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TECHNICAL NOTE 4112

GENERALIZED MASTER CURVES FOR CREEP AND RUPTURE

By George J. Heimerl and Arthur J. McEvily, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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GENERALIZED MASTER CURVES FOR CREEP AND RUPTURE

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SUMMARY

The similarity of Larson-Miller master curves for rupture life and minimum creep rate is shown for aluminum, two aluminum alloys, two steels, and two high-temperature high-strength alloys. In addition, the similarity of master curves for rupture life and for 0.2- and 0.5-percent creep strain is shown for the aluminum alloys. The approximate invariance of the product of rupture life and the minimum creep rate is shown for these materials. With equivalent parameters derived on the basis of this invariance, the master curves for the various applications are generalized essentially to a single curve in the high-temperature region for each material. The minimum creep rate and the 0.2- and 0.5-percent creep strain can be determined from the master curve for rupture by this method for the materials investigated.

INTRODUCTION

Since the introduction of the Larson-Miller time-temperature and rate-temperature parameters for rupture and creep in 1952 (ref. 1), the practice of summarizing rupture and creep data by means of master curves has been widely used. In addition to the Larson-Miller parameters, other empirical and semiempirical parameters have been proposed (refs. 2 to 5). With these parameters and master curves, predictions of rupture life and creep can often be made from limited data. A critical evaluation of these time-compensated parameters is given in reference 6; the advantages and shortcomings of the method are covered therein.

In reviewing published master curves (refs. 1 and 5) for rupture life, for minimum creep rate, and for creep strain, employing the Larson-Miller parameters, a marked similarity of the master curves for a given material is evident in most instances. This similarity suggests that the curves are related and that it should be possible to predict one curve from another or to generalize the results so that a single master curve will cover the various applications.

This paper illustrates the similarity of master curves (obtained with the Larson-Miller parameters) for rupture life, minimum creep rate, and 0.2- and 0.5-percent creep strain for a number of materials. A relationship between rupture life and minimum creep rate is also shown for these materials. On the basis of this relationship, the master curves for the different applications are generalized to a single curve for each material.

SYMBOLS

c	creep-strain constant, percent
C	constant
C_1	constant $\left(C_1 = C + \log_{10} c\right)$
C_2	constant $\left(C_2 = C + \log_{10} \frac{c}{\epsilon}\right)$
C_3	constant $\left(C_3 = C + \log_{10} \epsilon^m c\right)$
ϵ	creep strain, percent
m	slope of curve of $\log_{10} t_r$ plotted against $\log_{10} r$
r	minimum creep rate, percent hr^{-1}
t_ϵ	time for creep strain ϵ, hr
t_r	rupture life, hr
T_R	absolute temperature, $^{\circ}R$

GENERALIZED MASTER CURVES

Similarity of Master Curves

The materials included in this study are pure aluminum (ref. 7), 2024-T3 aluminum-alloy sheet (refs. 8 to 12), 7075-T6 clad aluminum-alloy sheet (ref. 13), carbon-molybdenum steel (ref. 1), 18-8 Cb stainless steel (ref. 14), and the "superalloys" S-590 (ref. 1) and Inconel X (ref. 15). Creep and rupture data for these materials are shown in figures 1 to 3. Master curves for these materials, shown in figure 1, are either those previously published or were constructed from the data. The correlation of the data with the master curves is shown for all the materials except the carbon-molybdenum steel and the superalloy S-590 for which the data were not available. The master curves shown are for rupture life, minimum creep rate, and 0.2-percent and 0.5-percent creep strain. Master curves for creep strain are shown only for the aluminum alloys inasmuch as strain data were not available for the other materials except for Inconel X. For Inconel X, a reasonably satisfactory correlation of the strain data with a master curve could not be obtained over the temperature range of the data.

Examination of figure 1 reveals a marked similarity of the master curves for rupture life, minimum creep rate, and 0.2-percent and 0.5-percent creep strain for a given material. The principal exception occurs in the low-temperature, high-stress region for the aluminum alloys (figs. 1(b) and 1(c)). In this region, the data frequently becomes discontinuous and a correlation of the data with a single curve is no longer obtained. The general similarity of the master curves suggests that for a given material a relationship exists between the curves except in the low-temperature, high-stress region.

Relationship Between Rupture Life and Minimum Creep Rate

The basis for the similarity of the master curves is given by the approximate invariance of the product of rupture life and the steady creep rate which may be expressed as

$$t_r r = c \tag{1}$$

In equation (1), t_r is the rupture life in hours, r is the minimum creep rate in percent hour^{-1}, and c is a creep-strain constant.

Equation (1) has been derived theoretically by Machlin (ref. 16) and can also be obtained from the empirical relationship between rupture life and minimum creep rate suggested by Monkman and Grant (ref. 17), which can be given as

$$\log_{10} t_r = m \log_{10} r + b \tag{2}$$

where m is the slope of a curve of $\log_{10} t_r$ plotted against $\log_{10} r$ and b is a constant. If the slope is -1, equation (2) reduces to equation (1) with $\log_{10} c = b$.

The slopes obtained from the log-log plots (ref. 17), however, varied from about -0.7 to -0.9 for aluminum, iron, nickel, titanium, cobalt, and copper alloys. Although the relative influence of low-temperature and high-temperature creep on the determination of the slopes could not be ascertained in reference 17 because the data were omitted, there is a possibility that consideration of the low-temperature creep may have resulted in lower slopes since, for low temperatures, different creep laws undoubtedly apply (ref. 4). For the case in which $m \neq -1$, equation (2) may be written

$$t_r r^{-m} = c \tag{3}$$

The experimental relationship between rupture life and minimum creep rate obtained for the various materials in the present investigation is shown in figure 2. A slope of -1 was assumed for the curves. In some instances a slope other than -1 might fit the data slightly better but the agreement in the region covered by the tests would only be altered slightly. Considerable scatter is evident, however, in some cases; for example, see figure 2(b) for 2024-T3 aluminum-alloy sheet in the long-time region. There is also an indication that the slope is somewhat less than -1 in the low-temperature region for some of the materials. (See fig. 2(c) for 7075-T6 clad aluminum alloy and fig. 2(e) for 18-8 Cb stainless steel.) Values of the intercept b (at $\log_{10} r = 0$, fig. 2) are given in table I for the different materials. The value of the intercept for pure aluminum was found to be 1.4, which is close to the value 1.5 calculated from reference 16.

The constant c in equation (1) can be described as a creep-strain constant (in percent) that is some measure of the viscous flow which occurs during steady creep but bears no known relation to the actual strain or elongation at rupture (ref. 17). Values of the creep-strain constant for each material are included in table I.

Relationship Between Parameters

For generalization purposes, the master curve for rupture is taken as the basic curve because the data for rupture are more available and reliable than other creep data. The Larson-Miller time-temperature parameter employed for this purpose is

$$T_R\left(C + \log_{10} t_r\right) \tag{4}$$

in which T_R is the absolute temperature ($^{\circ}R$), C is a constant, and t_r is the rupture life in hours. The constant C may have a value of 20 (ref. 1) or, for the best correlation of the data, some other value may be taken in some cases (ref. 5).

In order to determine a rate parameter which is equivalent to the time parameter (4), a relation between minimum creep rate and the rupture life is required. The assumption is made that equation (1) provides this relationship. Substitution of equation (1) into the time parameter (4) gives

$$T_R\left(C_1 - \log_{10} r\right) \tag{5}$$

in which $C_1 = C + \log_{10} c$. Inasmuch as parameter (5) is equivalent to parameter (4) at a given stress, the master curve for rupture now holds for the minimum creep rate as well. Parameter (5) has the same form as the Larson-Miller rate parameter (ref. 1). If the assumption is made that the slope is not equal to -1, equation (3) applies and the equivalent parameter becomes

$$T_R\left(C_1 + m \log_{10} r\right) \tag{5a}$$

A time parameter for a given amount of creep strain, which is equivalent to the rupture-life parameter, can be derived for steady-creep conditions from equation (1) and parameter (4). From equation (1), the time t_ϵ for the creep strain ϵ in terms of the creep-strain constant c and the rupture life t_r is

$$t_\epsilon = \frac{\epsilon}{c} t_r \tag{6}$$

By substituting equation (6) into parameter (4), the equivalent parameter for a given amount of creep strain ϵ_c is obtained

$$T_R\left(C + \log_{10} \frac{c}{\epsilon} + \log_{10} t_\epsilon\right) \tag{7}$$

Parameter (7) may be written in the more general form

$$T_R\left(C_2 + \log_{10} t_\epsilon\right) \tag{8}$$

in which $C_2 = C + \log_{10} \frac{c}{\epsilon}$. If the relation between rupture life and creep rate is given by equation (3) instead of equation (1), parameter (8) becomes

$$T_R\left(C_3 - m \log_{10} t_\epsilon\right) \tag{8a}$$

where $C_3 = C + \log_{10} \epsilon^m c$.

Comparisons of Generalized Master Curves

Generalized master curves for the minimum creep rate and for 0.2- and 0.5-percent creep strain (fig. 3) were constructed by means of the equivalent parameters (5) and (8) and the creep-strain constant c (table I). In this procedure, values of the minimum creep rate and the time for 0.2- and 0.5-percent creep strain were first determined for several stresses and temperatures from the master curves for minimum creep rate and strain (fig. 1). The corresponding values of the equivalent parameters were then calculated from these values. Inasmuch as the constant in the equivalent parameter usually differed from the original constant by only a small amount, the correlation of the data with the generalized curves is about the same as shown in figure 1. For clarity, the data were omitted from figure 3.

A comparison of the generalized master curves with the master curve for rupture for the various materials (fig. 3) shows that the generalized curves agree closely with the master curves for rupture except in the low-temperature region. The greatest variation was found for 2024-T3 aluminum alloy for stresses above about 40 ksi (fig. 3(b)). For the materials and applications shown, the minimum creep rate and various amounts of creep strain can therefore be determined in the high-temperature region from the master curve for rupture by means of the appropriate equivalent parameter.

Further investigation is required to determine the general applicability of the equivalent parameter (8) for the creep strain to other materials and various amounts of creep strain. The question as to how small or how large a creep strain can be utilized by this method also remains to be established for different materials. If the creep strain is small, an appreciable part may be primary or transient creep rather than steady creep, and, if the creep strain is large, tertiary creep may be involved. In general, if significant amounts of primary or tertiary creep are present, this method may be expected to underestimate the actual magnitude of the creep strain.

CONCLUDING REMARKS

Master curves (employing the Larson-Miller time-temperature and rate-temperature parameters) for rupture life, minimum creep rate, and 0.2-percent and 0.5-percent creep strain may be generalized to a single curve by means of equivalent parameters derived from the invariance of the product of rupture life and the minimum creep rate. The agreement of the generalized master curve for the minimum creep rate with the master curve for rupture is satisfactory in the high-temperature region for each of the materials investigated. The generalized master curves for 0.2- and 0.5-percent creep strain were also in good agreement with the master curve for rupture in the high-temperature region for the two aluminum alloys. A single master curve, the master curve for rupture, can therefore be utilized for the determination of the minimum creep rate and for the 0.2- and 0.5-percent creep strain for the cases investigated.

Although a variety of metals have been covered, the method presented herein should not be applied to other materials without further experimental evidence because the correlation of the data with the master curves may not always be satisfactory and the product of the rupture life and the minimum creep rate may not always be approximately constant. This is particularly the case with regard to the application to creep strain, which may involve some degree of primary or tertiary creep that is not taken into account by this method. In addition, the generalized master curve should be used only within the range of the data unless it can be shown that extrapolation can be employed with reasonable accuracy. Although the method of generalizing the master curves has been carried out with the Larson-Miller parameters, other suggested temperature-modified time or rate parameters could be utilized in a similar manner.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 8, 1957.

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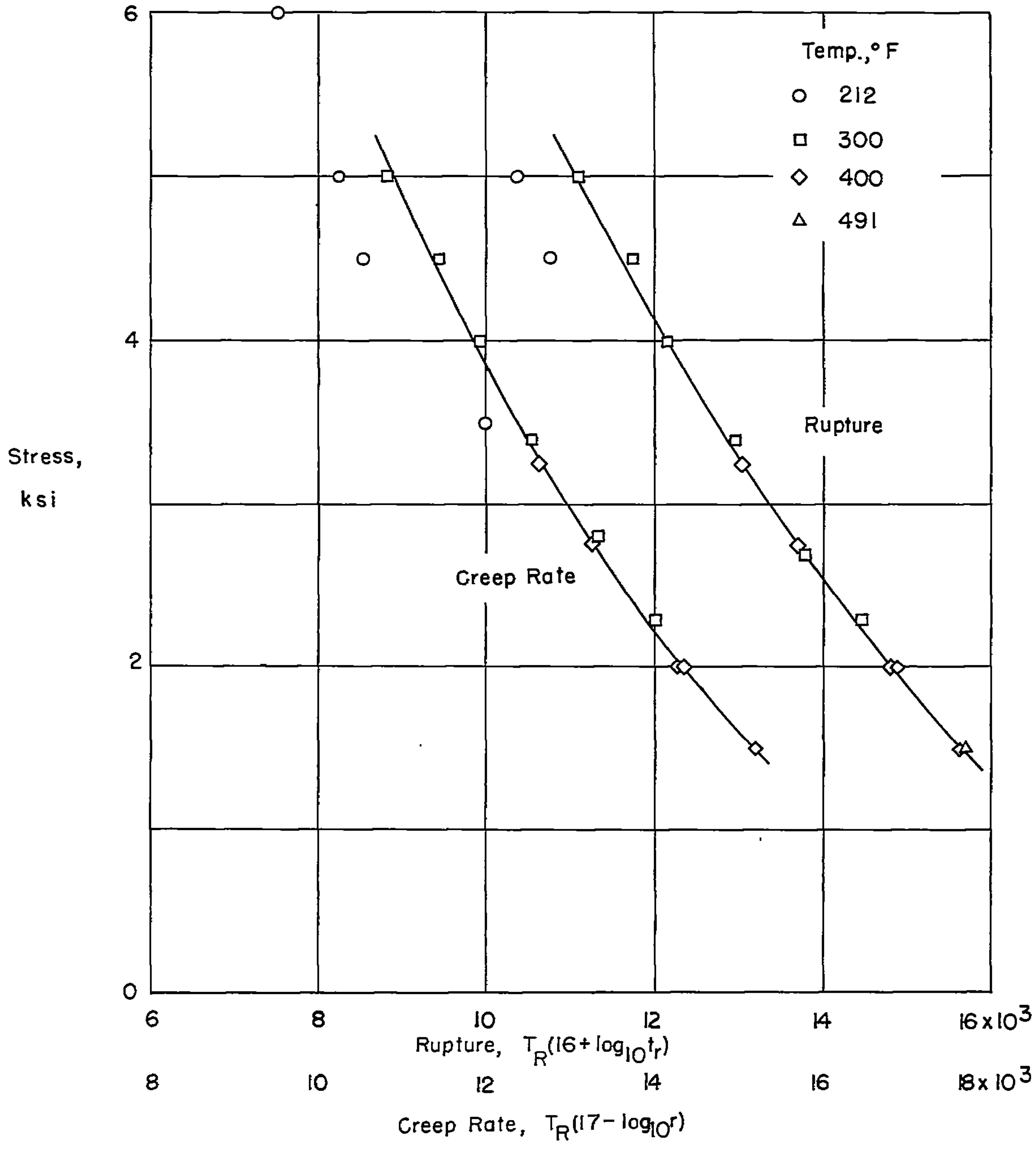
TABLE I

CREEP-STRAIN CONSTANT c AND INTERCEPT b

Material	[1]Creep-strain constant c, percent	Intercept b (from fig. 2)
Pure aluminum	25.1	1.4
2024-T3 aluminum-alloy sheet	1.6	0.2
7075-T6 clad aluminum-alloy sheet	1.0	0.0
Carbon-molybdenum steel	39.8	1.6
18-8 Cb stainless steel	10.0	1.0
S-590	6.3	0.8
[2]Inconel X	0.16	-0.8

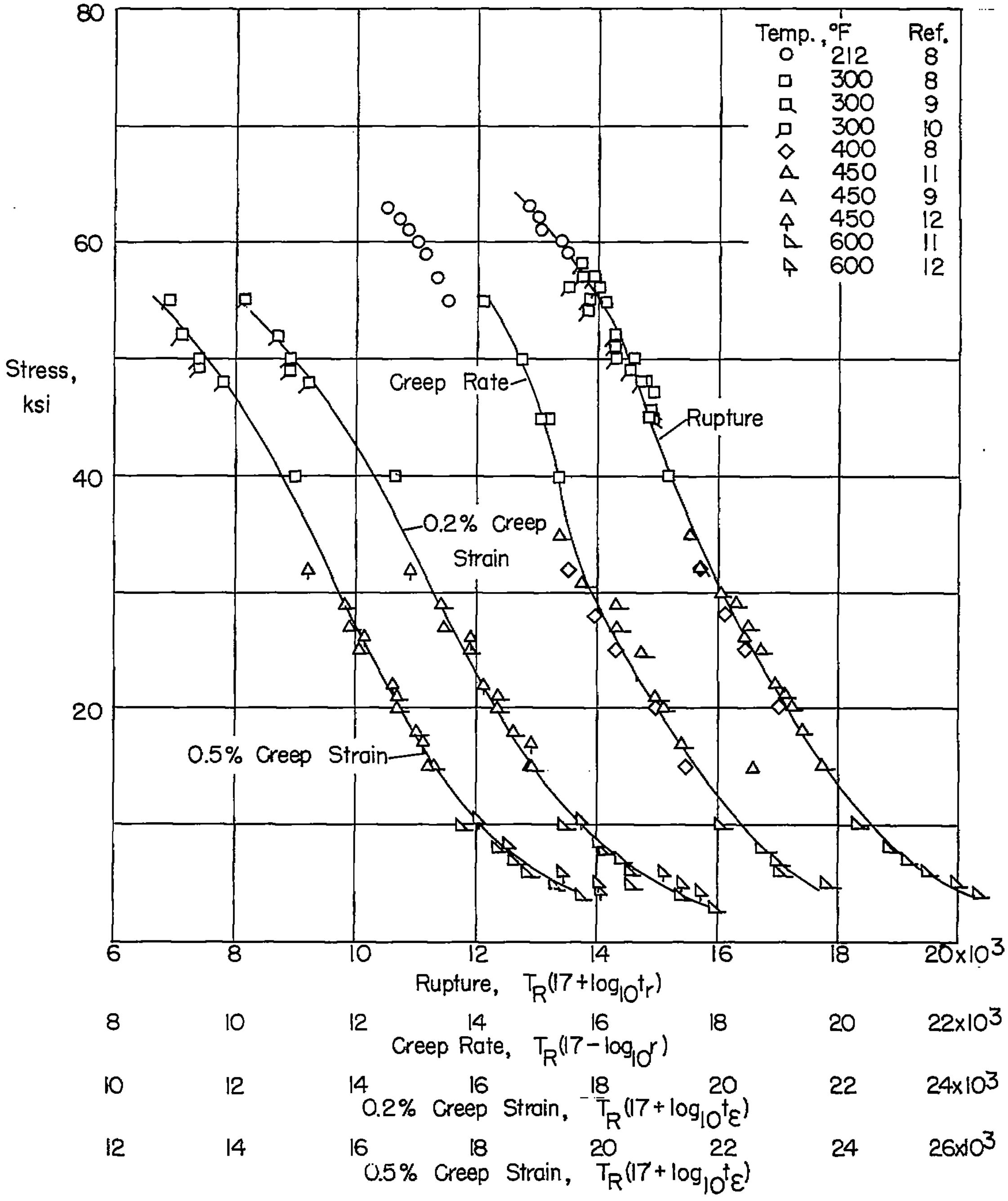
[1] $\log_{10} c = b$.

[2] Bar stock heat-treated 4 hours at 2100° F, 24 hours at 1500° F, and 20 hours at 1300° F.



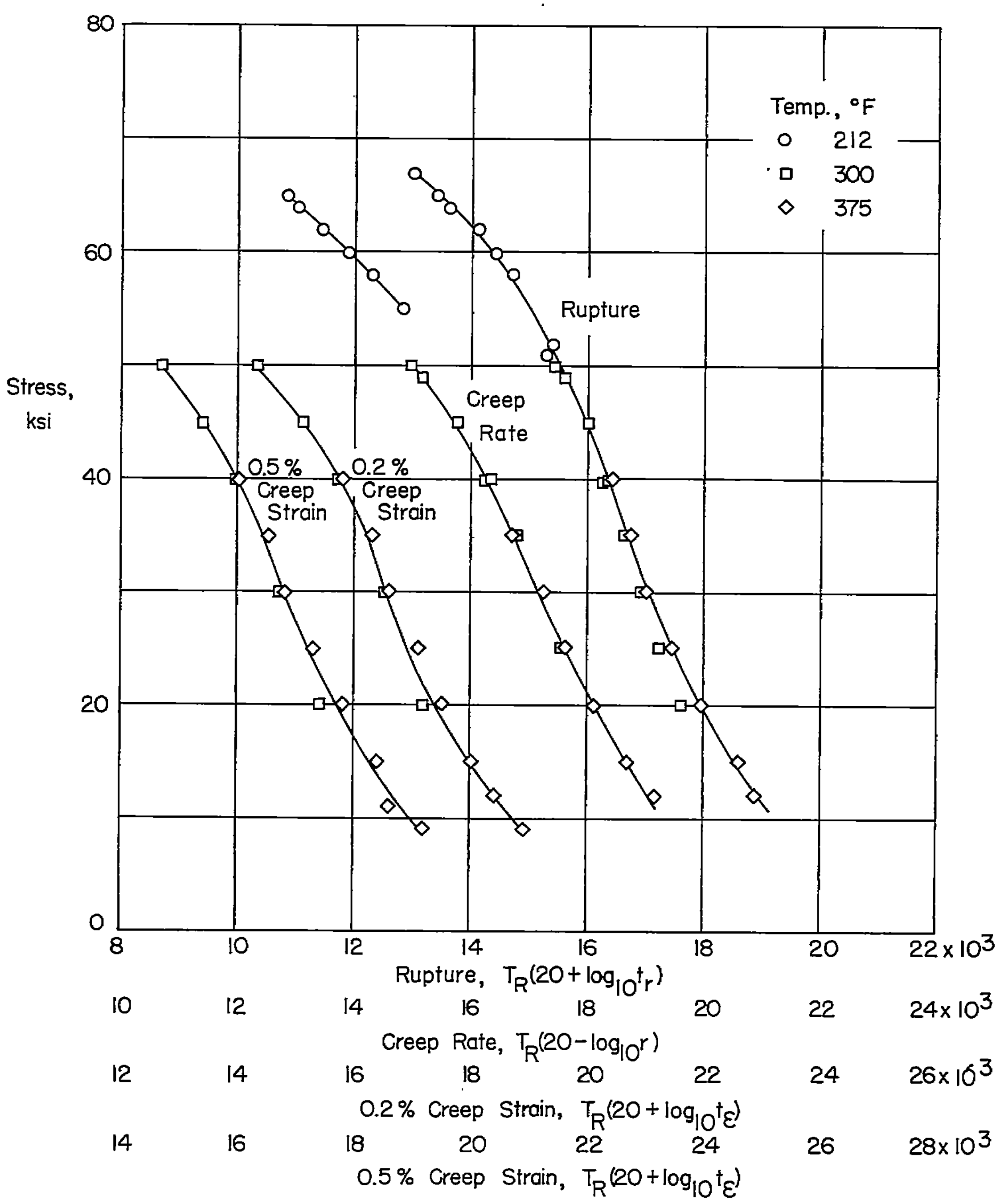
(a) Pure aluminum (data from ref. 7).

Figure 1.- Master curves for rupture and minimum creep rate for various materials. (Master curves for 0.2- and 0.5-percent creep strain shown for aluminum alloys.)



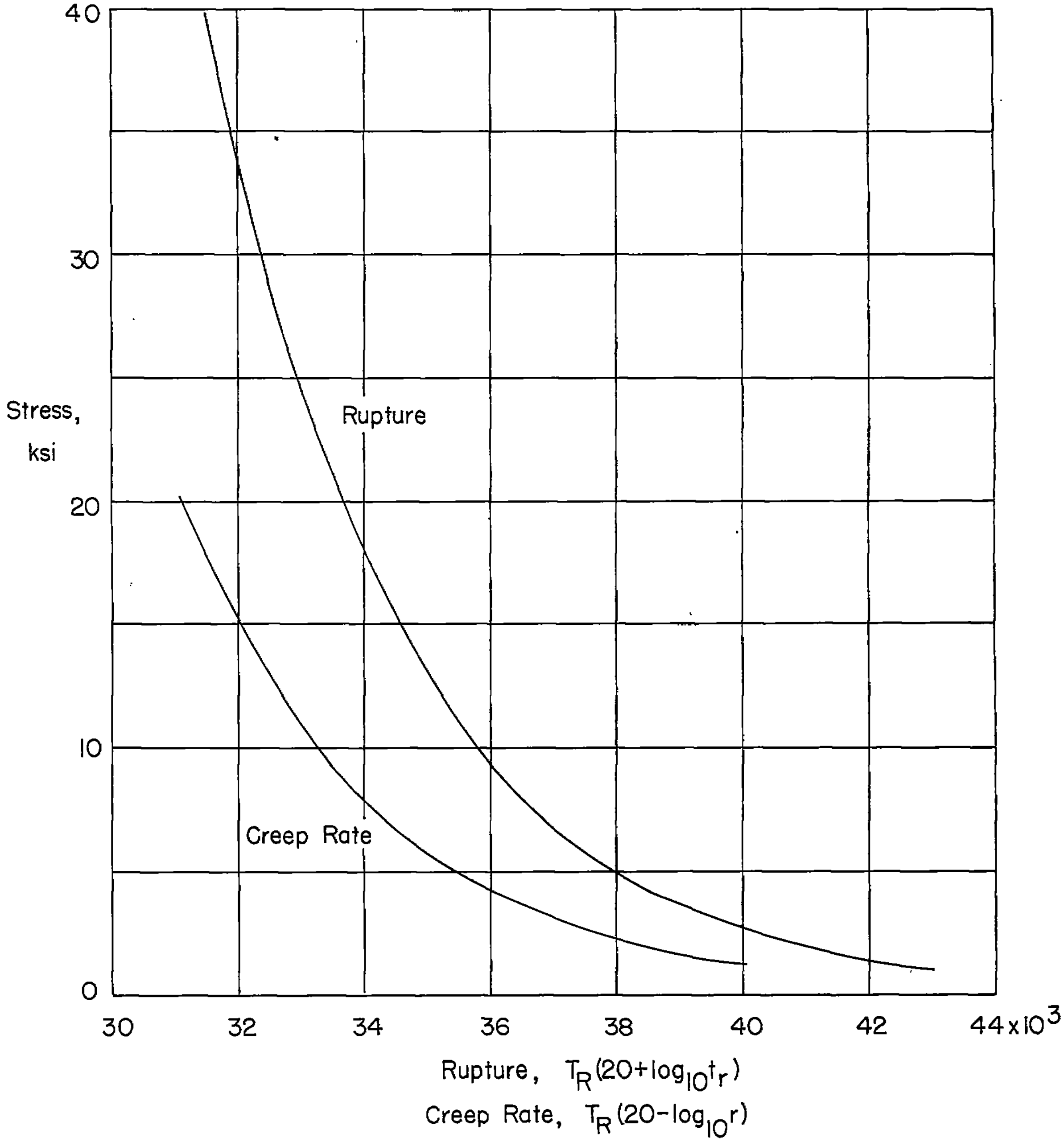
(b) 2024-T3 aluminum-alloy sheet.

Figure 1.- Continued.



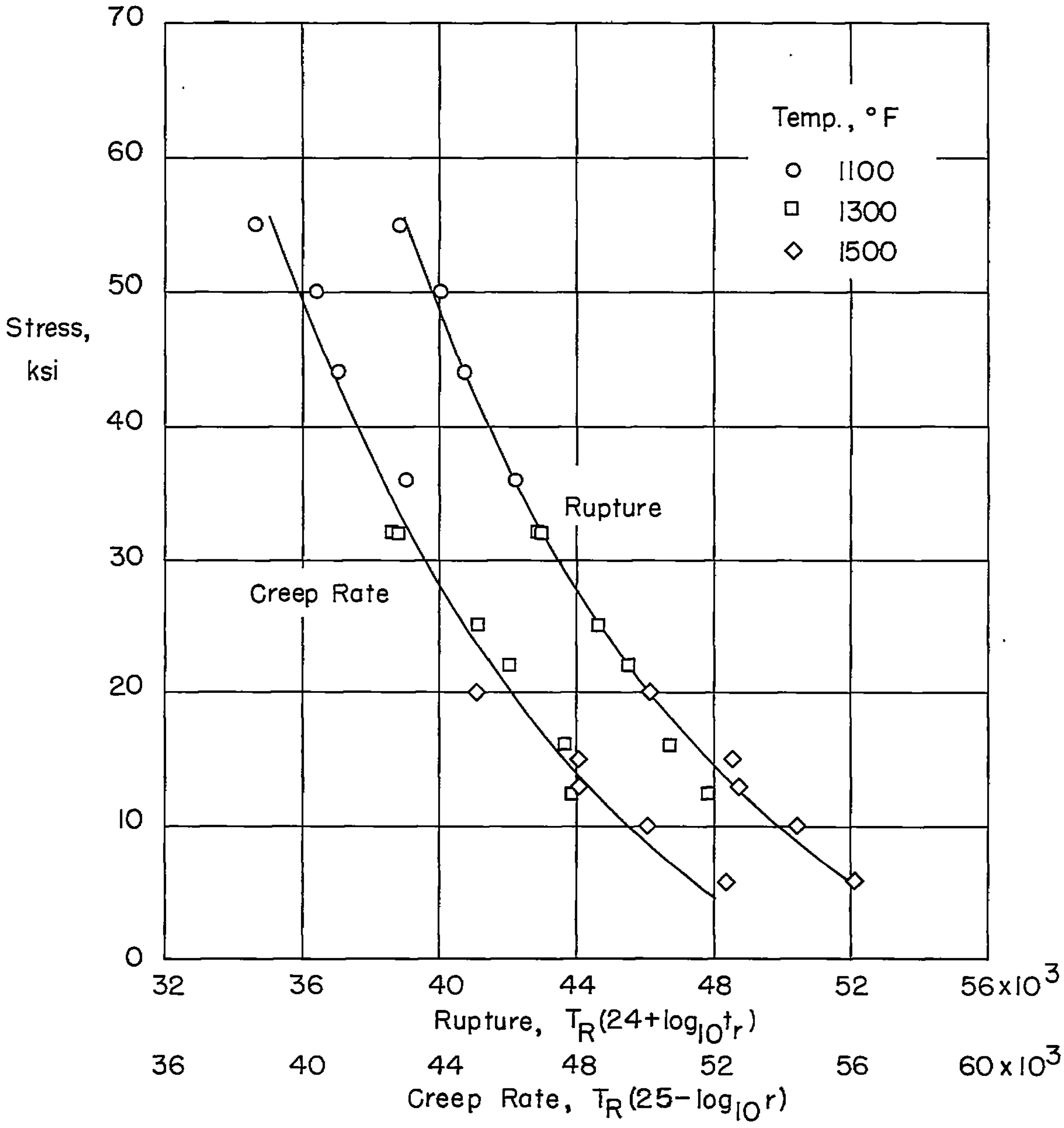
(c) 7075-T6 clad aluminum-alloy sheet (data from ref. 13).

Figure 1.- Continued.



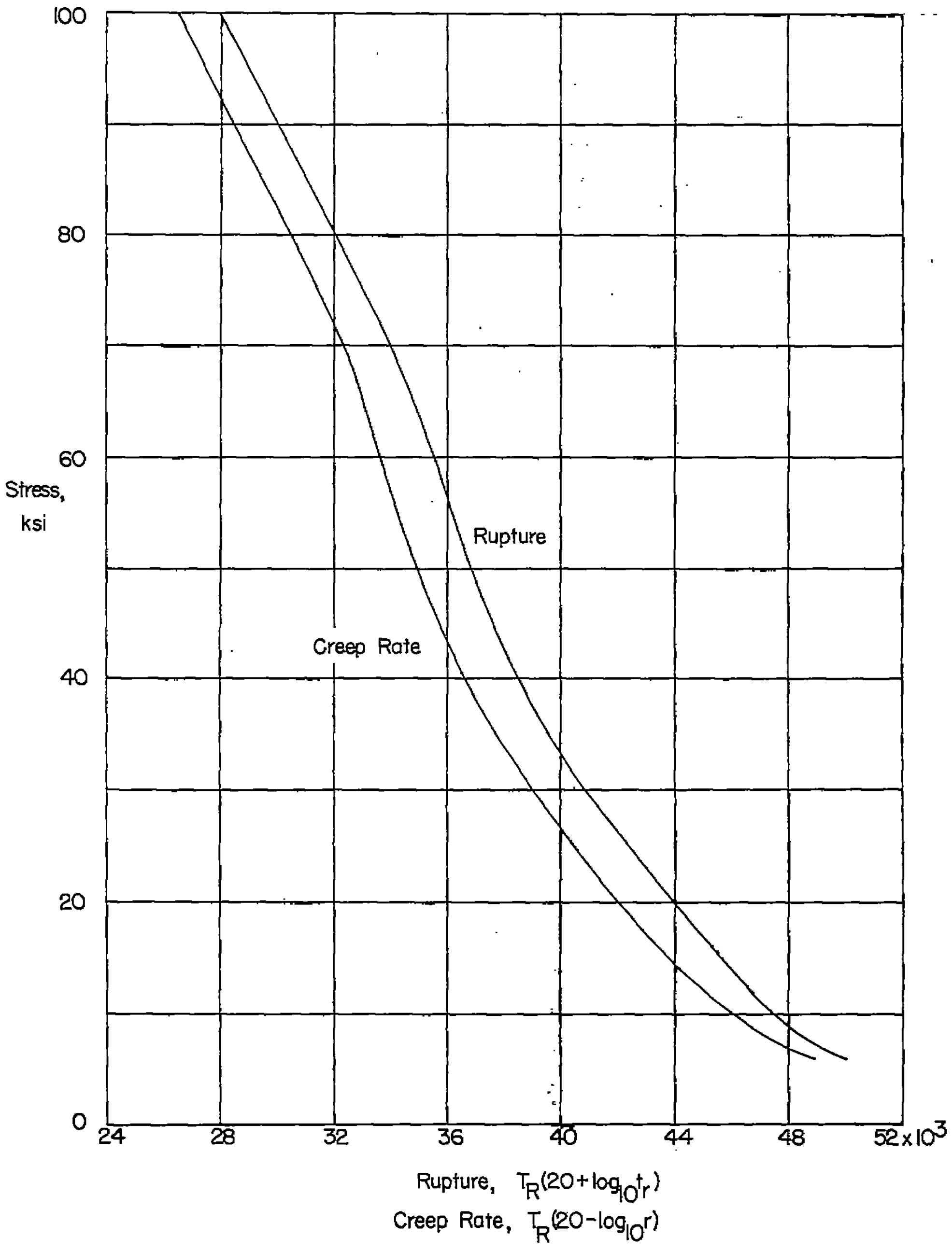
(d) Carbon-molybdenum steel (temperature range of data from 900° to 1200° F; data from ref. 1).

Figure 1.- Continued.



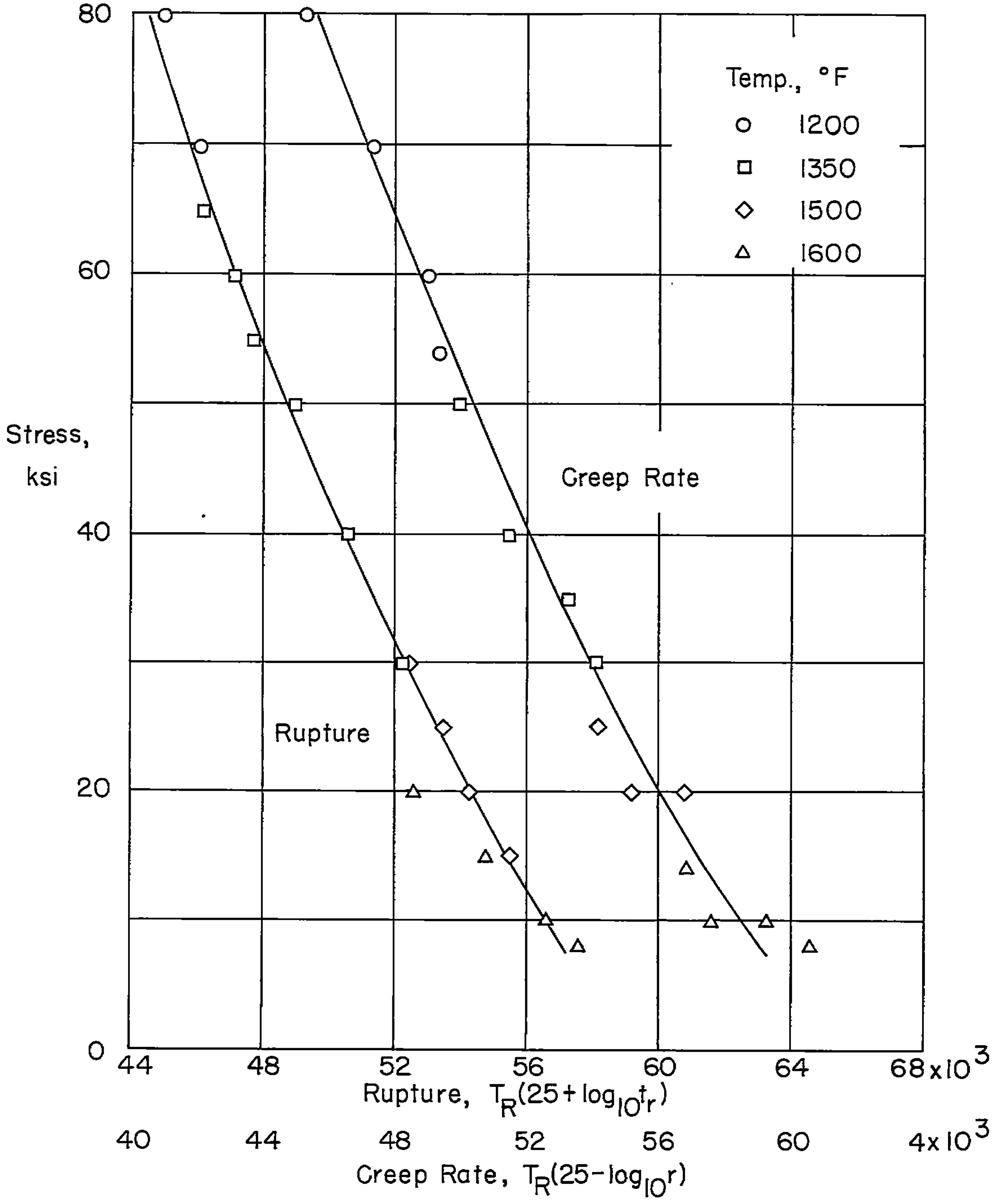
(e) 18-8 Cb stainless steel (data from ref. 14).

Figure 1.- Continued.



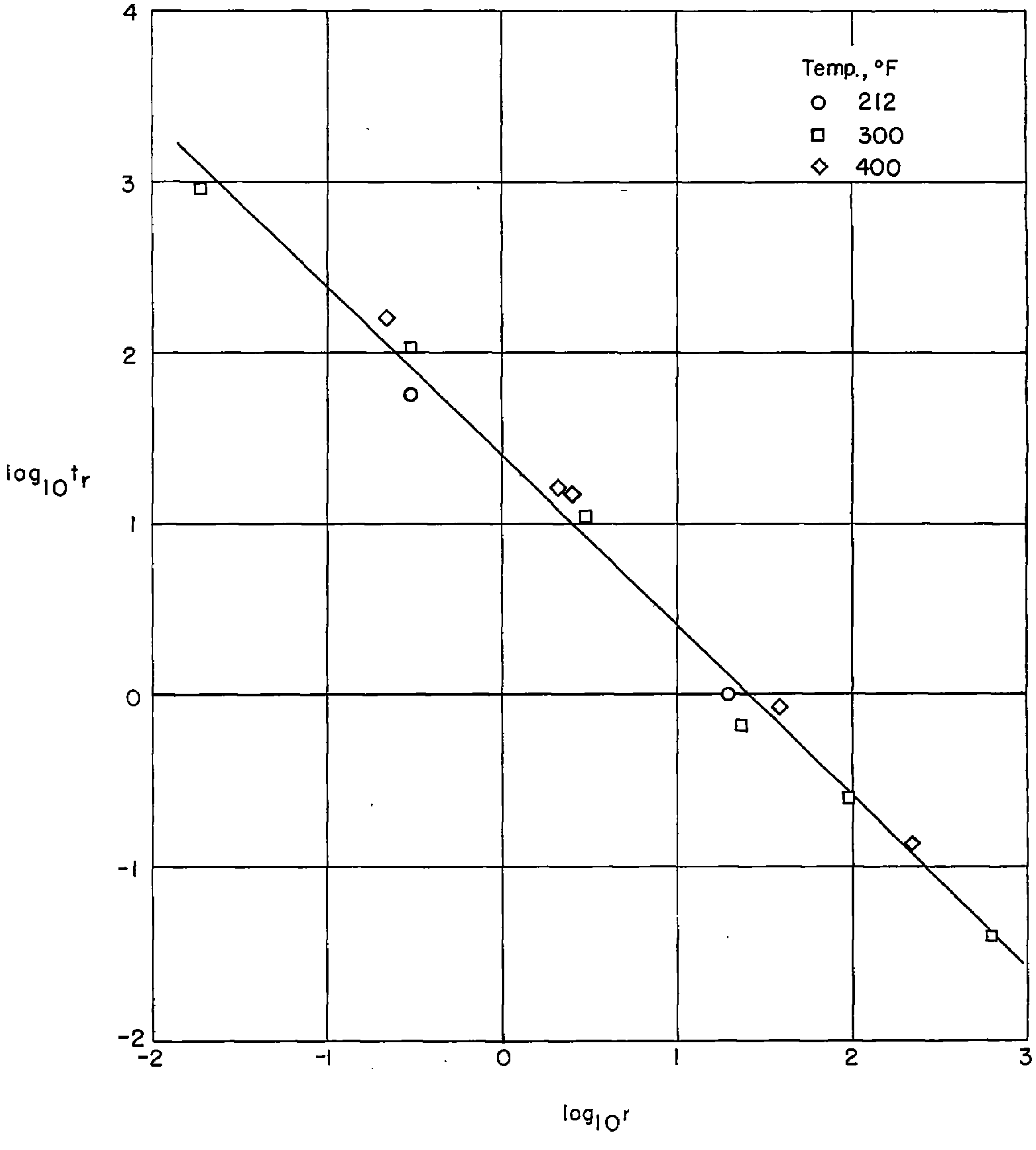
(f) S-590 alloy (temperature range of data from 1200° to 1900° F; curves from ref. 1).

Figure 1.- Continued.



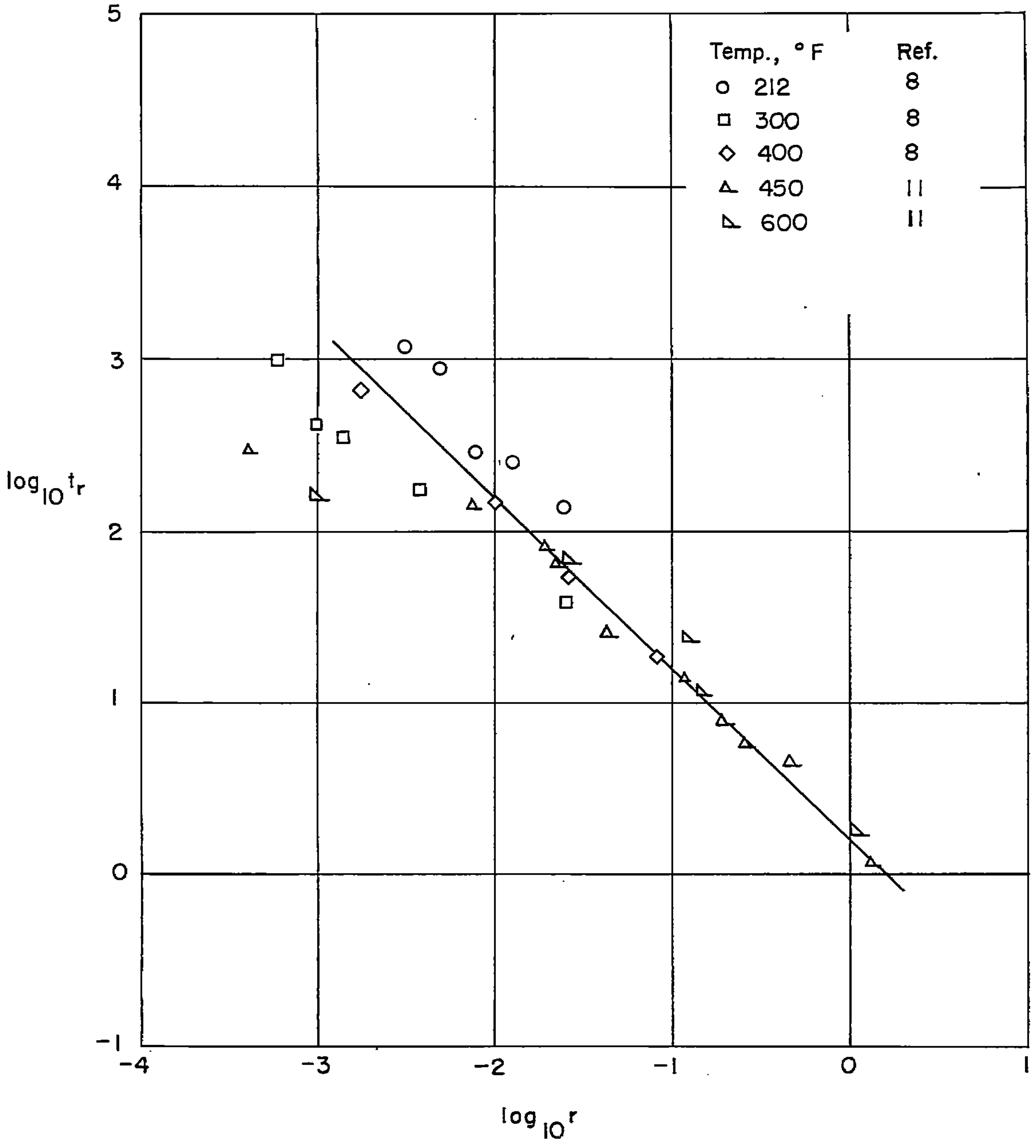
(g) Inconel X (data from ref. 15).

Figure 1.- Concluded.



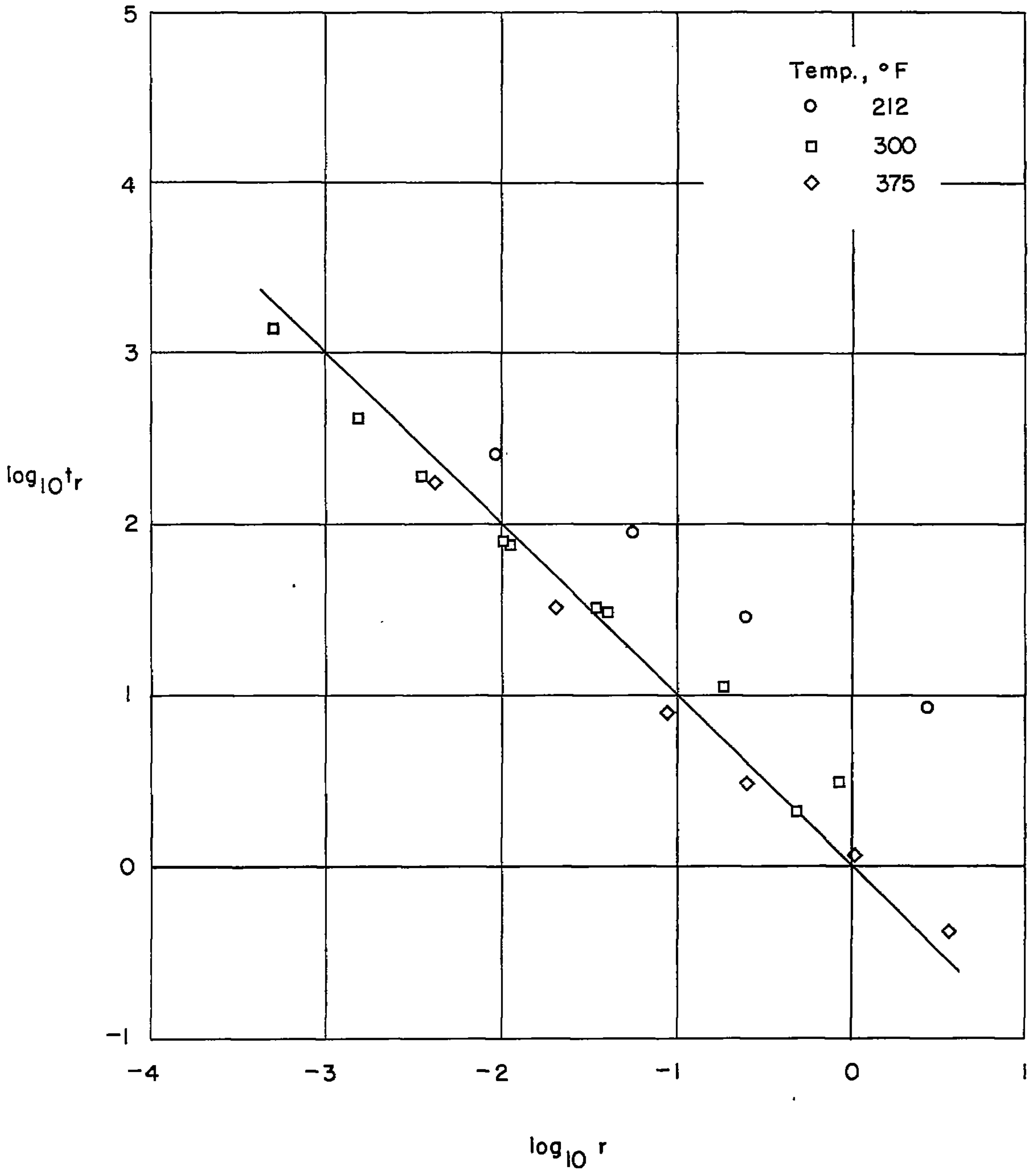
(a) Pure aluminum (data from ref. 7).

Figure 2.- Relation between rupture life and minimum creep rate for various materials.



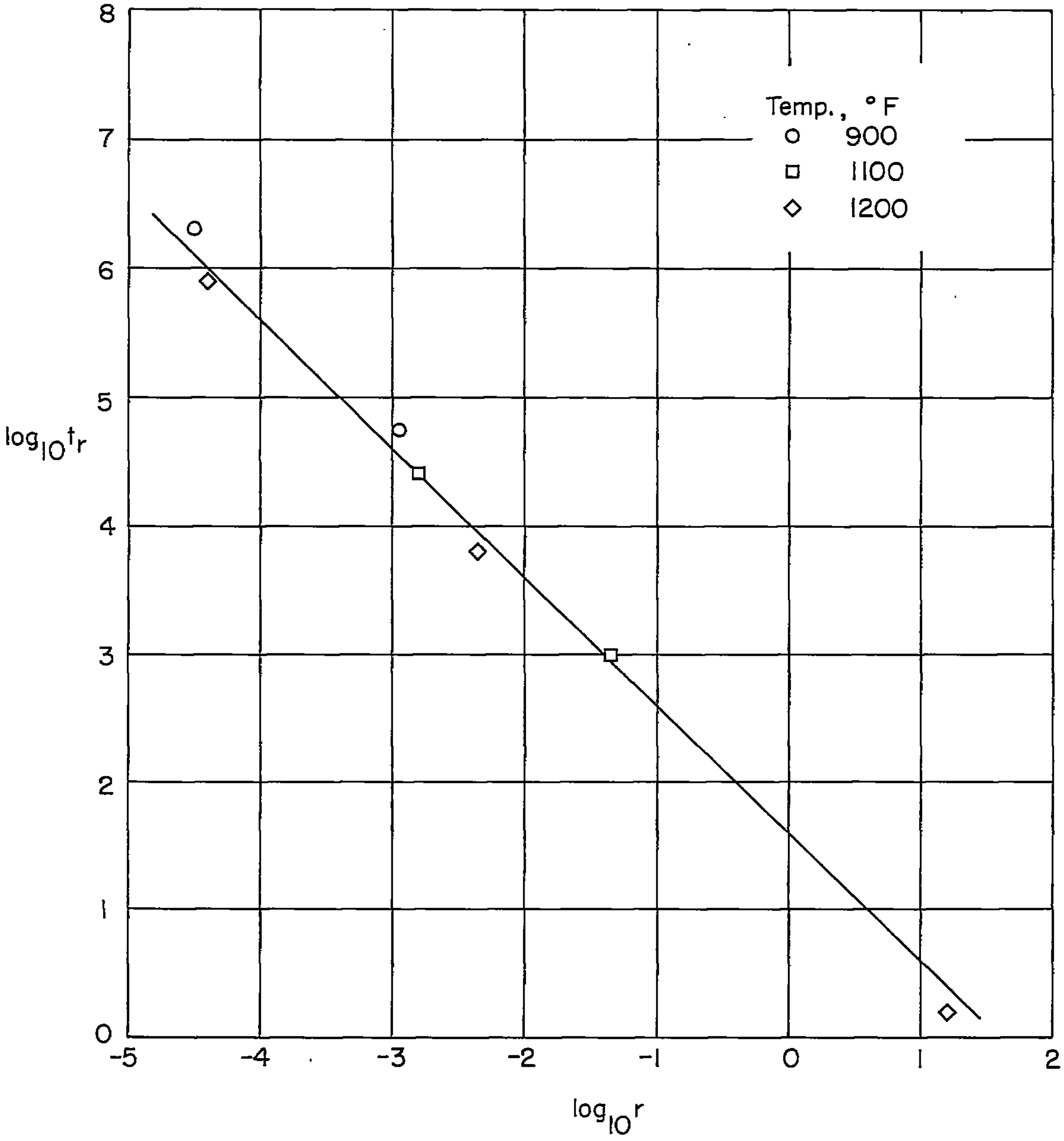
(b) 2024-T3 aluminum-alloy sheet.

Figure 2.- Continued.



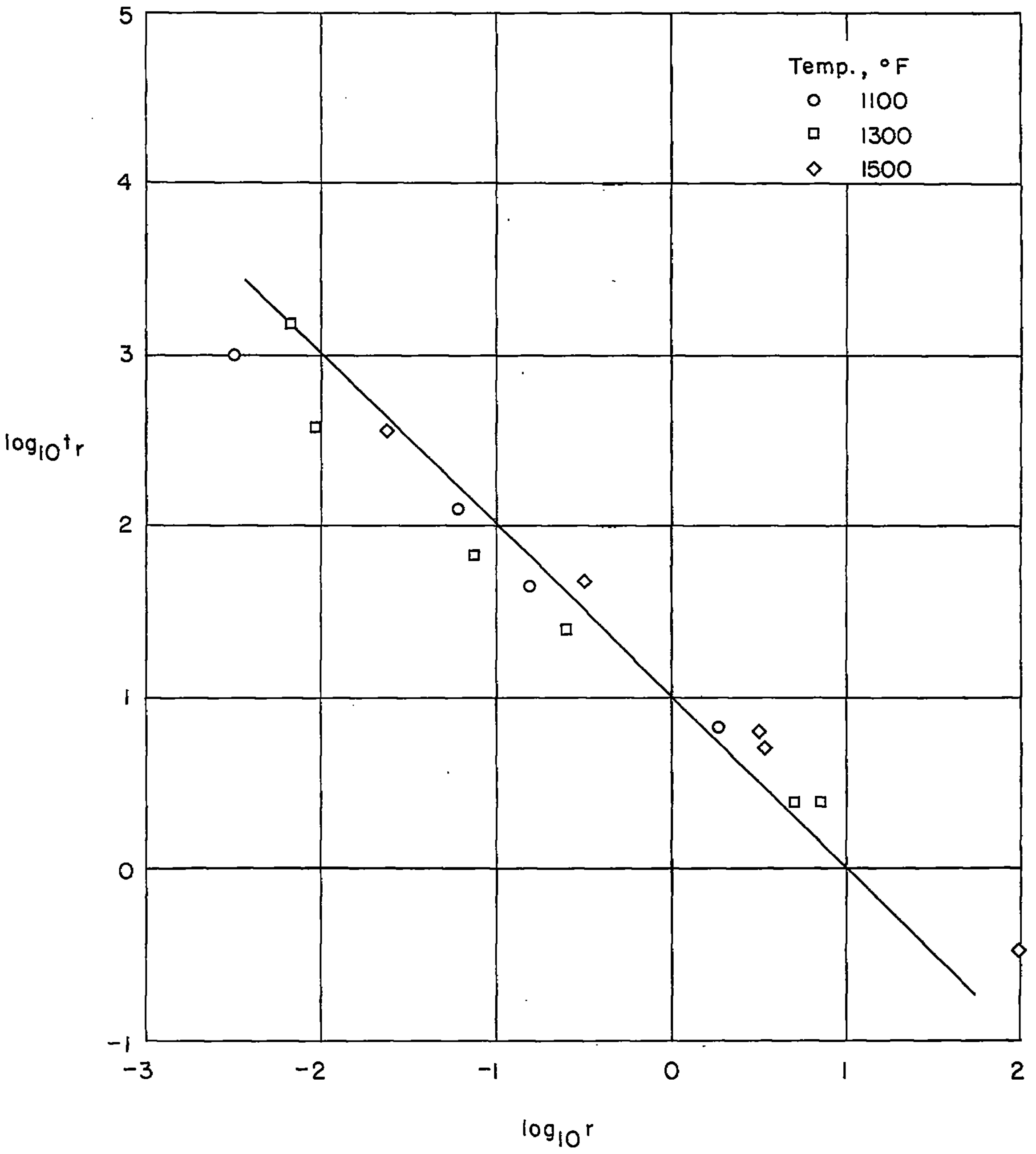
(c) 7075-T6 clad aluminum-alloy sheet (data from ref. 13).

Figure 2.- Continued.



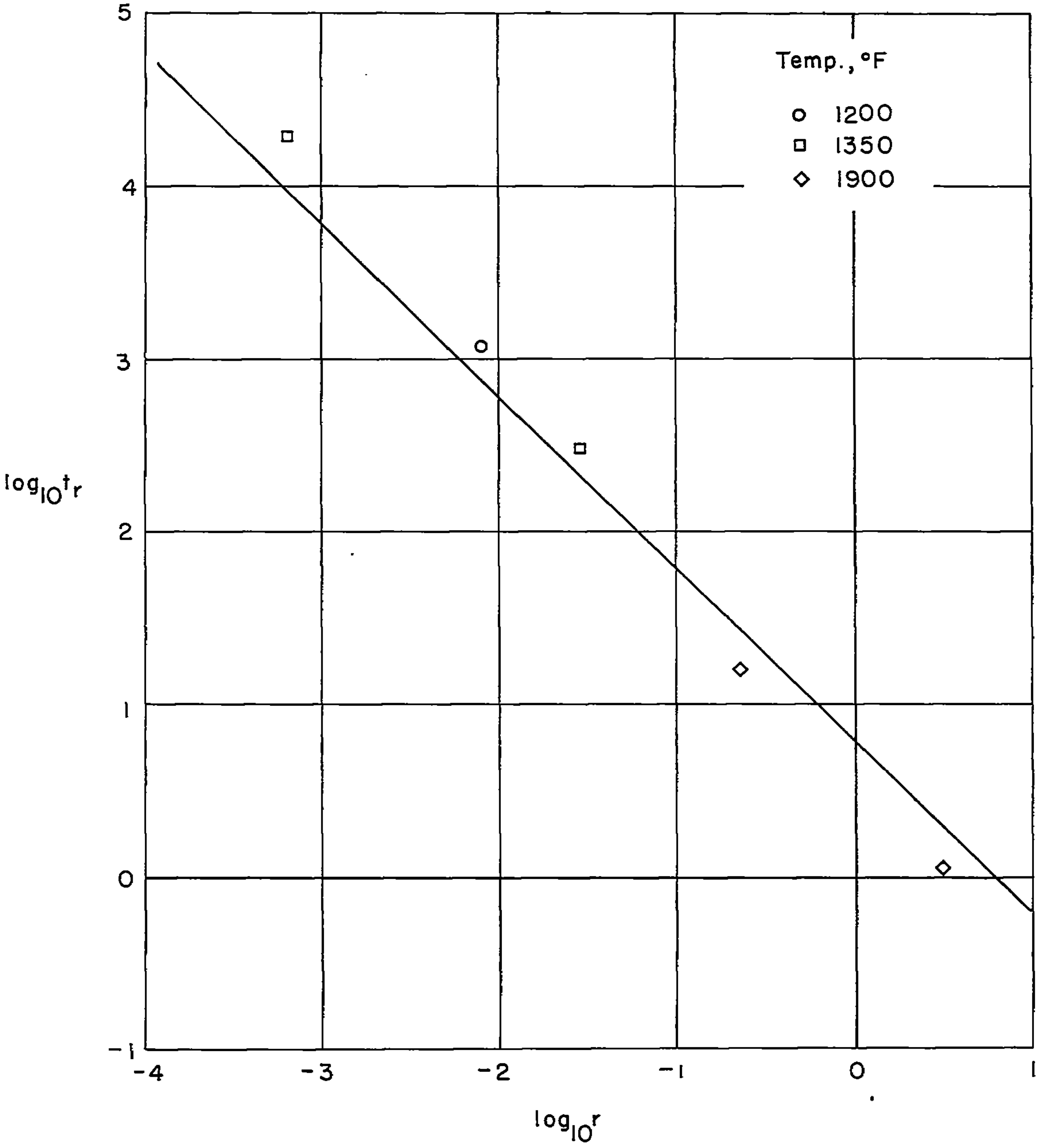
(d) Carbon-molybdenum steel (points calculated from fig. 1(d)).

Figure 2.- Continued.



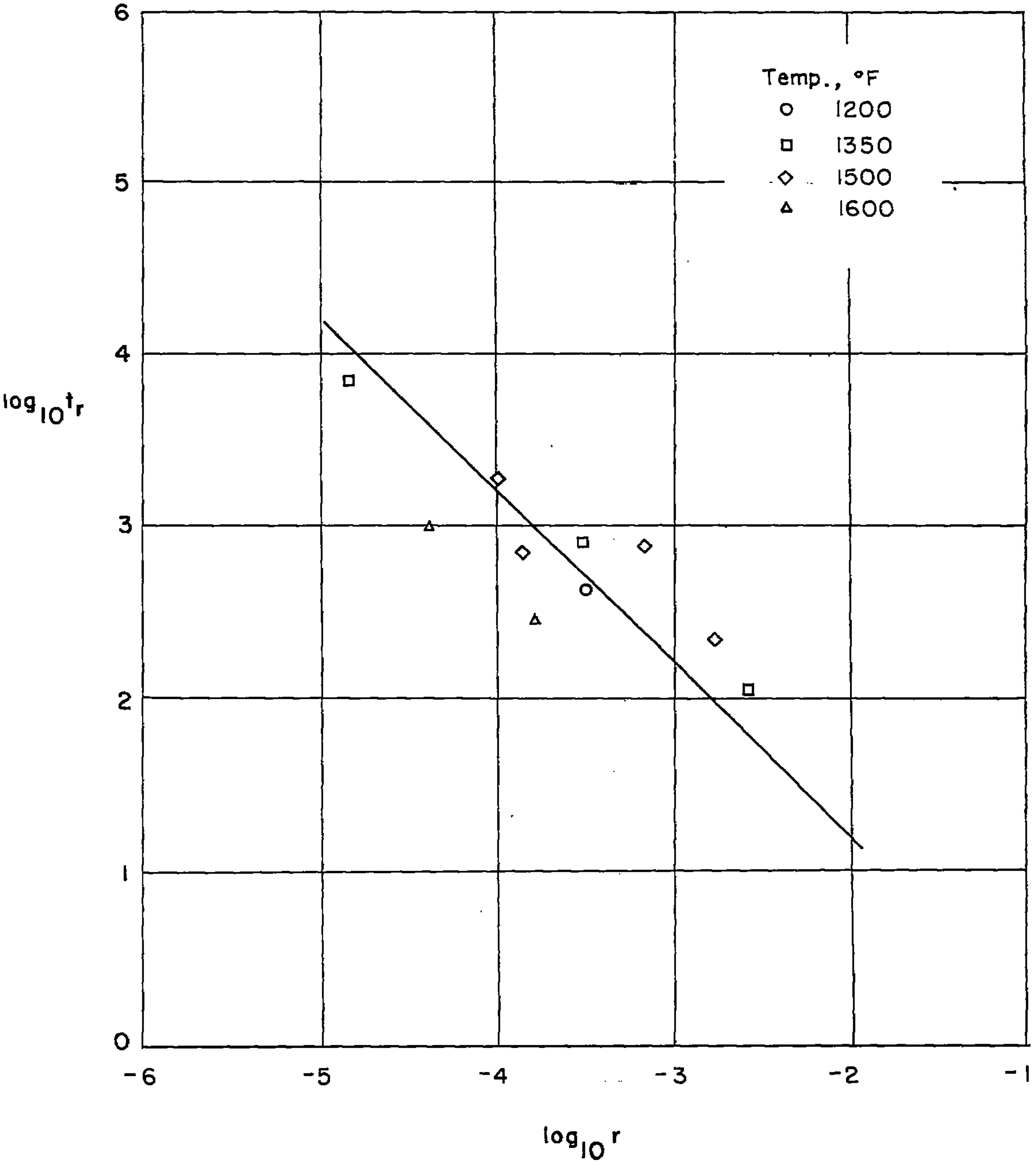
(e) 18-8 Cb stainless steel (data from ref. 14).

Figure 2.- Continued.



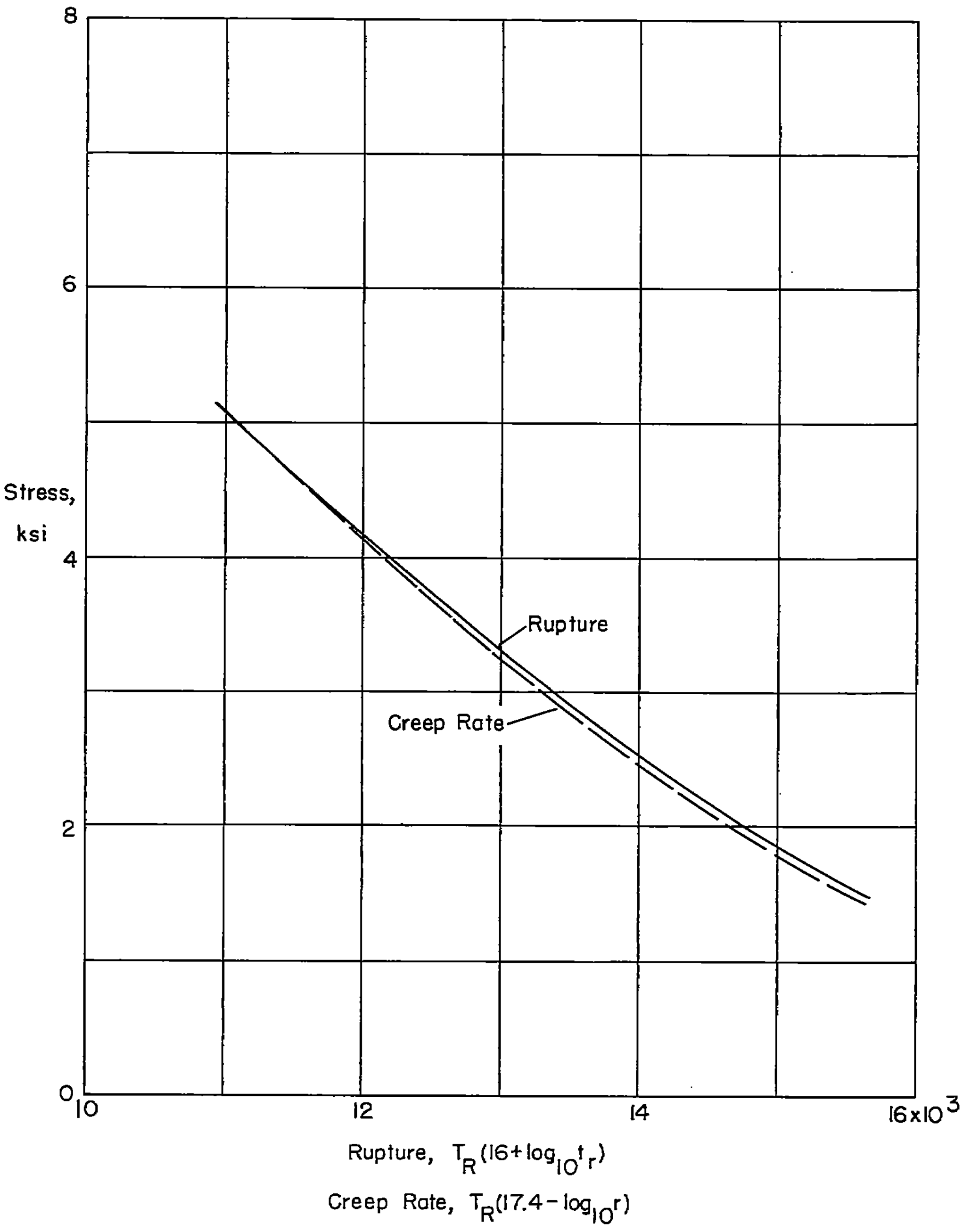
(f) S-590 alloy (points calculated from fig. 1(f)).

Figure 2.- Continued.



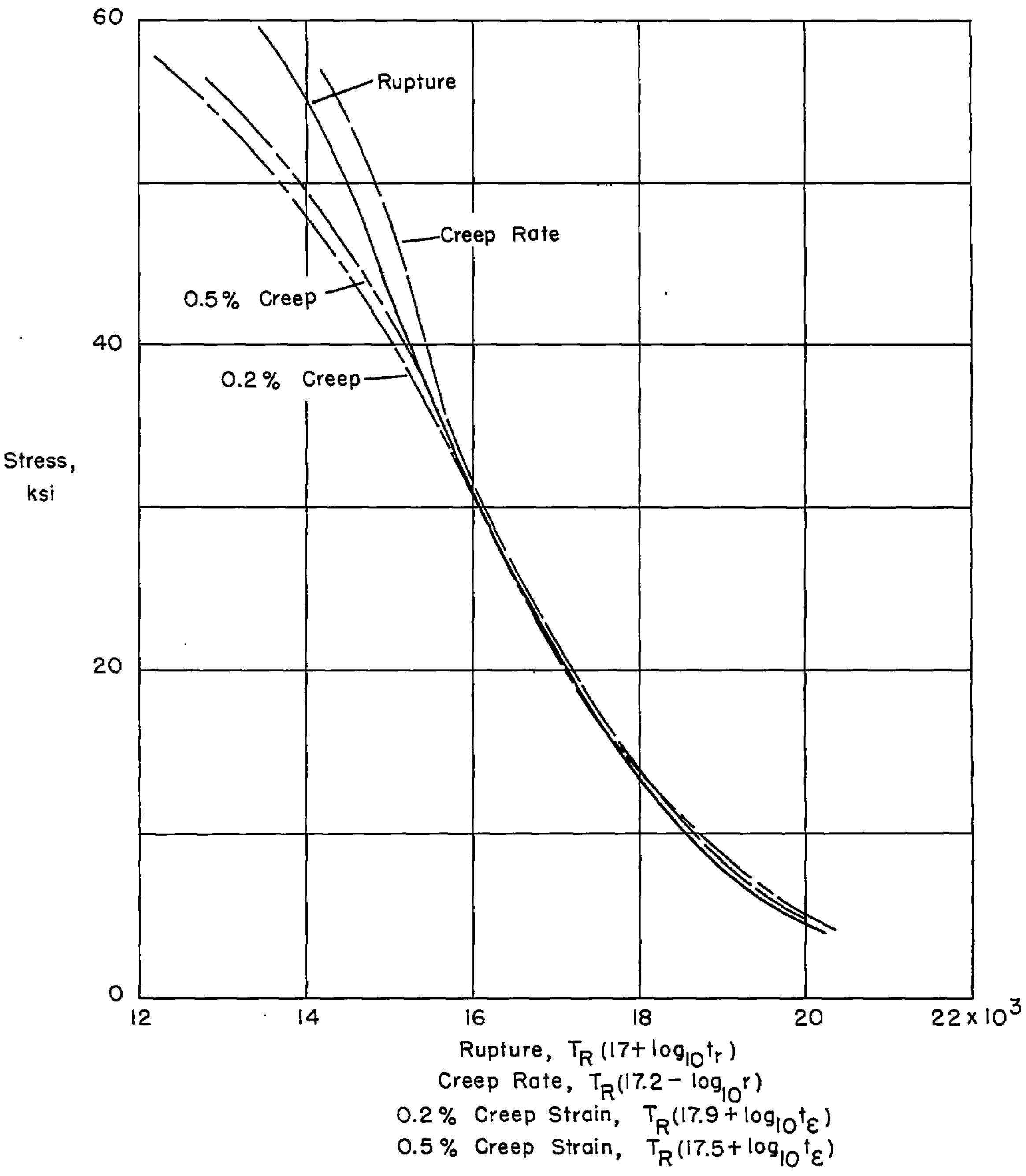
(g) Inconel X (data from ref. 15).

Figure 2.- Concluded.



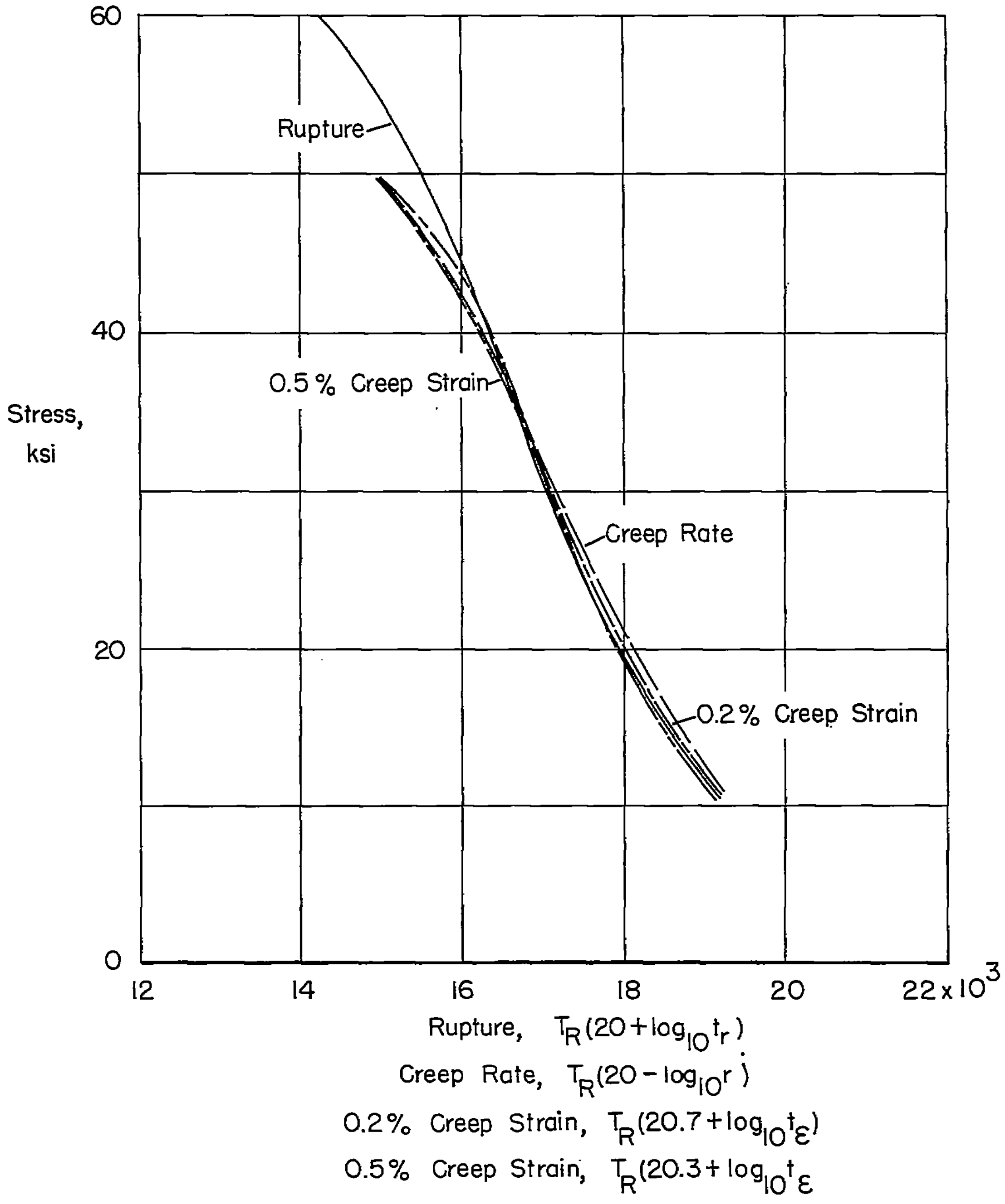
(a) Pure aluminum (temperature range of data from 300° to 491° F).

Figure 3.- Comparison of generalized master curves for minimum creep rate (and for 0.2- and 0.5-percent creep strain for aluminum alloys) with master curves for rupture for various materials.



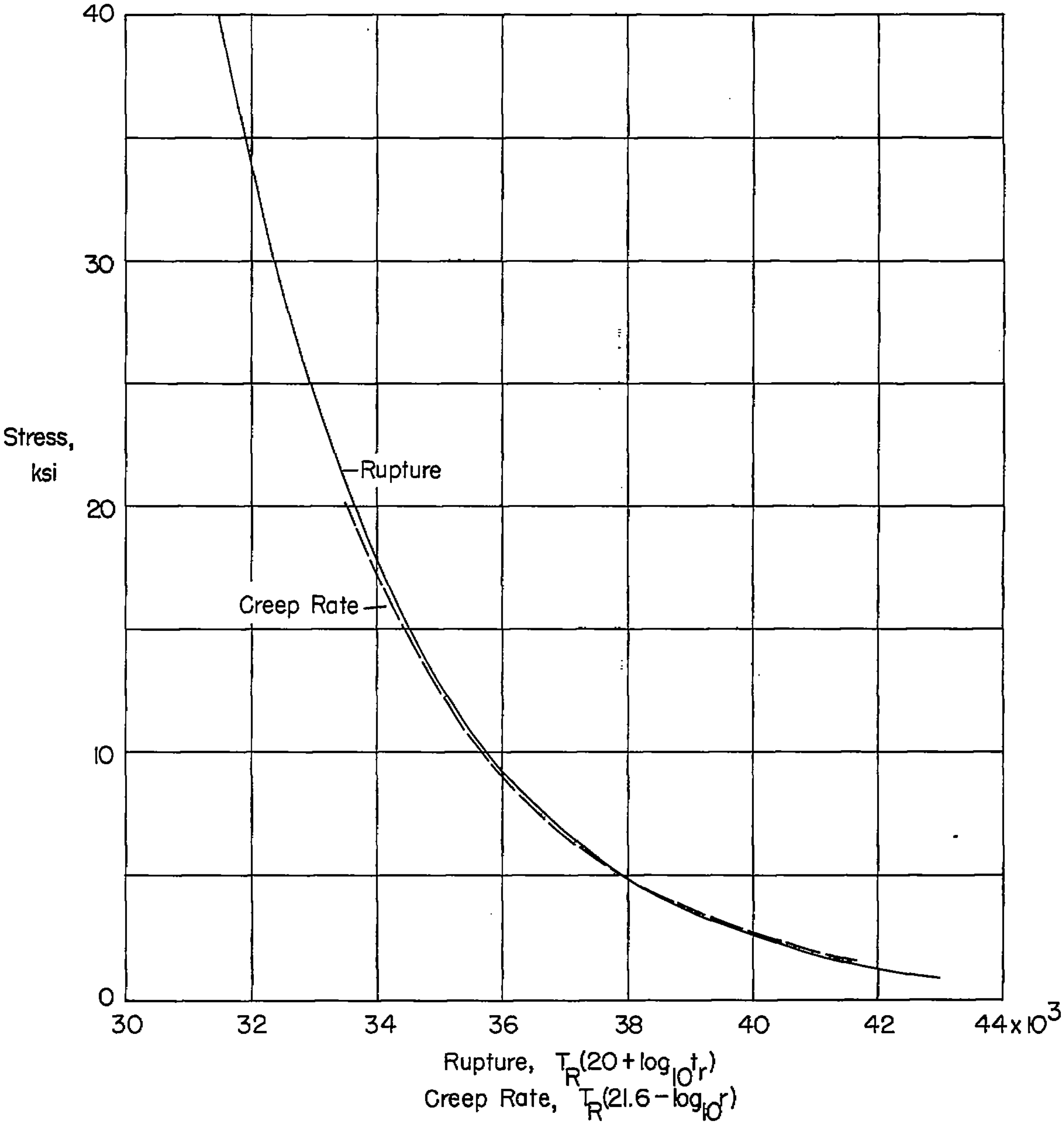
(b) 2024-T3 aluminum-alloy sheet (temperature range of data from 212° to 600° F).

Figure 3.- Continued.



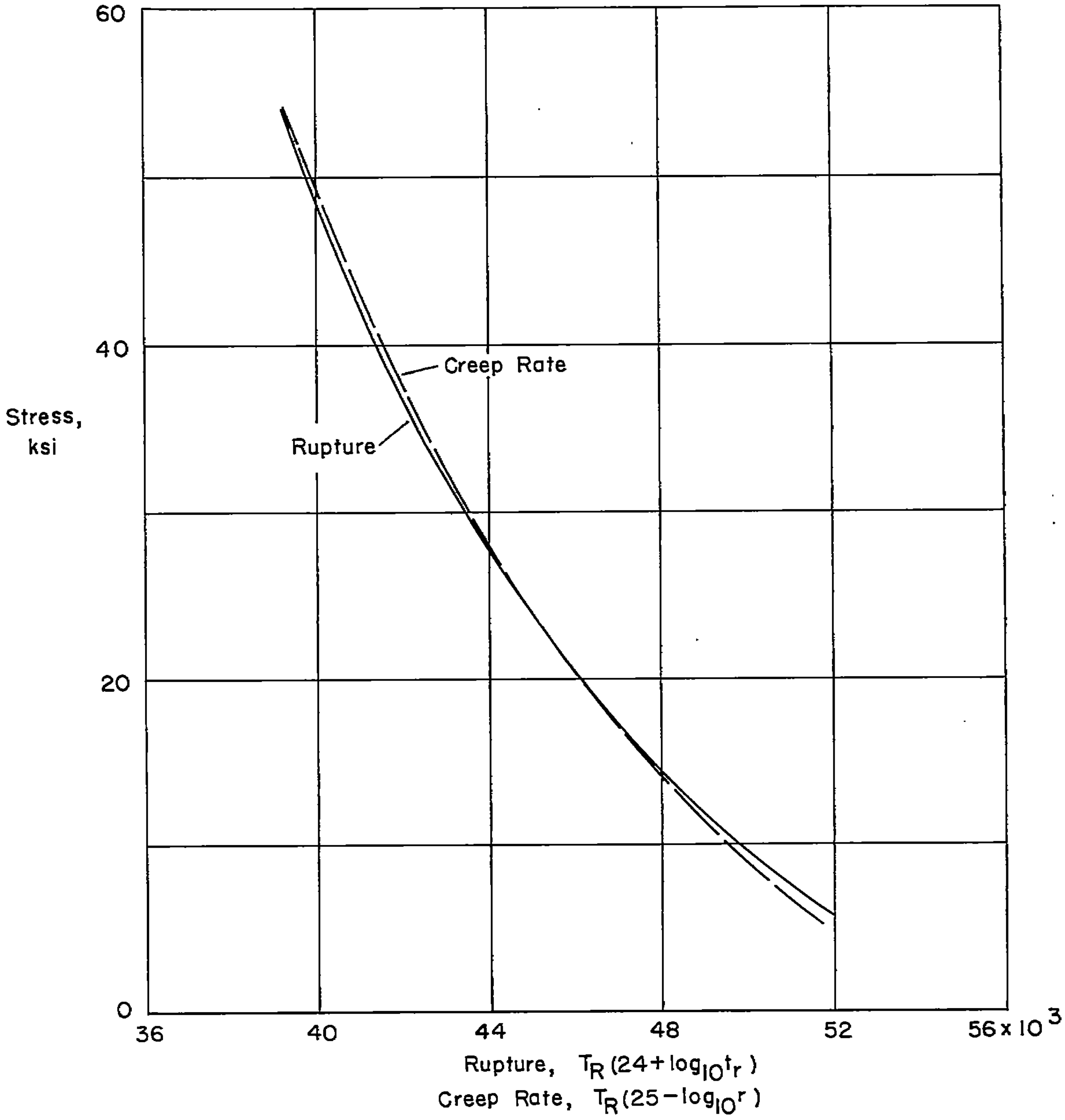
(c) 7075-T6 clad aluminum-alloy sheet (temperature range of data from 300° to 375° F).

Figure 3.- Continued.



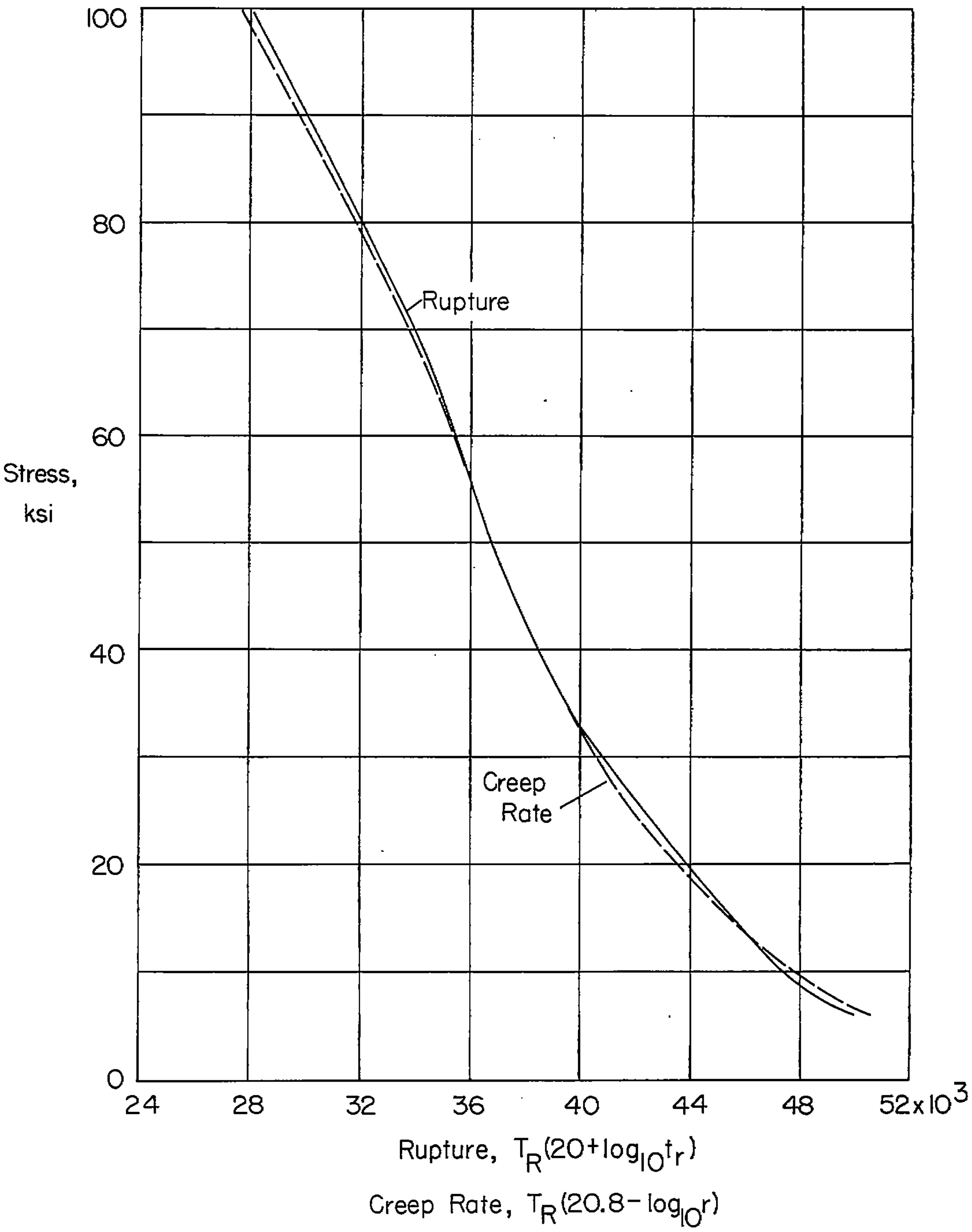
(d) Carbon-molybdenum steel (temperature range of data from 900° to 1200° F).

Figure 3.- Continued.



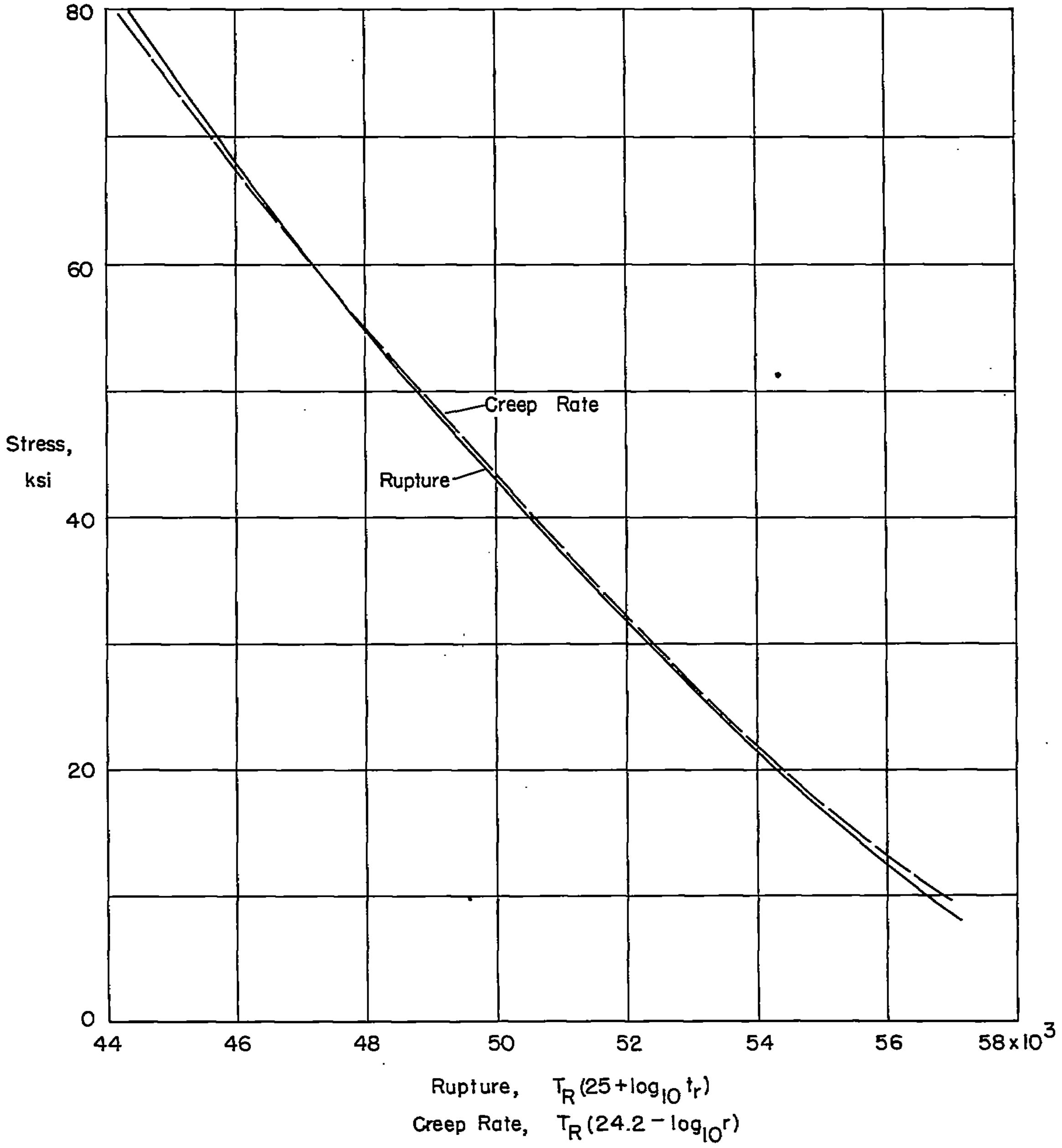
(e) 18-8 Cb stainless steel (temperature range of data from 1100° to 1500° F).

Figure 3.- Continued.



(f) S-590 alloy (temperature range of data from 1200° to 1900° F).

Figure 3.- Continued.



(g) Inconel X (temperature range of data from 1200° to 1600° F).

Figure 3.- Concluded.

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