b)
5E-48-2	4.54	.0227	.044	.12
5E-30	5.16	.0258	3.0	[c]9.0
5E-25	3.53	.0171	9.3	9.0
4F-78	(b)	(b)	.051	(b)
4F-68	3.14	.0157	.25	.26
4F-50	3.67	.0183	23	33
5F-45	4.63	.0232	.44	.98
5F-35	4.50	.0225	2.5	2.6

[a] 0.005 × Equivalent length.

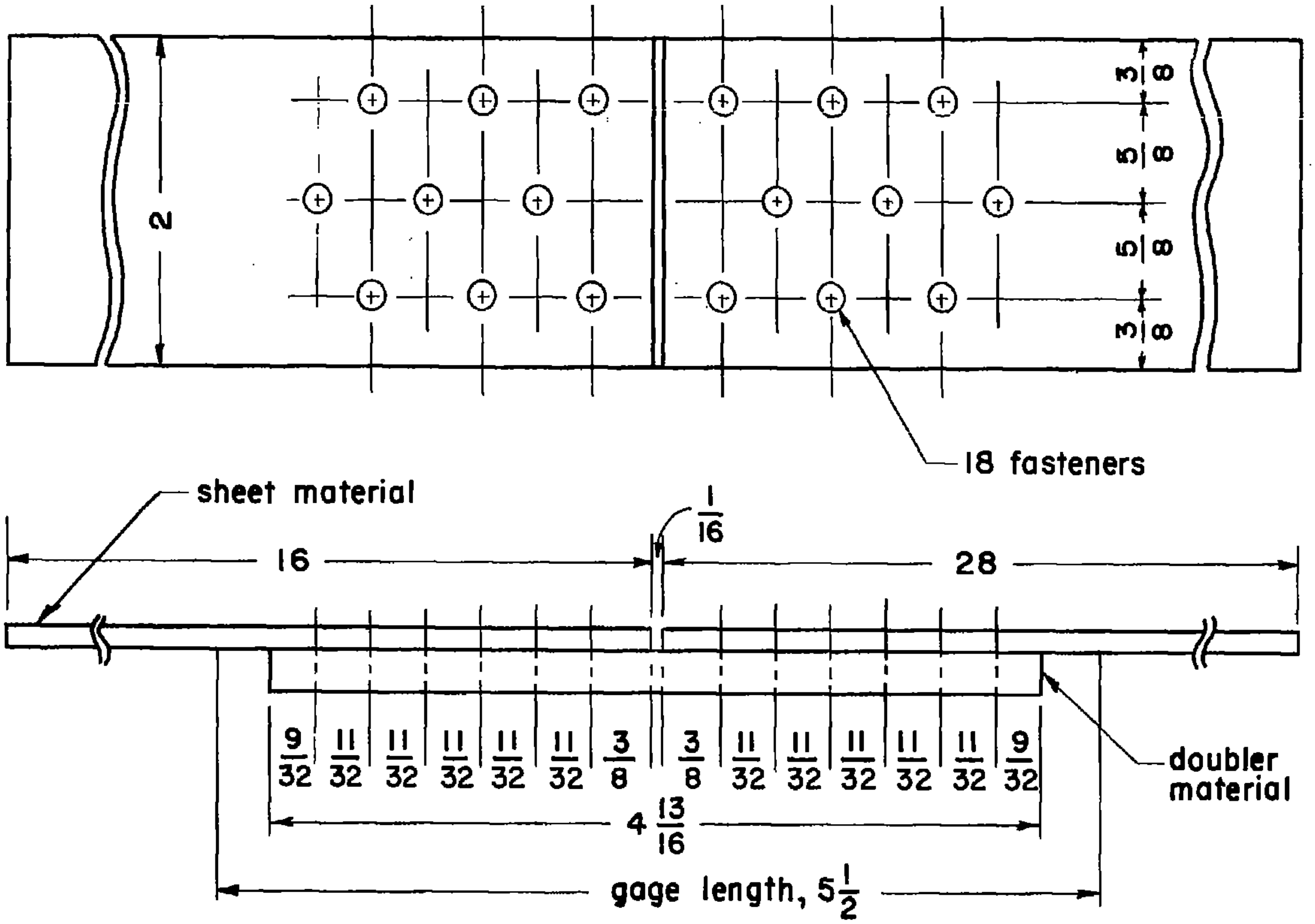
[b] Insufficient data to determine.

[c] By extrapolation.



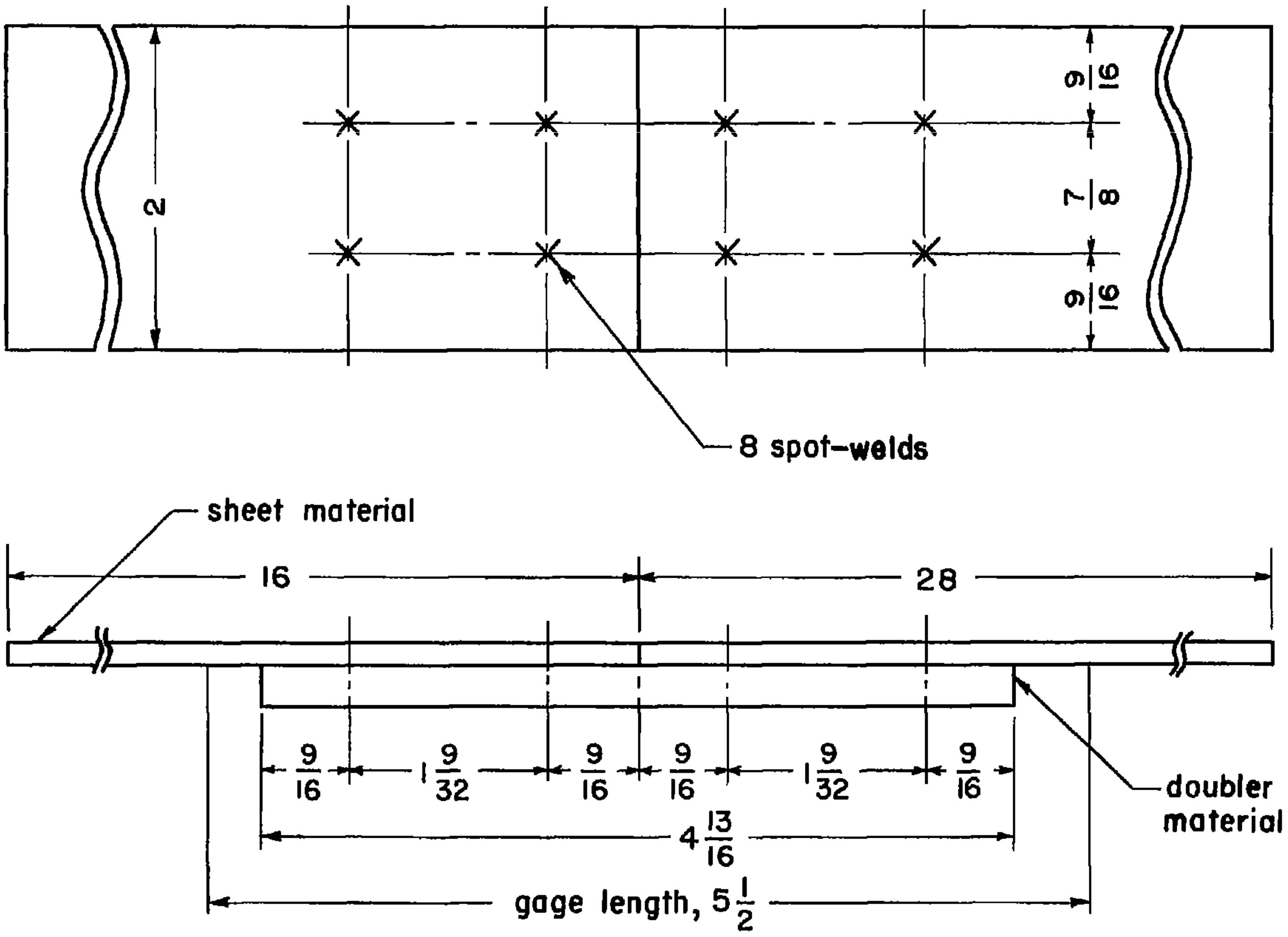
(a) Groups D, E, T, and U.

Figure 1.- Dimensions of specimens. All dimensions are in inches; see also table 1.



(b) Group F.

Figure 1.- Continued.



(c) Group G.

Figure 1.- Concluded.

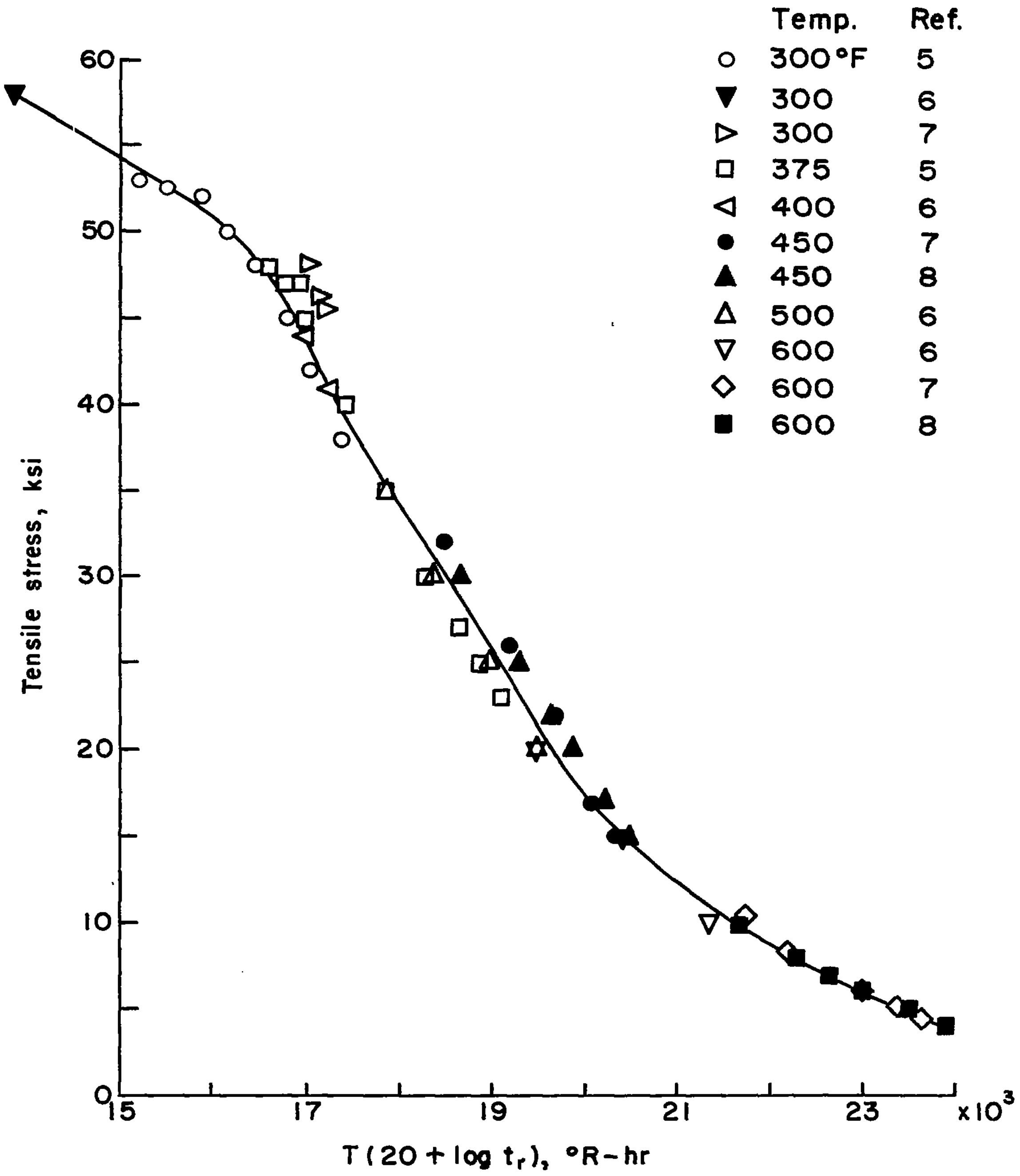


Figure 2.- Master rupture curve for 2024-T3 clad aluminum alloy in tensile creep.

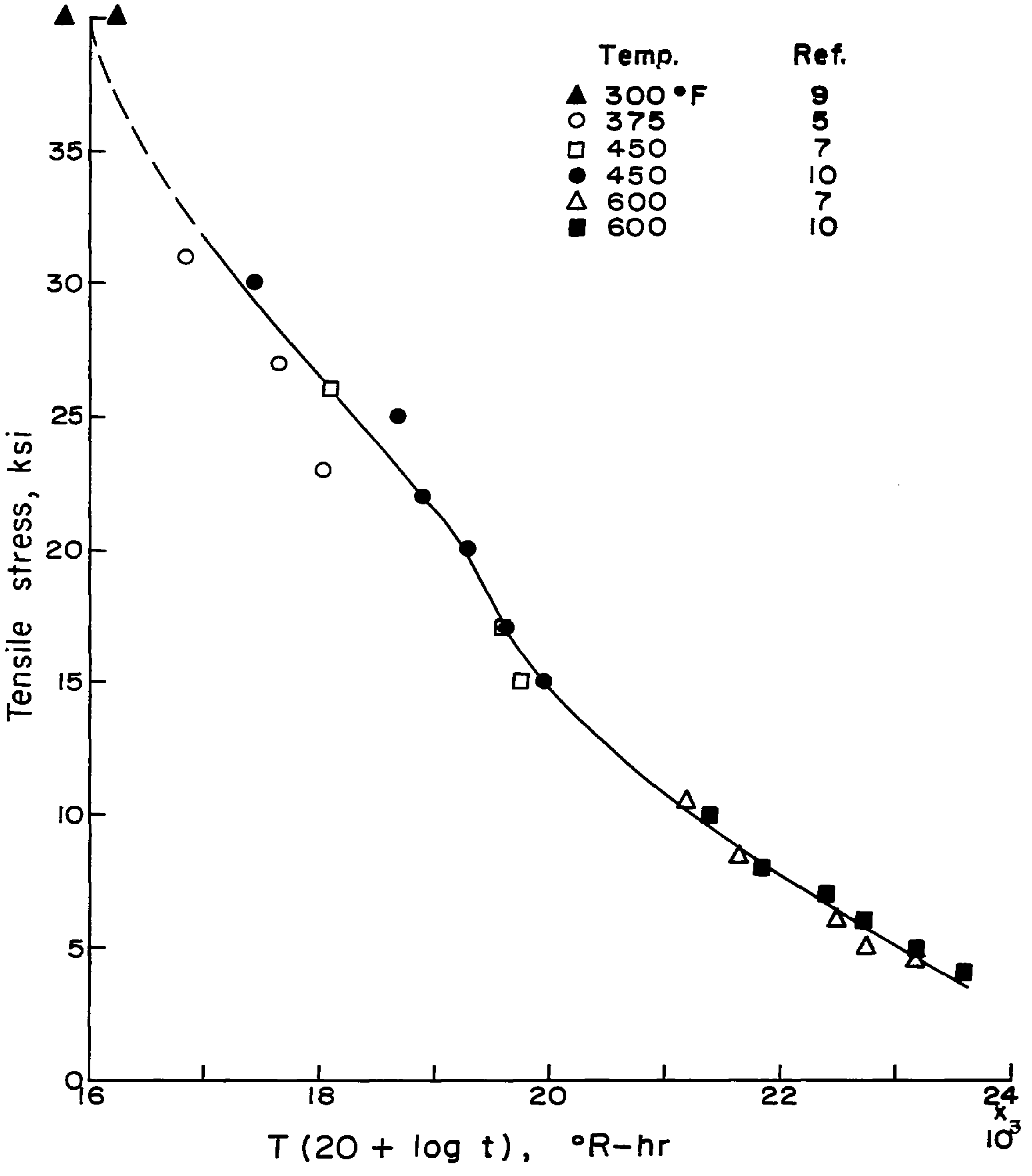


Figure 3.- Master curve for 0.5 percent total deformation of 2024-T3 clad aluminum alloy in tensile creep.

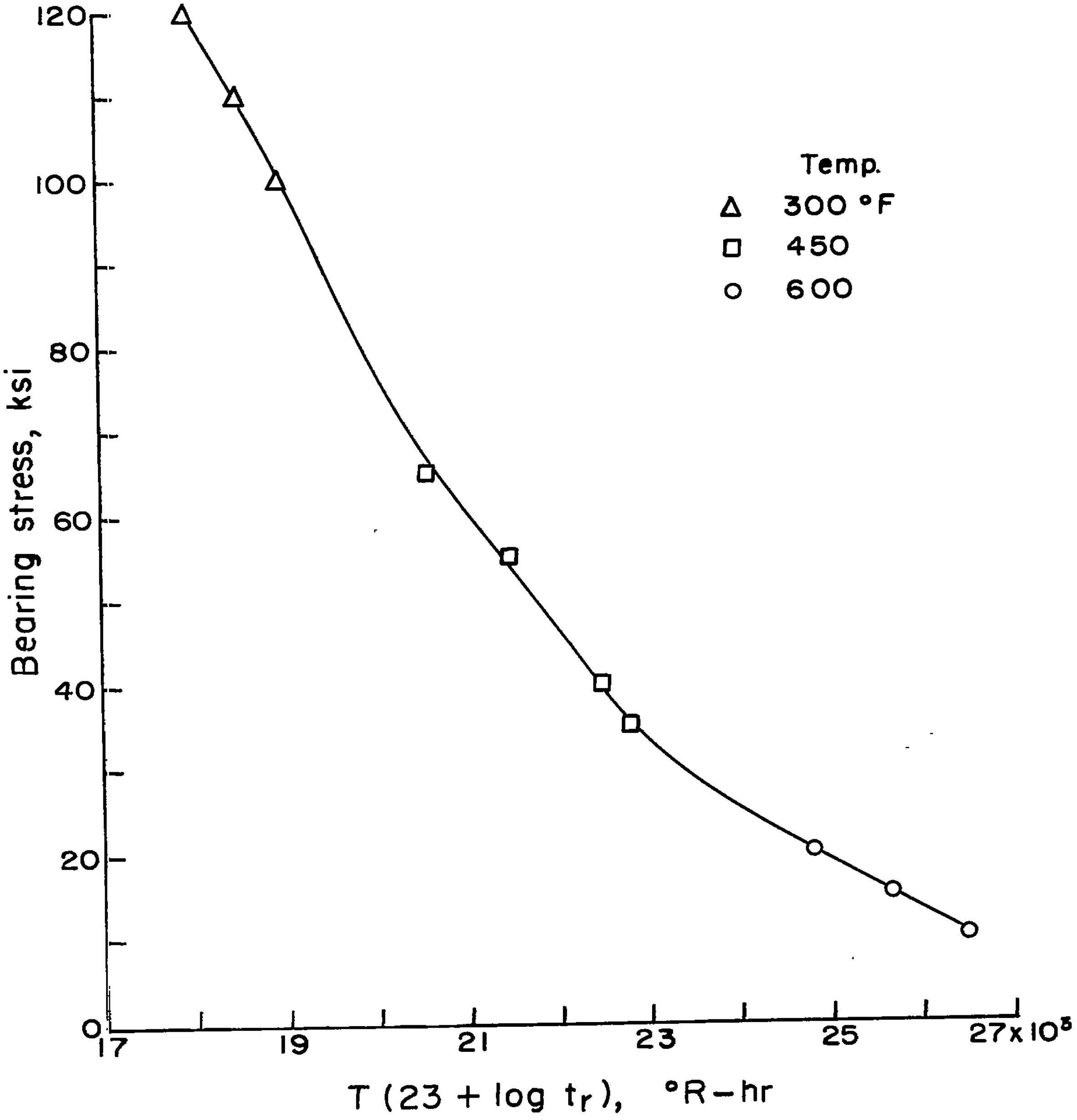


Figure 4.- Master rupture curve for 2024-T3 bare aluminum alloy in bearing creep (ref. 11). e = 2d.

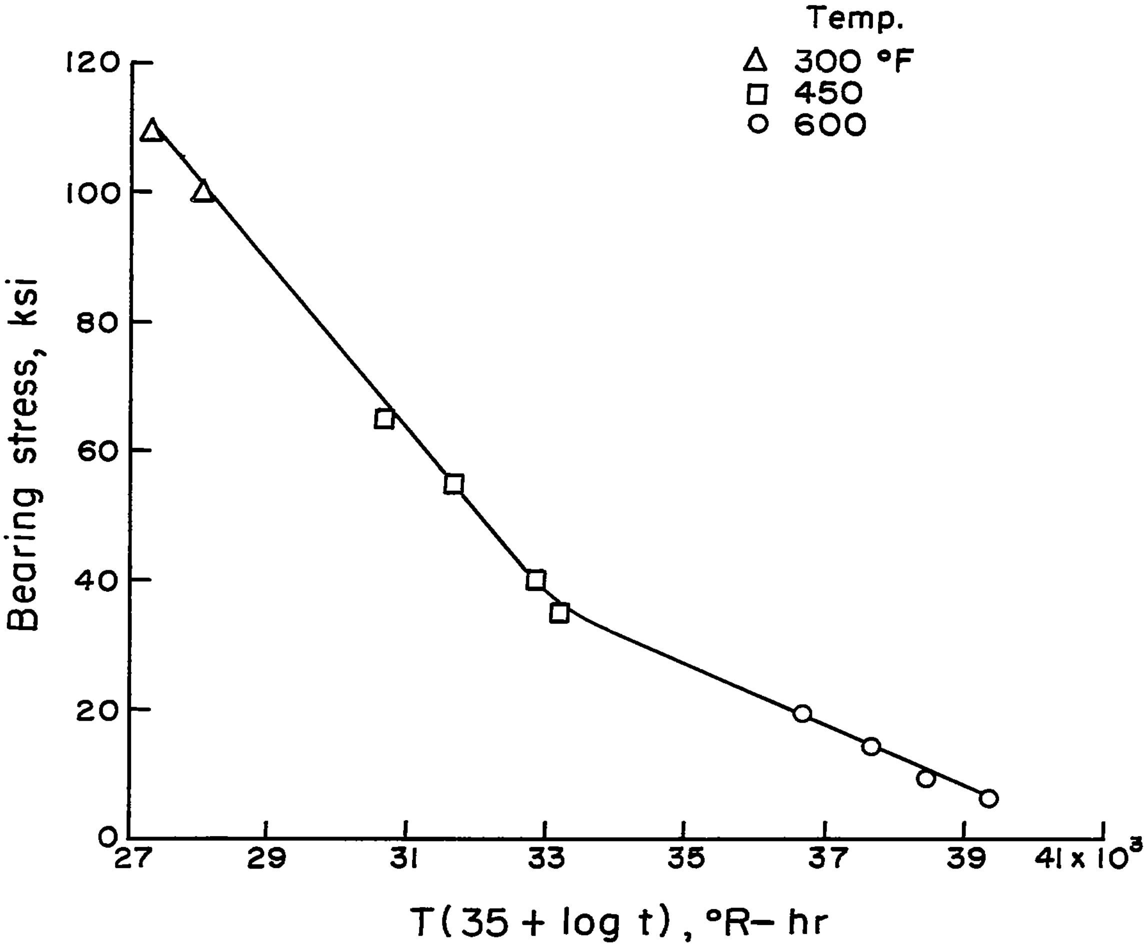


Figure 5.- Master curve for bearing creep deformation of 5 percent of diameter in 2024-T3 bare aluminum alloy (ref. 11). e = 2d.

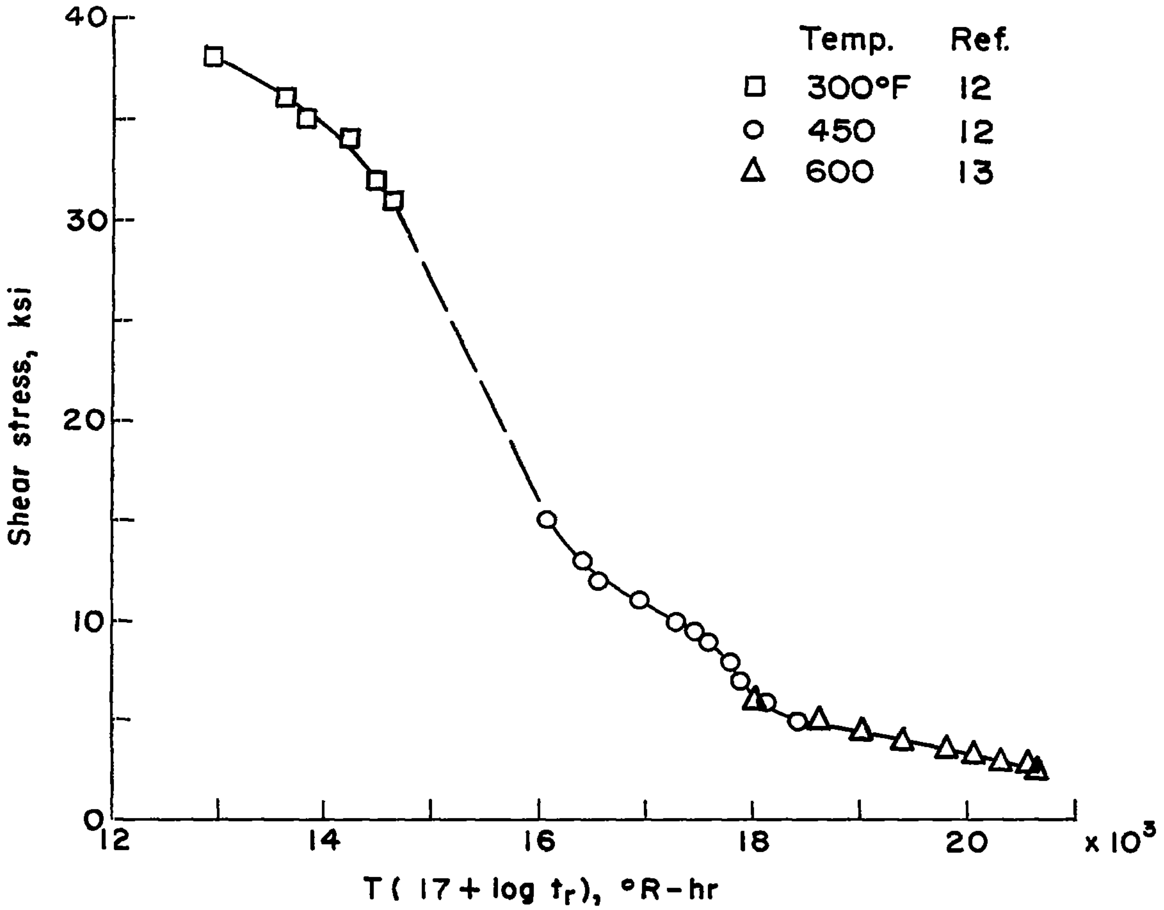


Figure 6.- Master rupture curve for 2024-T3 bare aluminum-alloy pins in shear creep.

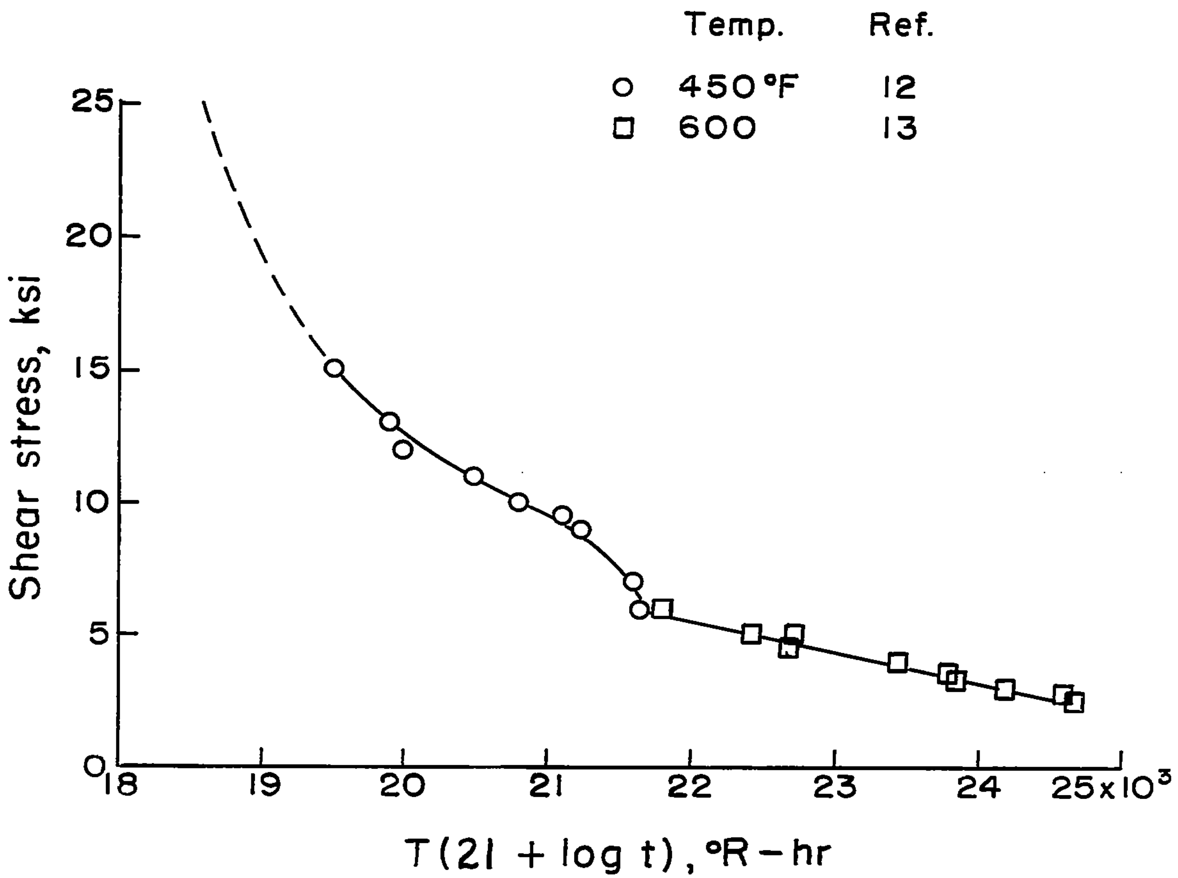


Figure 7.- Master curve for 8-percent creep deformation of 2024-T3 bare aluminum-alloy shear pins.

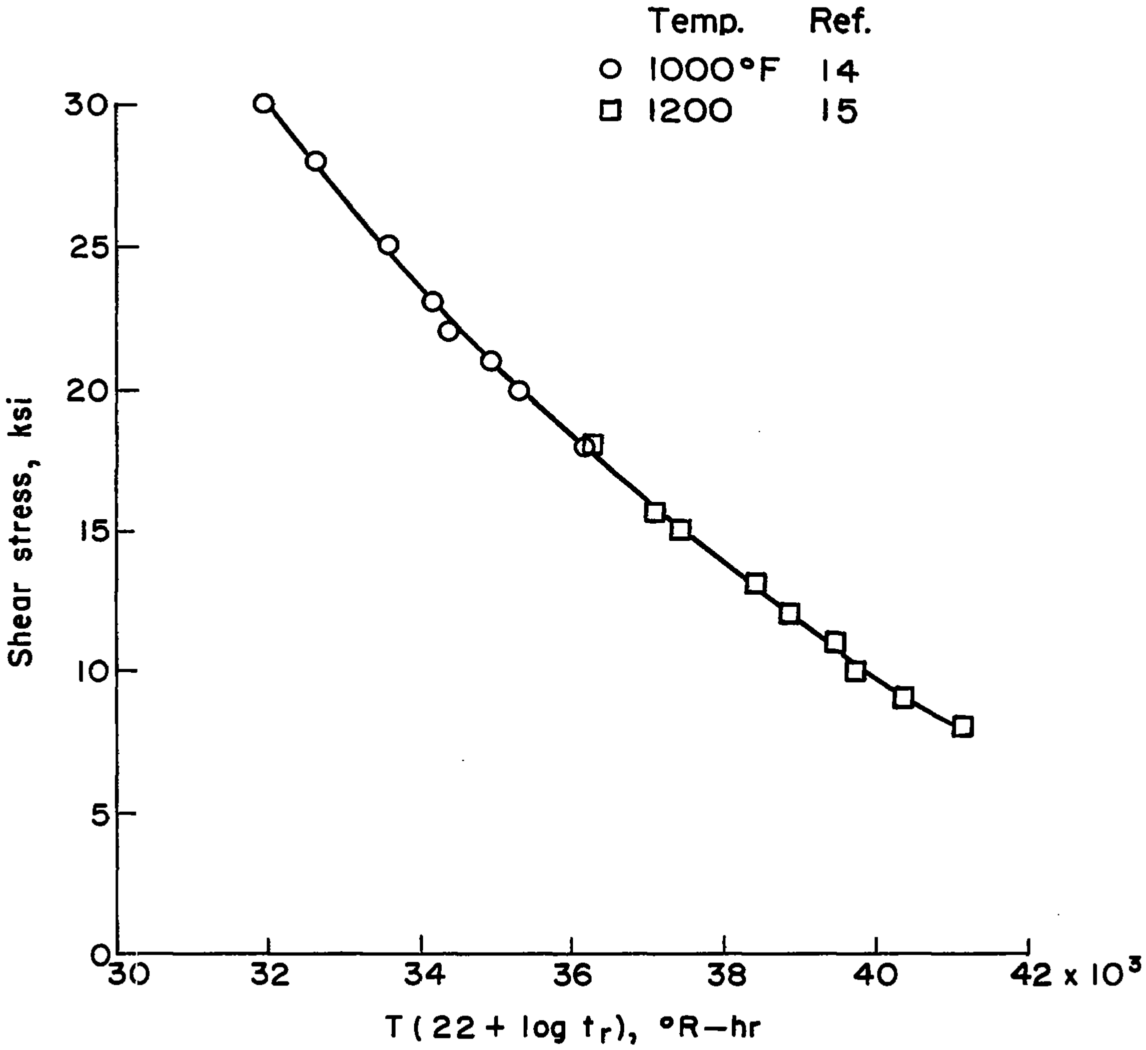


Figure 8.- Master rupture curve for Monel pins in shear creep.

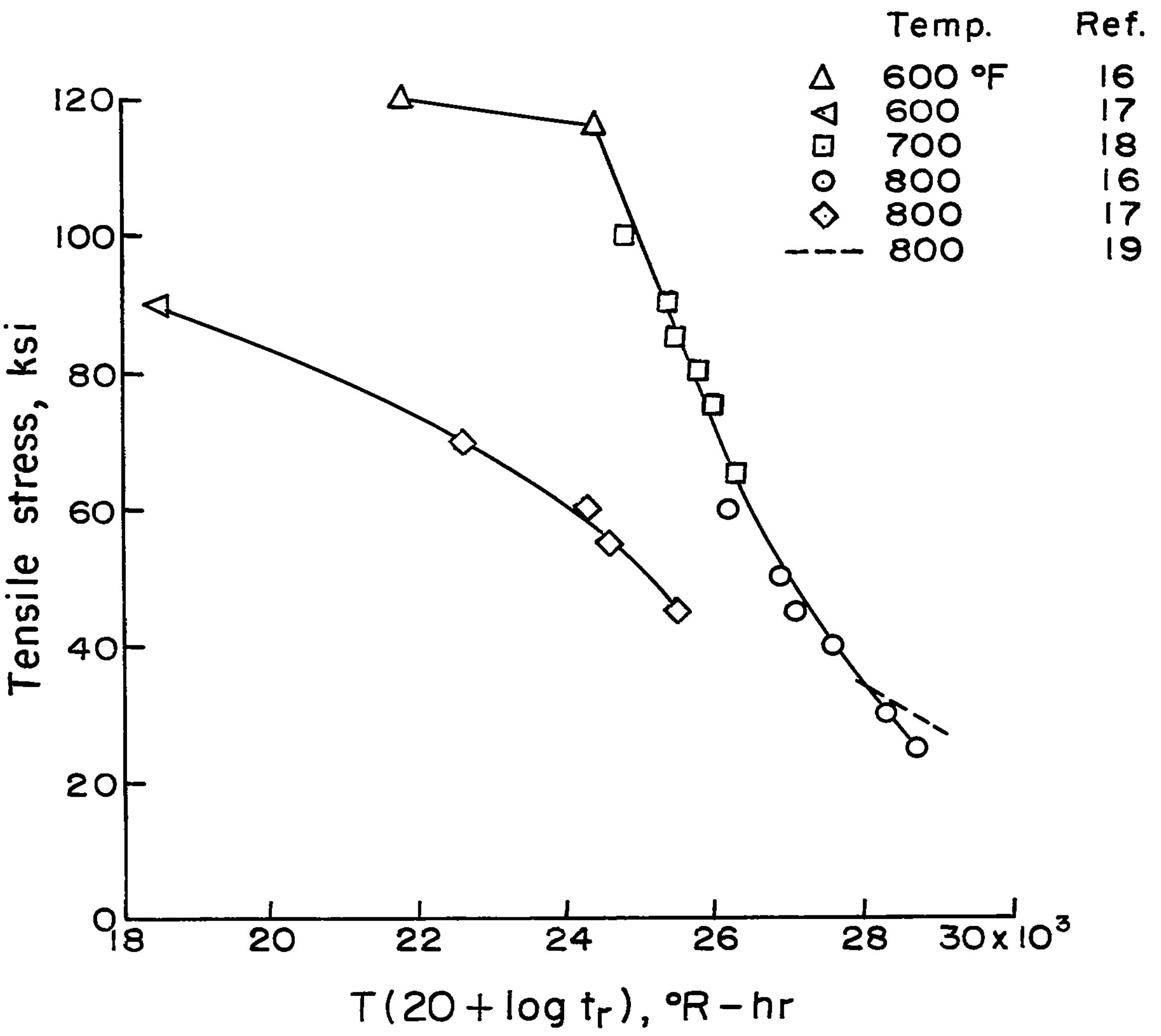
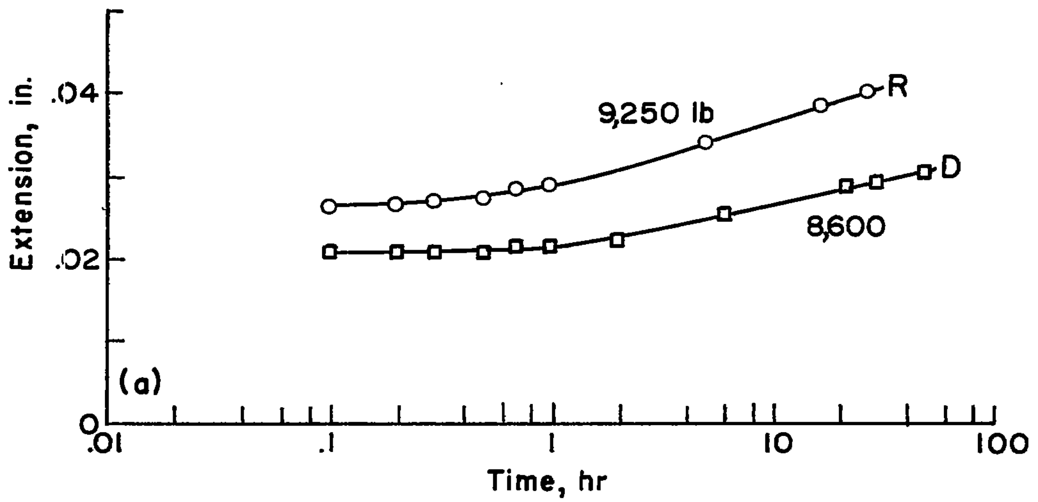
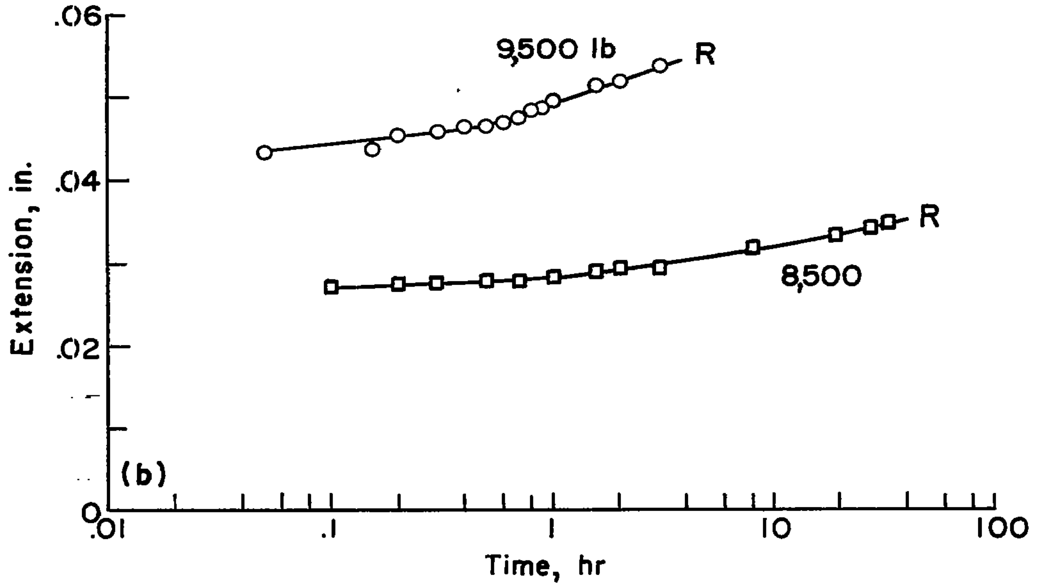


Figure 9.- Master rupture curve for RC-130A titanium alloy in tensile creep.



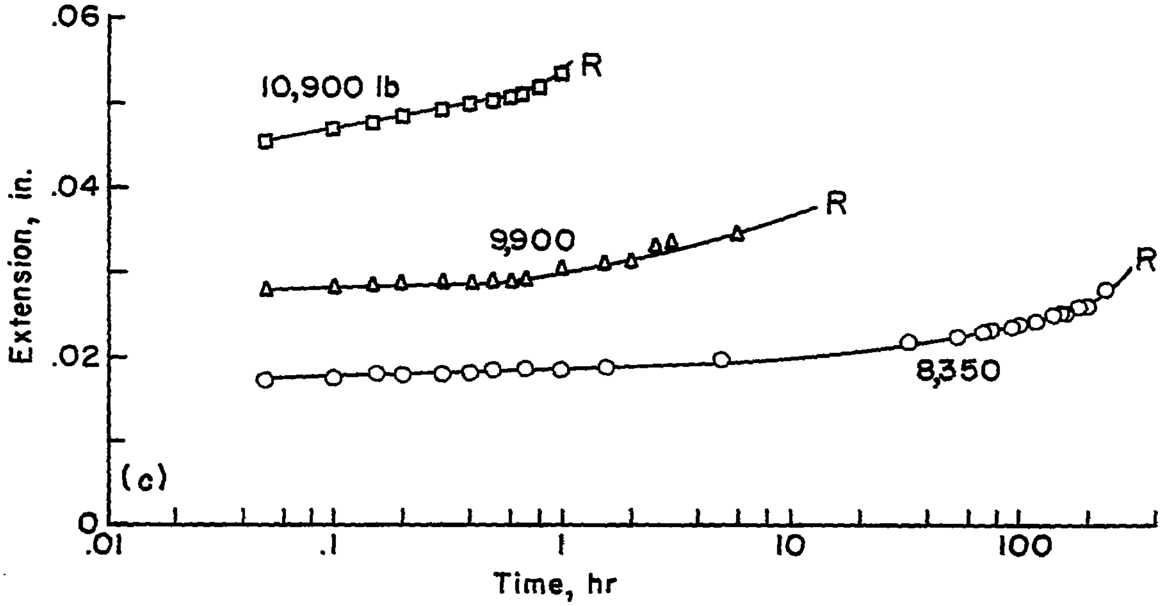
(a) Group D.

Figure 10.- Creep curves of joints at 300° F. R indicates that test was carried to rupture; D indicates that test was discontinued before rupture.



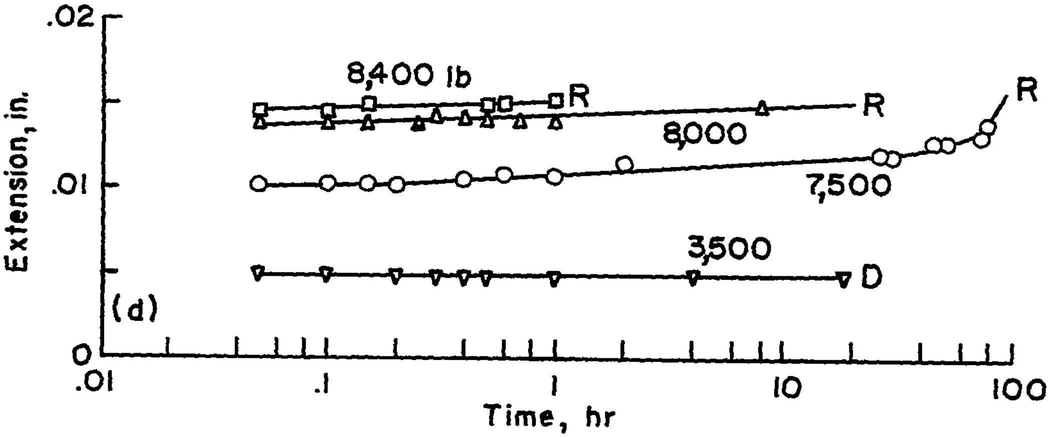
(b) Group E.

Figure 10.- Continued.



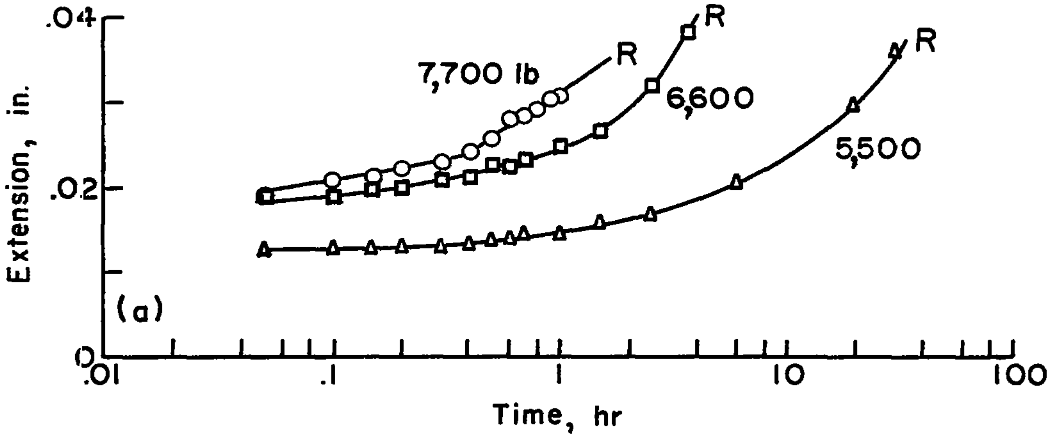
(c) Group F.

Figure 10.- Continued.



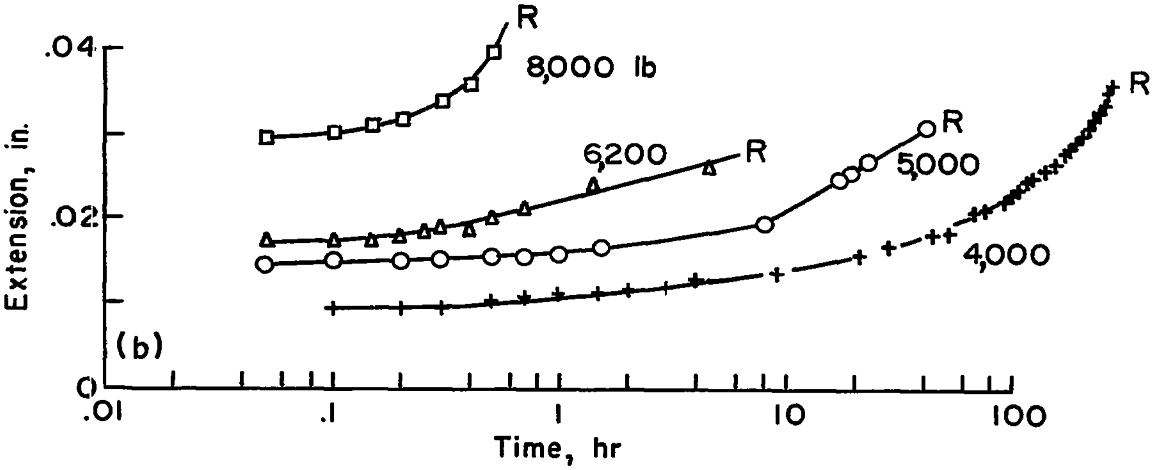
(d) Group G.

Figure 10.- Concluded.



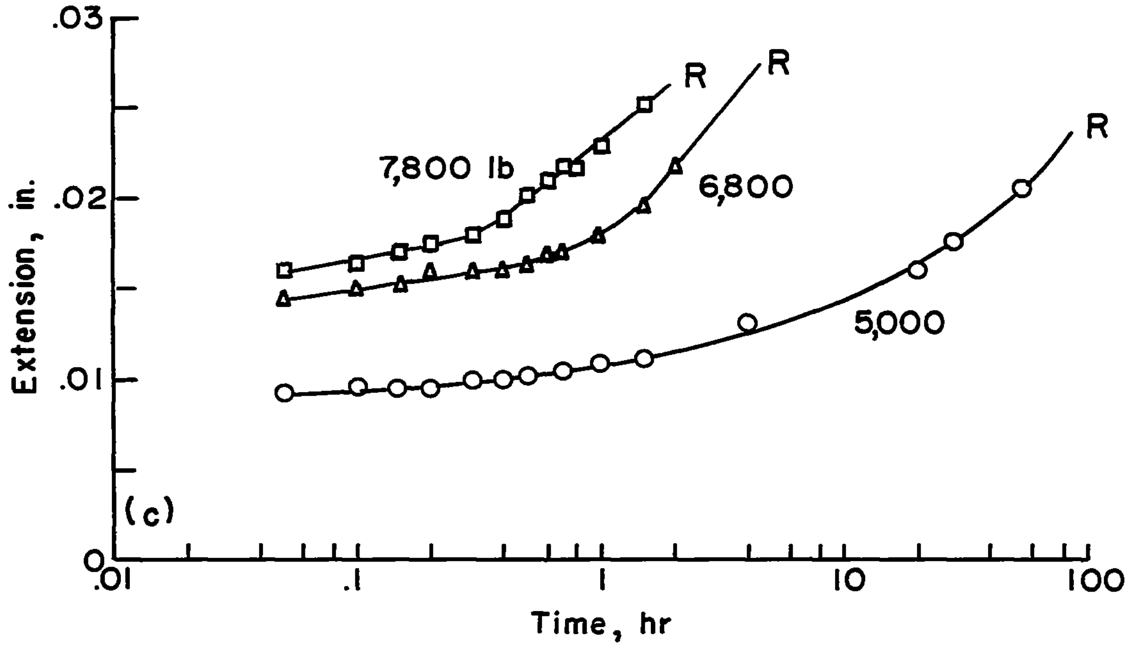
(a) Group D.

Figure 11.- Creep curves of joints at 400° F. R indicates that test was carried to rupture.



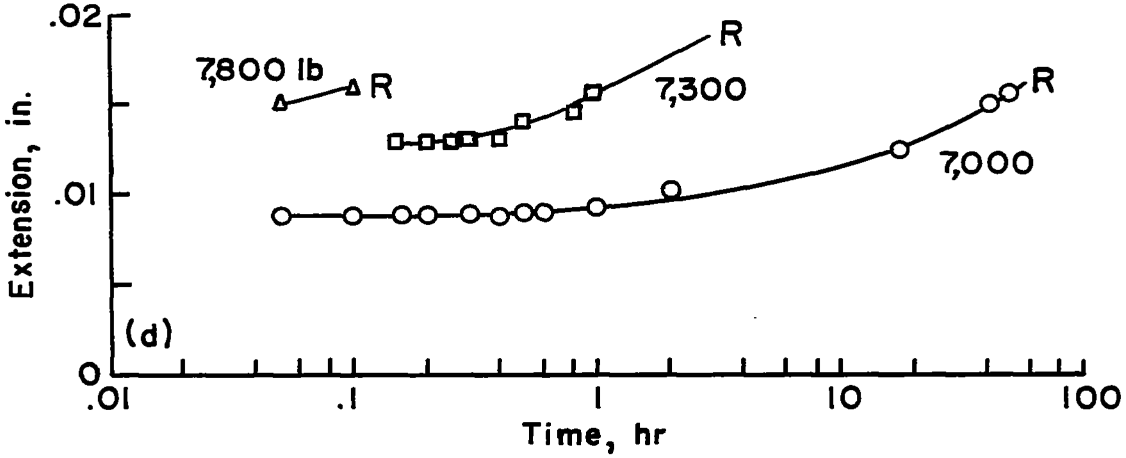
(b) Group E.

Figure 11.- Continued.



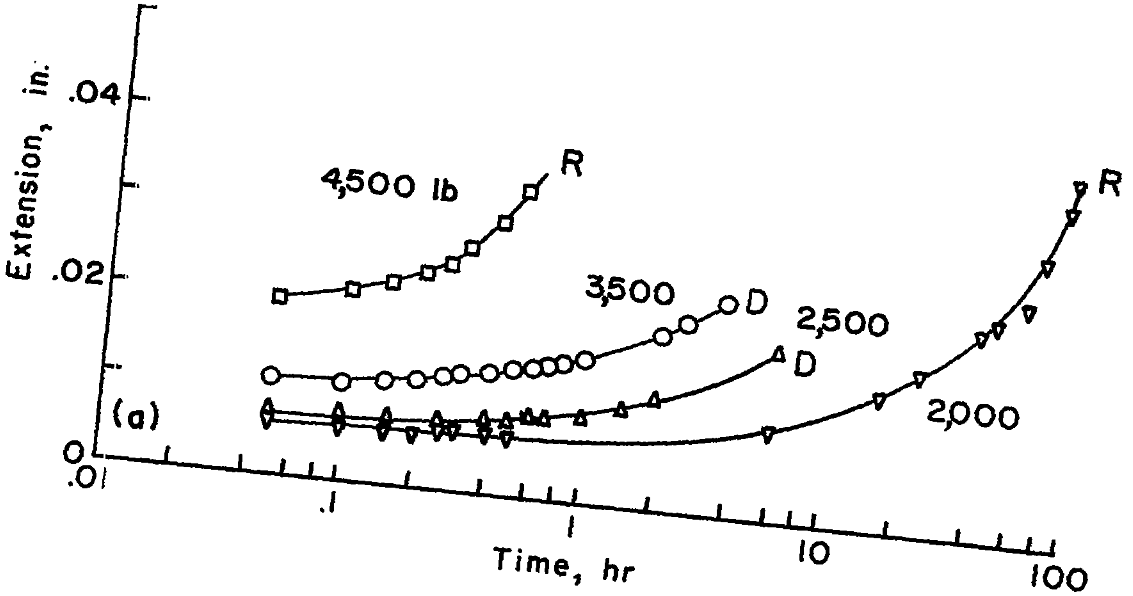
(c) Group F.

Figure 11.- Continued.



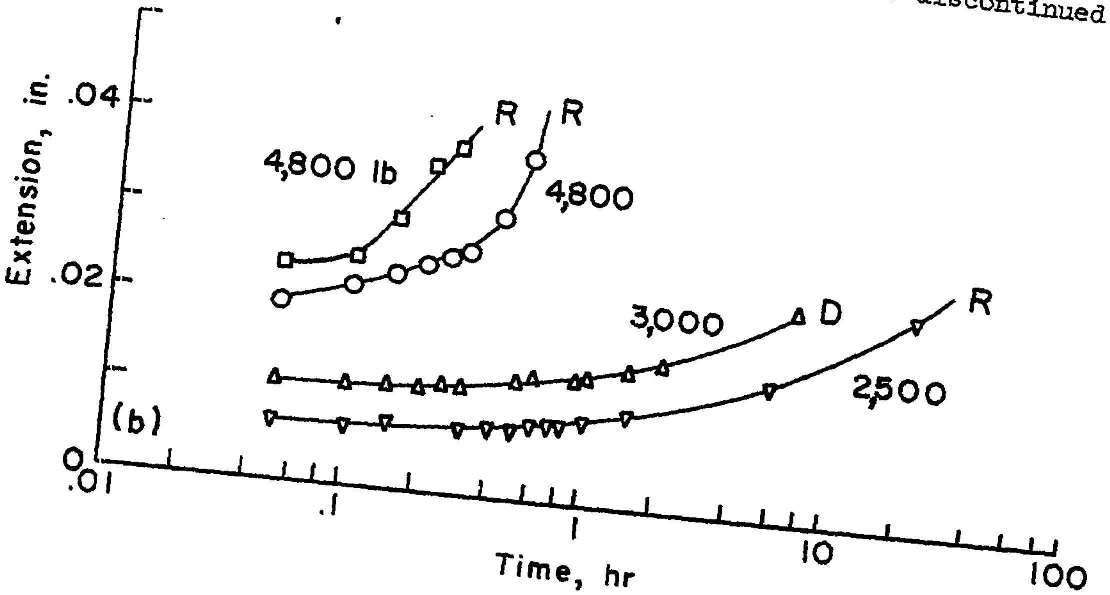
(d) Group G.

Figure 11.- Concluded.



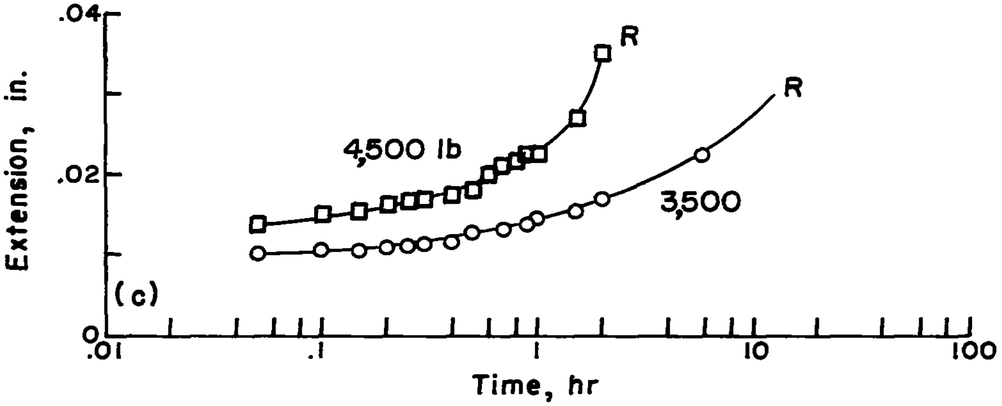
(a) Group D.

Figure 12.- Creep curves of joints at 500° F. R indicates that test was carried to rupture; D indicates that test was discontinued before rupture.



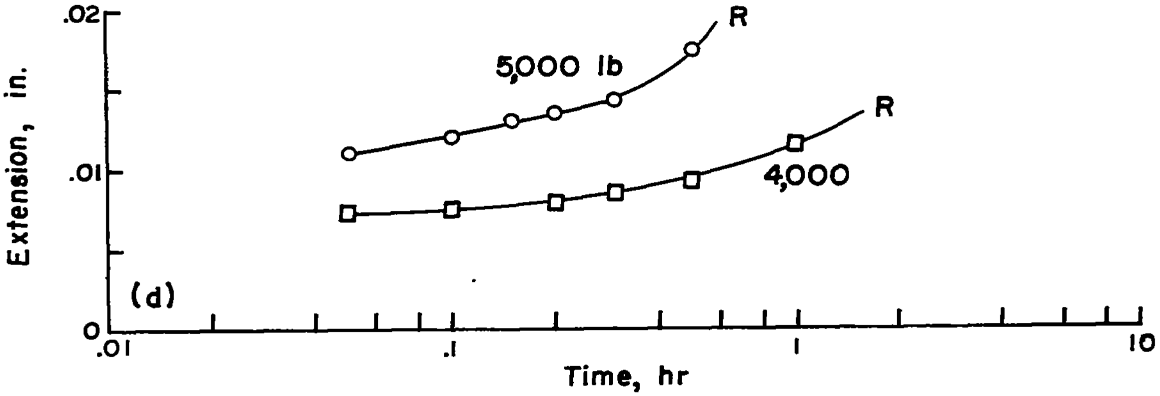
(b) Group E.

Figure 12.- Continued.



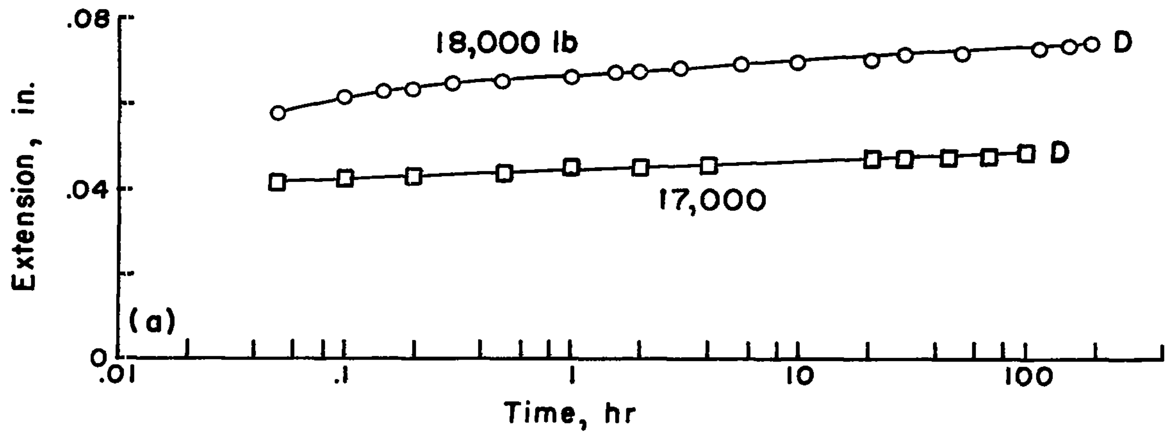
(c) Group F.

Figure 12.- Continued.



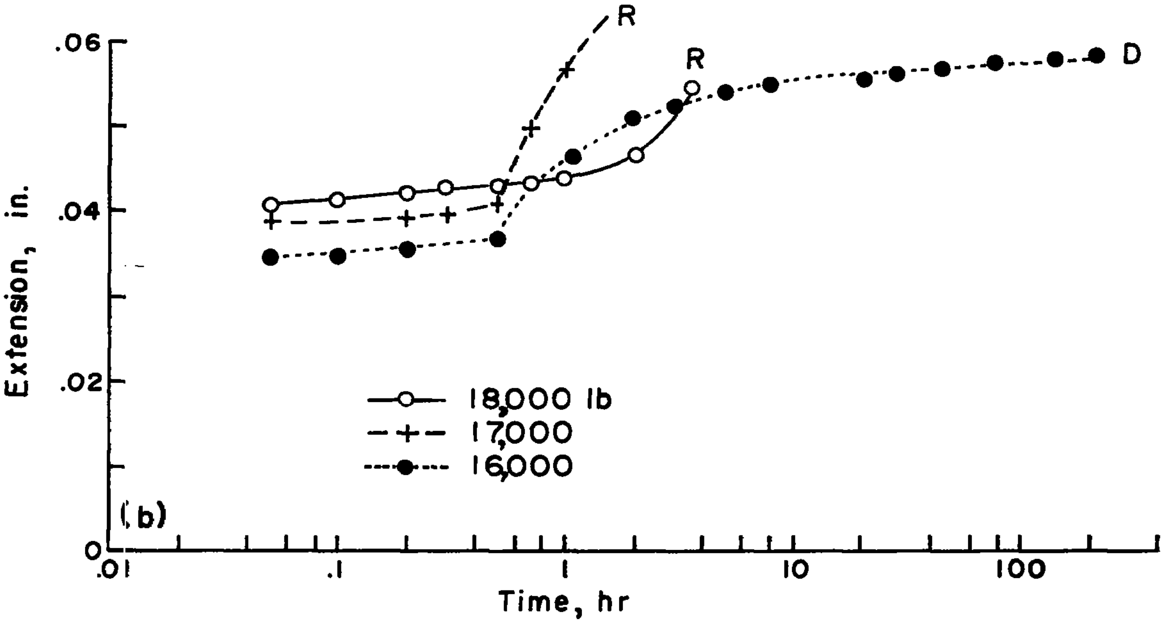
(d) Group G.

Figure 12.- Concluded.



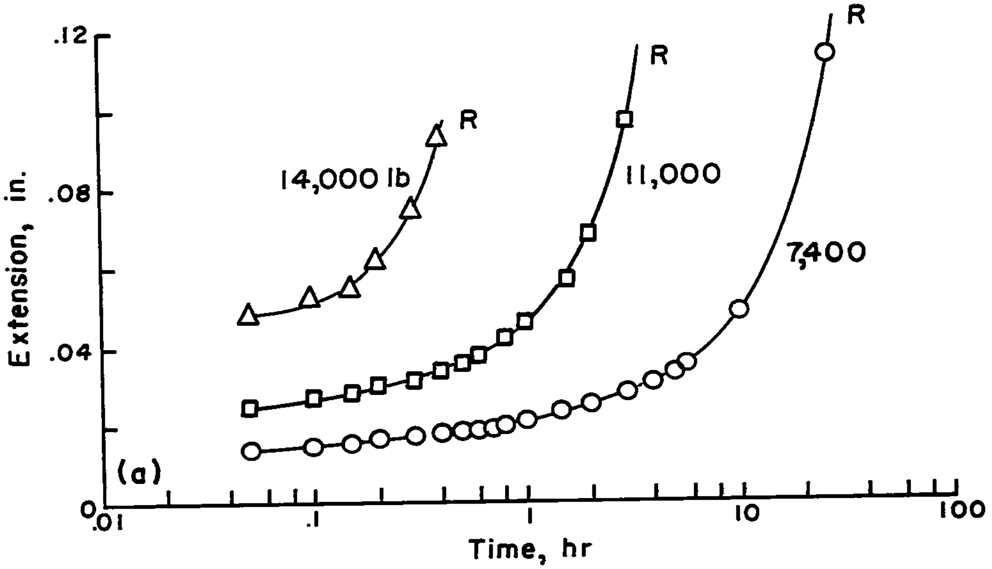
(a) Group T.

Figure 13.- Creep curves of joints at 600° F. R indicates that test was carried to rupture; D indicates that test was discontinued before rupture.



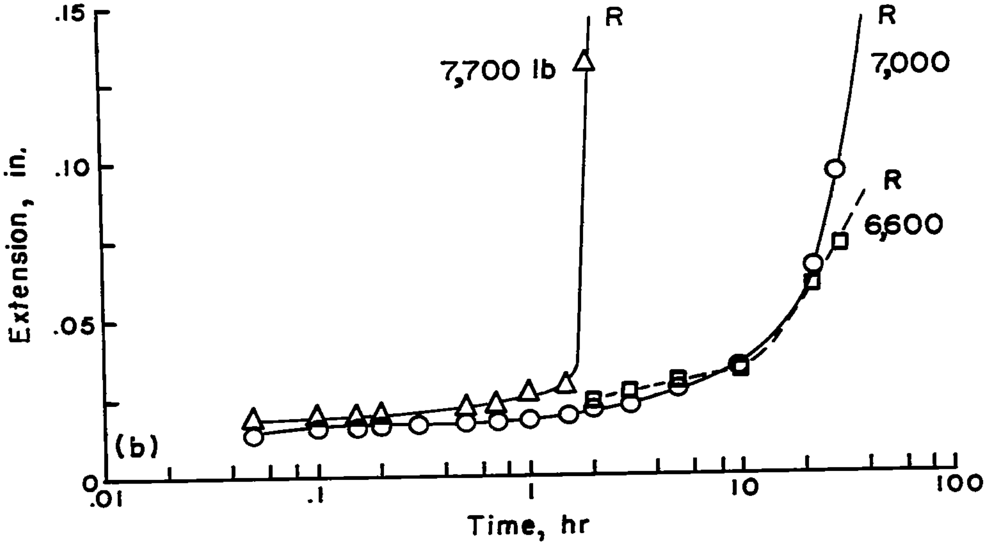
(b) Group U.

Figure 13.- Concluded.



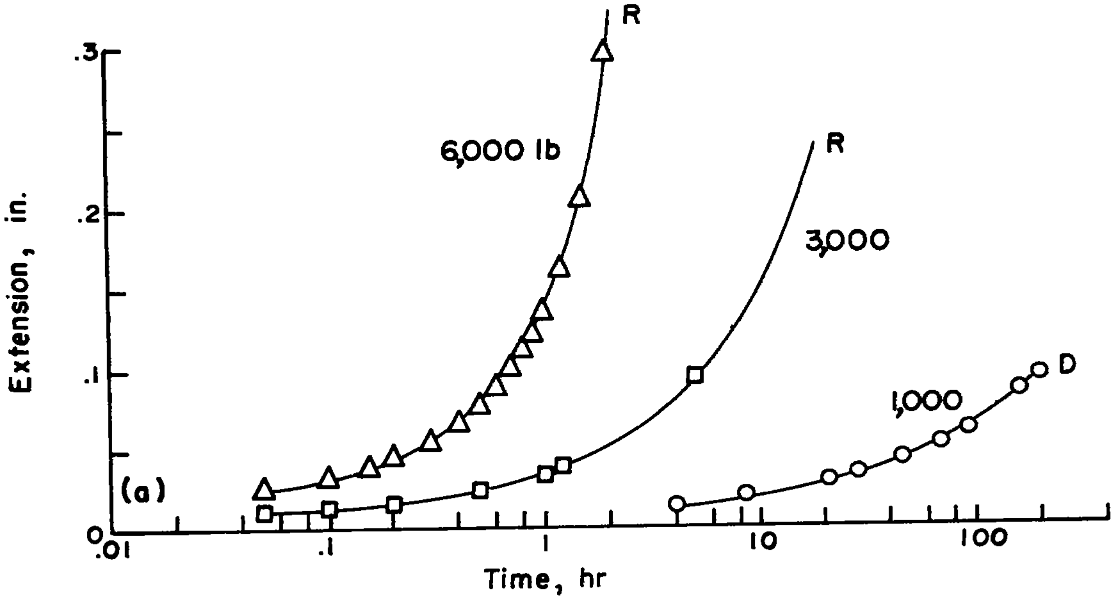
(a) Group T.

Figure 14.- Creep curves of joints at 800° F. R indicates that test continued to rupture.



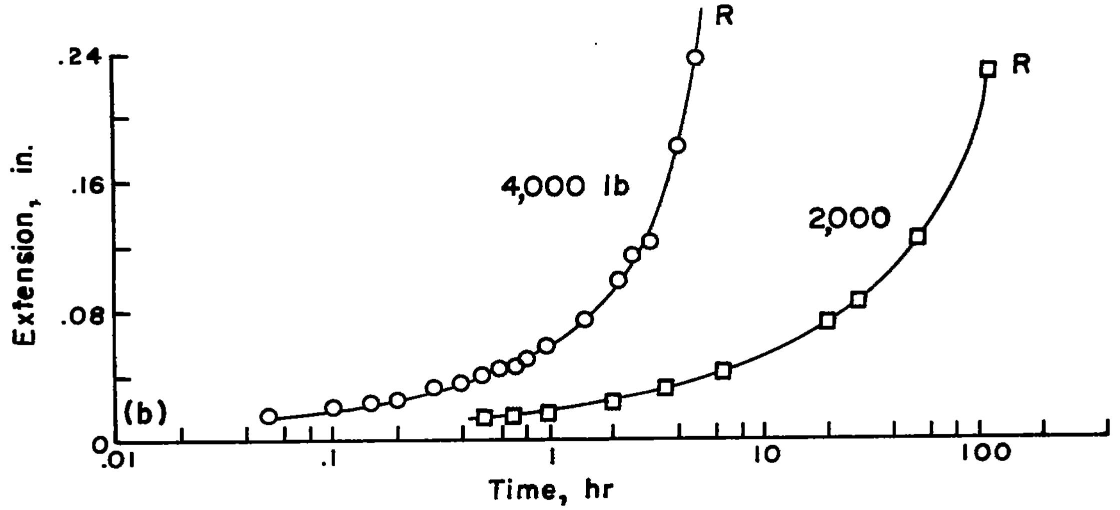
(b) Group U.

Figure 14.- Concluded.



(a) Group T.

Figure 15.- Creep curves of joints at 940° F. R indicates that test continued to rupture.



(b) Group U.

Figure 15.- Concluded.

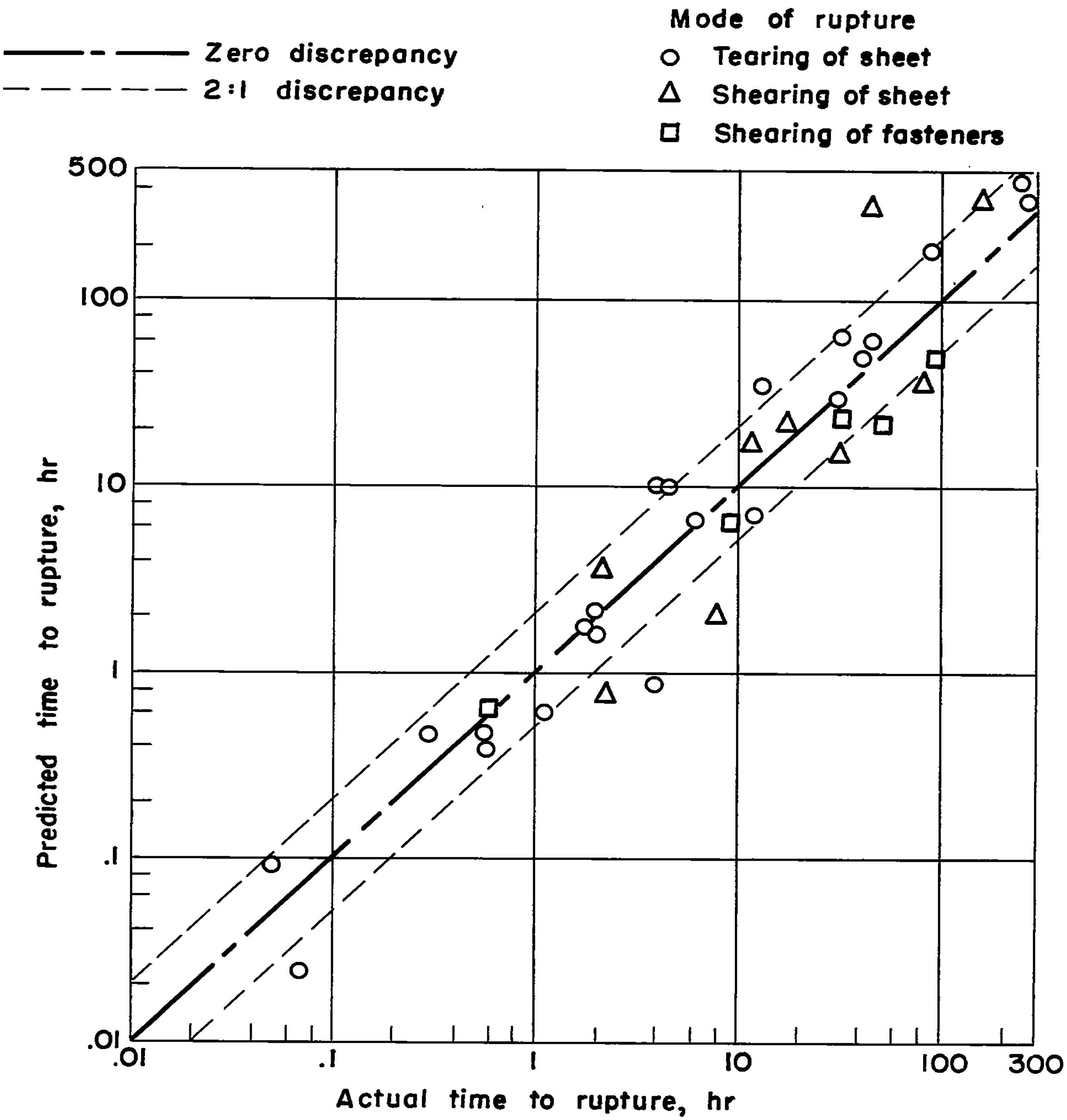


Figure 16.- Comparison of predicted and actual times to rupture for riveted aluminum-alloy joints.

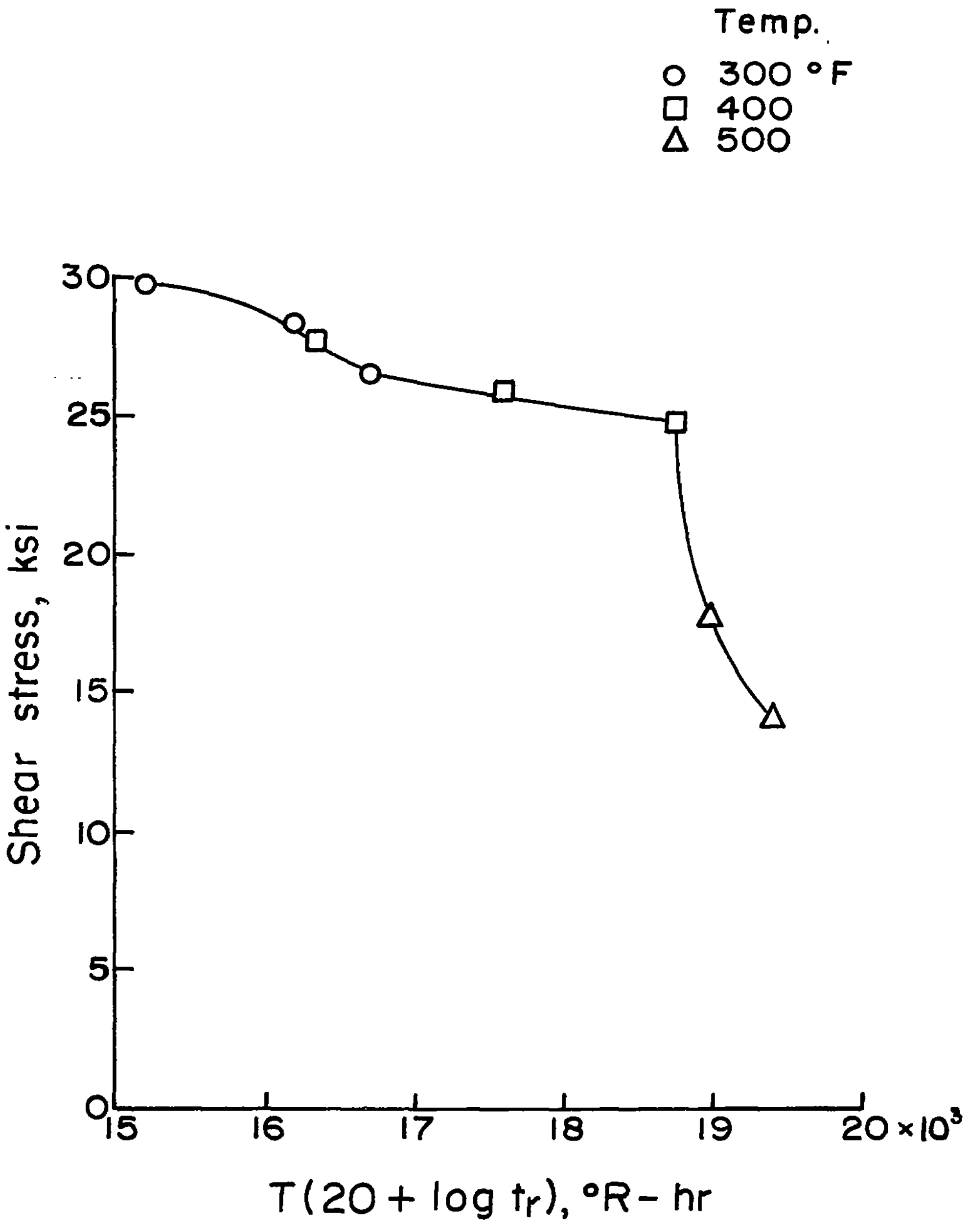


Figure 17.- Master rupture curve for spot-welds in 2024-T3 clad aluminum alloy in shear creep.

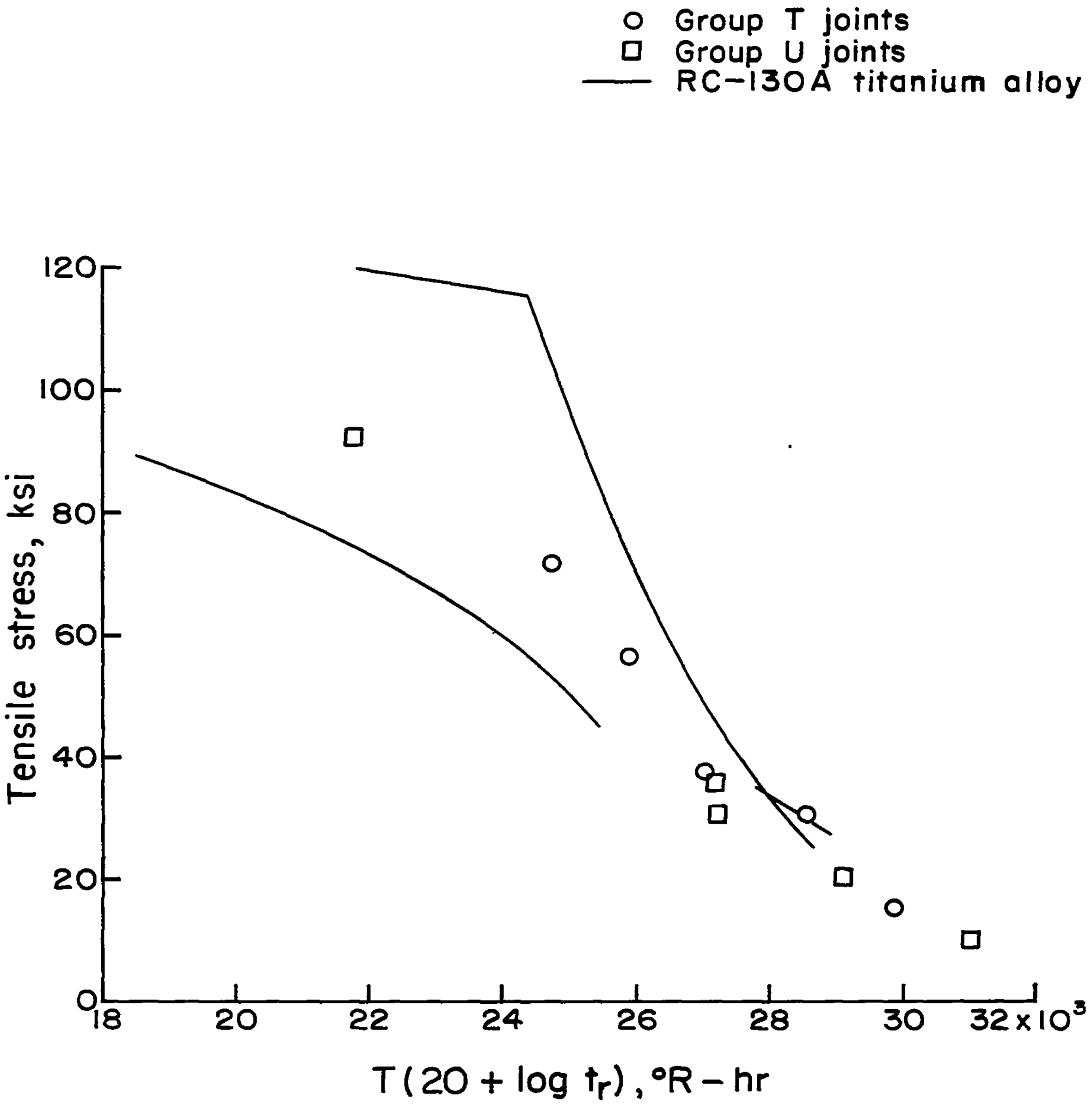


Figure 18.- Comparison of tensile creep rupture of RC-130A titanium-alloy sheet and joints.

NACA - Langley Field, Va.