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TIME-TEMPERATURE PARAMETERS AND AN APPLICATION TO RUPTURE AND CREEP OF ALUMINUM ALLOYS

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SUMMARY

The application of time-temperature parameters to stress-strain, rupture, and creep data for metals and alloys is reviewed. Some comparisons are made of theoretical and experimental parameters. A parameter based upon rate-process theory was successfully applied to rupture and creep data for aluminum and various aluminum alloys. The value of the constant in the parameter, which provided the best correlation of the data, was determined for each material and application. Master curves of stress against the parameter which summarize extensive data on the aluminum alloys are presented for rupture, minimum creep rate, and time to 1 percent strain. Predictions of long-time life from short-time data are shown to be possible.

INTRODUCTION

Many attempts have been made to formulate relationships for stress, strain, strain rate, and temperature in order to predict the strength and behavior of materials under elevated-temperature conditions. Such attempts, however, have not been generally successful (ref. 1).

A promising approach to this problem, which has considerable practical significance, has been the use of time-temperature parameters for analyzing stress-strain, rupture, and creep data. Two time-temperature parameters have recently been shown to be applicable to stress rupture and creep data for many materials, particularly steels and high-temperature alloys (refs. 2 and 3). A time-temperature parameter has also been successfully applied to stress-strain data obtained under constant straining rates for various materials, especially low-carbon steels (refs. 4 and 5). Other such parameters have been used for some solid-solution aluminum alloys to correlate creep and tensile data and for reducing creep-strain data to a single curve (ref. 6). Similar parameters have also been applied to creep and tensile data for face-centered cubic, body-centered cubic, and hexagonal close-packed metals (ref. 7) and to rupture data for some pure metals, steels, and high-temperature alloys (ref. 8).

All the various parameters which have been proposed consist of some combination of the variables of time or rate and temperature together with suitable constants. With such parameters, a single or master curve of stress against the parameter can frequently be obtained for a given material and application over the entire time or rate and temperature range. Thus, equivalent combinations of time or rate and temperature can be readily ascertained for any stress level, and the need for working with whole families of curves is obviated. Aside from being convenient for summarizing data, such parameters are of a great value for extrapolating test results. Comparisons of calculated values of long-time life with actual values, based upon short-time data, have shown that accurate predictions of long-time life are possible with such parameters. The necessity for making extensive long-time tests of materials at elevated temperatures appears to be largely reduced or even eliminated in some cases.

The various time-temperature parameters which have been proposed are briefly described and compared. In order to show the applicability of a time-temperature parameter to rupture and creep of aluminum and aluminum alloys, an analysis using the Larson-Miller parameter (ref. 2) was made of published data for 18 materials (refs. 6 and 9 to 15). Values of the constant in the parameter were determined for the different materials and applications. The correlation of the data is shown in master plots for rupture, minimum creep rate, and time to 1 percent strain for most of the materials.

TIME-TEMPERATURE PARAMETERS

Rate-Process Theory

The time-temperature parameters discussed herein, with one exception, are based upon a rate-process theory which appears to hold for such diverse processes as creep, tempering, and diffusion of metals as well as for tension (refs. 2 and 4 to 8). The rate at which such processes take place under given conditions has been expressed in a simple form as

$$r = Ae^{-Q/RT} \tag{1}$$

where A is a constant, Q is the activation energy for the material and process, R is the gas constant, and T is the absolute temperature. For creep, r is the minimum creep rate associated with a given stress and temperature.

A more complete formulation of the theory is given by equation (1) of reference 7 which shows that the constant A is dependent upon the entropy, the frequency of activation, and possibly upon the structure of the metal. The creep rate is also a function of the stress; therefore, equation (1) cannot be used explicitly for the determination of creep rates at different stress levels. The activation energy Q has been found to be a constant for a given metal (refs. 6 to 8).

If the time is assumed to be inversely proportional to the creep rate as in reference 2, the theory predicts a linear relation between log t and 1/T. Plots of the data for different materials substantiate this prediction to a certain extent (for example, see figs. 13 and 14 of ref. 2), although a critical examination of the data for 16-13-3 steel (fig. 14 of ref. 3) indicates that some degree of nonlinearity can probably be expected.

Although the theory has been found to hold for many applications and materials, it has definite limitations insofar as creep is concerned. The theory is based upon viscous or steady-flow considerations; thus, transient-creep conditions in which the creep rate is decreasing continuously cannot be taken into account without some modification of the theory. The utility of the theory for applications involving any considerable degree of transient creep is therefore doubtful. The results of tensile and creep tests for many different metals also indicate that the theory is not generally valid for temperatures below about 0.45 times the melting temperature absolute of the material (ref. 7).

Larson-Miller Parameter

One of the simpler time-temperature parameters, derived from the rate-process theory (see eq. (1)), is that of Larson and Miller (ref. 2). For application to stress rupture and creep data, the parameter has the form

$$T(C + \log t) \tag{2}$$

where T is the absolute temperature, C is a constant, and t is the time to rupture or to a specified strain. (In ref. 2, T was taken in degrees Rankine and t in hours.) This parameter has been found to work satisfactorily over a wide range of times and temperatures for many steels, high-temperature alloys, and some aluminum alloys. Detailed results on the aluminum alloys, however, were not presented in reference 2.

If the minimum creep rate is under consideration, the parameter becomes

$$T(C - \log r) \tag{3}$$

where r is the minimum creep rate. (In ref. 1, r was taken in percent strain per hour.) According to Larson and Miller, the validity of the rate-temperature parameter (3) has not been established to the same extent as that of the time-temperature parameter (2). If the theory is valid, however, the rate parameter should prove even more satisfactory than the time parameter because it can be obtained directly from the theory without the necessity of assuming that time and creep rate have a constant inverse proportionality over the entire stress range.

A value of C of 20 has been found to be satisfactory for many high-temperature alloys (ref. 2); thus, direct comparisons of rupture and creep results for various combinations of time or rate and temperature can be made. A universal constant of 20, however, does not always provide the best correlation of the data. This effect is illustrated for 18-8 stainless steel in figure 1. In such instances, many inaccuracies may result from the use of a master curve based upon an erroneous value of the constant.

The general indications appear to be that C is approximately a constant for a given material. This conclusion is borne out by the fact that the linear constant-stress lines in plots of $\log t$ against $1/T$ tend to converge at a common point (ref. 2) and that good correlation of the data is obtained for numerous materials over the entire stress range when C is taken as a constant. This result also implies that A in equation (1) is also a constant.

MacGregor-Fisher Parameter

A rate-temperature parameter, described as the velocity-modified temperature, was presented earlier by MacGregor and Fisher (refs. 4 and 5). This parameter, which was applied chiefly to stress-strain data obtained under constant strain-rate conditions, was based upon a rate-process equation similar to equation (1) and presented in the form

$$T\left(1 - k \log \frac{r}{r_o}\right) \tag{4}$$

where k and r_o are constants and r was taken either as the rate of straining in the stress-strain test or the average creep rate to a given strain in the creep test. (In refs. 4 and 5, T was taken in degrees Kelvin and r in units of strain per second.) Except for an additional constant, the MacGregor-Fisher parameter (4) is similar to the Larson-Miller parameter (3). The MacGregor-Fisher parameter was also shown to be applicable to transient creep by using the average creep rate for a given strain. The materials investigated were mostly low-carbon steels, although aluminum, one aluminum alloy, and a few other materials were included. With stress-strain data at constant strain rates, individual curves of stress against the parameter are obtained for each material for given values of strain. With creep data, individual curves are similarly obtained by using the average creep rates for given values of strain.

Sherby-Orr-Dorn Parameters

Another time-temperature parameter, obtainable from equation (1), was proposed recently by Sherby and Dorn (ref. 6) for correlating the creep rate with the tensile strength of aluminum and some dilute solid solutions of aluminum in the form

$$\log_e r + \frac{Q}{RT} \tag{5}$$

where r refers either to the rate of straining in the tensile tests or to the minimum creep rate of the creep tests. (In ref. 6, T was taken in degrees Kelvin and r in strain per hour.) The activation energy Q was found to be a constant for these materials and equal to 35,800 calories per mole. Correlations of tensile strength and creep data are made in plots of stress against the parameter.

In the application to creep, Sherby and Dorn used the parameter

$$te^{-Q/RT} \tag{6}$$

where t is the time required to reach a given strain (t was taken in hours). Plots of strain against this parameter yield single curves for a given material and stress.

Sherby, Orr, and Dorn have also successfully applied similar parameters to creep and tensile data for platinum, nickel, copper, gold, lead, iron, and zinc (ref. 7). For creep strain, parameter (6) was used. A modification of parameter (6), however, was proposed for correlating creep-rate data as follows:

$$re^{Q/RT} \tag{7}$$

A single curve of stress against parameter (7) was obtained for each material for temperatures above about 0.45 times their melting points. Activation energies were found to be constant for a given metal. A good correlation of data for the ultimate tensile strength of copper was also obtained with parameter (7) for stress-strain tests over the range 400° F to 1000° F for strain rates varying by a factor of 10^6.

Orr, Sherby, and Dorn (ref. 8) have more recently extended the use of parameter (6) to the rupture of various metals and alloys by taking t as the rupture time. Good correlations of the data in plots of stress against the parameter were obtained for pure metals and 24 commercial alloys. The activation energy was found to be a constant for a given metal. The activation energies for the commercial alloys were all approximately the same, about 90,000 calories per mole.

The work of Sherby, Orr, and Dorn, as well as that of Larson, Miller, MacGregor, and Fisher, in successfully applying rate parameters based upon the rate-process theory for a great number and variety of materials for both tensile and creep applications gives credence to their generality and validity.

Manson-Haferd Parameter

The most recent of the time-temperature parameters is that of Manson and Haferd, which has an experimental rather than a theoretical basis (ref. 3). For use with stress-rupture and creep data, the parameter is

$$\frac{T - T_a}{\log t - \log t_a} \tag{8}$$

in which T_a and t_a are constants of temperature and time, respectively. (In this instance, T and T_a were taken in degrees Fahrenheit and t and t_a in hours.) This parameter has been found to work well for many materials - steels, high-temperature alloys, and aluminum alloys - over a wide range of rupture times. Detailed results are given in reference 3 for the steels and high-temperature alloys but not for the aluminum alloys.

For use with the minimum creep rate, this parameter is

$$\frac{T - T_a}{\log r + \log r_a} \tag{9}$$

where T_a and r_a are constants of temperature and rate, respectively. (Here, r was in percent strain per hour.)

Parameter (8) was derived from the approximately linear relation found experimentally between $\log t$ and T and the trend of the data to converge at a common point (T_a, $\log t_a$). The basis for the parameter is shown schematically in figure 5 of reference 3. This parameter measures the slopes of straight lines obtained for given values of stress. Values of T_a and $\log t_a$ which best fit the data vary for the different materials. According to reference 3, values of T_a for most of the materials ranged from 0° F to 200° F; values of t_a also varied appreciably.

Although single values of T_a and $\log t_a$ might be found which could be universally used with satisfactory results, this possibility has not as yet been demonstrated. For the time being, it is evident that accurate results can be expected with this parameter, as with the Larson-Miller parameter, only if the proper values of the constants are used for each material.

Comparisons of Parameters

Inasmuch as the Larson-Miller, MacGregor-Fisher, and Sherby-Orr-Dorn parameters are based upon the rate-process theory, no comparisons of their validity and applicability are made. Comparisons are given, however, between the Larson-Miller parameter and the experimentally based Manson-Haferd parameter because, although basically different, both are proposed for accurately predicting rupture life and creep behavior. The Larson-Miller parameter was chosen for this comparison with the experimental parameter because of its simple and convenient form.

Various comparisons between the Larson-Miller and the Manson-Haferd parameters have already been made in reference 3 for a number of materials. These comparisons tended to show that the Manson-Haferd parameter gave the more accurate predictions of rupture life. (Compare figs. 8 and 10 of ref. 3.) One of the comparisons was based, however, upon the assumption that a value of 20 could be used for C for all the materials. Although this assumption is in accord with the recommendations of reference 2, it is evident from the master curves shown in figures 1 and 9 of reference 3 that better correlation with the data could be obtained if a value of C other than 20 were used in some instances. Consequently, the accuracy of the predictions obtained from the two parameters might then be more nearly comparable.

The other more specific type of comparison included in reference 3 was an examination of the linearity of plots of log t against 1/T and T for 16-13-3 steel. This comparison showed, using the same data, that plots of log t against T were more nearly linear than that of log t against 1/T; thus, greater accuracy would be expected from the Manson-Haferd parameter than from the Larson-Miller parameter for this material.

In order to illustrate the extent to which the accuracy of predictions obtained from the Larson-Miller parameter is affected by the value of C in the parameter, comparisons of predicted life with actual life are made for 18-8 stainless steel for two values of the constant and with the same data. The master curves for $C = 15$ and $C = 20$ are shown in figure 1. With C equal to 20, distinct families of curves can be seen for each temperature, and the correlation of the data with a master curve is poor. With C taken as 15, however, the families of curves just mentioned have merged into a single curve, and the correlation of the data with the master curve is very good. Predictions based upon the two master curves of figure 1 are compared with the test data in figure 2. As can be anticipated from the better correlation of the data shown in figure 1 when C equals 15, the predictions based upon a value of C of 15 are more accurate than those obtained when C is taken as 20. Data for times under 100 hours follow the master curve for C of 15 so closely that predictions based upon a separate curve through those points would not yield significantly different results. The agreement between calculated results and the test data, when C is taken as 15, is now about the same as for the Manson-Haferd parameter for this same material (see fig. 2).

On the basis of these comparisons, it is apparent that the accuracy of predictions obtainable from the Larson-Miller parameter for a particular material depends very largely upon the value of the constant C which is used therein. Similarly, the accuracy obtainable with the Manson-Haferd parameter will also be dependent upon the values of the constants taken in that parameter. Satisfactory results can be obtained from either parameter if the data can be made to correlate well with the master curves.

APPLICATION OF THE LARSON-MILLER PARAMETER TO ALUMINUM ALLOYS

Procedure

Because of the adequacy and simplicity of the Larson-Miller parameters, parameters (2) and (3) have been used in processing published data for pure aluminum and some 17 aluminum alloys (refs. 6 and 9 to 15). Master curves for rupture, minimum creep rate, and time to 1 or 2 percent strain are shown in figures 3 to 18 for the materials considered to be of interest. Values of the constant C which appeared to give the best fit to the data are shown in table 1 along with the tensile properties and other information on the materials. With one exception, the data were all obtained under constant load and temperature conditions. The strain values are total strain which includes elastic and thermal strains as well as plastic strain. In the Larson-Miller parameters, T is the absolute temperature in degrees Rankine, t is the time in hours, and r is the minimum creep rate in percent strain per hour.

In the determination of the constant which gave the best correlation for the various materials and applications, values of the parameter were first calculated from the data for each material by assuming that C equaled 20. Examination of these results in plots of stress against the parameter showed a good correlation of the data in some cases; thus, a single or master curve gave a good approximation of the data. In others, families of curves were obtained so that the data could not be satisfactorily approximated by a single curve.

For cases in which the assumption of 20 did not prove to be satisfactory, a value of the constant which provided better correlation was estimated from calculations made at various stress levels, where data for two or more temperatures were given. If it is assumed that the theory is valid and that C is a constant for a given material and application, the following expressions for equivalent combinations of time or rate and temperature hold for the different stress levels:

$$T_1\left(C + \log t_1\right) = T_2\left(C + \log t_2\right) \tag{10}$$

$$T_1\left(C - \log r_1\right) = T_2\left(C - \log r_2\right) \tag{11}$$

In equations (10) and (11), t_1,r_1 and t_2,r_2 are the times and creep rates associated with the temperatures T_1 and T_2, respectively. The average value of C obtained from equations (10) or (11) for the particular application for several stress levels usually gave a result which provided a good correlation of the data.

The method described in reference 2 for the determination of C makes use of plots of $\log t$ against $1/T$. The method, however, is practical only if the data are fairly extensive. Even then, cross plots of the data by the method described in the appendix of reference 3 may be required in order to obtain satisfactory plots.

Inspection of plots of stress against the parameter will also clearly show whether the proper value of the constant has been determined if the data are adequate for the purpose. (See fig. 1, for example.) If the data are not adequate, values of C cannot be established with certainty. If only relatively short-time data are available for only a few temperatures, a reliable value of the constant cannot be determined. Long-time as well as short-time data are required for enough temperature levels to provide some degree of overlapping of the data, that is, equivalent combinations of time and temperature at a number of stress levels.

Results and Discussion

General application.- The master curves (figs. 3 to 18) show that the Larson-Miller parameters (2) and (3) can be successfully applied in general to aluminum and the aluminum alloys for rupture, minimum creep rate, and time to 1 or 2 percent strain. Satisfactory correlations of the data with the master curves were obtained for the solid solution, forging, and casting as well as the wrought alloys investigated.

Discontinuities and deviations.- Discontinuities at the lower temperatures (for example, fig. 3) were evident in the master plots for some of the materials and applications. Discontinuities at the lower temperatures indicate that the theory does not hold below some limiting temperature. This result is consistent with the findings of reference 7 in which a correlation using rate-process-theory parameters was not obtained at temperatures below about 0.45 times the melting temperature absolute for a wide variety of metals. In the case of the wrought aluminum alloys, this temperature would correspond to approximately 150° F to 300° F. Discontinuities were not found for some of the materials and applications at low temperatures (for example, figs. 6 and 9). The reason for this inconsistency is not apparent. For cases in which the data are very limited at the lower temperatures, however, it is sometimes difficult to determine whether discontinuities actually are present. The fairing of the master curve may be very arbitrary and uncertain in such cases.

Noticeable deviations of some of the data from the master curve occurred at the higher temperatures for some of the materials (for example, fig. 14) and indicated imperfect agreement of the theory in such regions. Such deviations may actually exist even though they are not evident in the master plots if the data do not cover a sufficiently wide range of times for a particular temperature. Consequently, fairly extensive data are required to determine whether the parameter actually provides a satisfactory correlation over the entire stress range.

Values of C.- Values of the constant C varied from 16 to 40 for the different materials and applications. (See table 1.) A value of 20 provided a good correlation of the data for about half the materials for some of the applications but resulted in a poor correlation for the others. The constant for a particular material was not always the same for rupture, minimum creep rate, and time to 1 percent strain but frequently differed for some one or more of the applications. Even though a constant of 20 appears to suit a number of aluminum alloys for some of the applications, the data covered herein clearly show that the value of the constant must be varied to provide reasonably good correlation for many of the materials. This result differs from that of reference 2 in which a value of C of 20 was found to be satisfactory for all the high-temperature steels and other alloys considered. As the data for some of the materials covered herein are very limited and do not include sufficient equivalent combinations of time or creep rate and temperature, values of the constant obtained for these materials may be subject to revision.

Results for some specific materials.- The data for 24S-T3 aluminum alloy (fig. 6) are more extensive than for the other materials and were obtained from several sources (refs. 9 to 12). Consistent results are evident even though independent sets of data from different laboratories are employed. The value of C which best fits the data varied from 17 for the stress rupture and 1 percent strain to 20 for the minimum creep rate. With the exception of the rupture data, marked discontinuities were evident at the lower temperatures for the minimum creep rate and 1 percent strain.

The data for Alclad 75S-T6 aluminum alloy (fig. 18) differ in that they are obtained from short-time, high-temperature creep tests (ref. 15) in which the specimens after loading were heated electrically at rates of about 75° F to 100° F per second to the test temperature. The duration of the tests varied from about 0.3 to 300 minutes. Master curves can also be drawn through these data except for the discontinuities appearing at 600° F. This agreement is surprising in view of the fact that even the longest durations are so short that transient conditions would be expected to predominate.

Extrapolation of Short-Time Data

In order to illustrate the accuracy with which long-time life can be predicted from short-time data for one of the aluminum alloys, predictions of long-time rupture life have been made from data under 10 hours for Alclad 75S-T6 aluminum alloy. Comparisons between predicted and actual life are shown in figure 19 by the dashed curves which were calculated from the rupture curve in figure 13 passing through data under

10 hours. The agreement at 212° F is good over the entire range. At 300° F, the agreement is good up to intermediate times; for longer times, the predictions are substantially unconservative. At 375°, the agreement is very good to 25 ksi. Predictions at 375° F below about 25 ksi would be hazardous, however, unless additional short-time data above 375° F were available. The solid curves in figure 19 are calculated from the rupture curve faired through all the data in figure 13. The agreement between these calculated values and the test data is fairly good except at 300° F. Predictions based upon data under 10 hours and from all the data are in close agreement.

Similar extrapolations are given in figure 10 of reference 3 for a number of steels and high-temperature alloys, based upon the master curves (fig. 9 of ref. 3) using the Larson-Miller parameter with a universal constant C of 20. As the correlation of the data with the master curves was rather poor for most of these materials when this value of the constant was used, the extrapolations of the data for 100 hours or less were subsequently in poor agreement with the tests. If values of the constant had been taken which would have provided a better correlation of the data, more accurate extrapolations would have been possible, as shown for the case of 18-8 steel in the section "Comparisons of Parameters."

Good agreement between calculated or predicted results and the data was obtained for these same materials (fig. 8 of ref. 3) by using the Manson-Haferd parameter with constants adjusted to give the best correlation of the data in the master plots (fig. 7 of ref. 3). Reliable predictions of long-time life from short-time data are evidently possible from the use of either the theoretically or experimentally based parameters provided that the proper values of the constants have been determined for the material and application.

CONCLUDING REMARKS

Recent developments in the application of time-temperature parameters to stress-strain, rupture, and creep data have been reviewed. A number of investigators have proposed various parameters for such applications and have shown that these parameters can be used successfully to take into account the simultaneous effects of time or rate and temperature for many metals and alloys over a wide range of times and temperatures. These developments are of much current interest because a practical method is provided for extrapolating and correlating data, and the need for extensive tests is largely reduced in some cases.

The Larson-Miller parameter was successfully applied herein to published data on rupture, minimum creep rate, and time to 1 or 2 percent strain for aluminum and the aluminum alloys. The materials included some solid-solution, forging, and casting alloys, as well as a number of wrought alloys. Values of the constant in the parameter which gave the best correlation of the data were found to vary for the different materials and applications. Extrapolation of short-time data to long times appears feasible for these materials, if the constant for the material and application is known.

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TABLE 1

VALUES OF CONSTANT C AND TENSILE PROPERTIES AT 75° F FOR ALUMINUM AND THE ALUMINUM ALLOYS

Source		Aluminum Alloy	Sheet thickness, in.	Exposure time, hr	Direction of loading	Values of C			Tensile properties for direction of loading		
Figure	Reference					Rupture	Minimum creep rate	Time to 1 percent strain	Yield stress, ksi	Ultimate stress, ksi	Elongation in 2 inches, percent
3	6	Pure aluminum	0.070	1	With grain	16	20	--	----	----	----
--	6	0.101 percent Cu in Al	.070	1	With grain	16	16	--	----	----	----
--	6	1.6 percent Cu in Al	.070	1	With grain	16	16	--	----	----	----
--	6	1.6 percent Zn in Al	.070	1	With grain	16	16	--	----	----	----
4	9	3S-H12	.064	1	With grain	40	40	30	17.0	19.0	10
5	9	3S-H18	.064	1	With grain	30	30	30	26.0	29.0	4
6	9	24S-T3	.064	1	With grain	17	20	17	50.0	70.0	19
6	10	24S-T3	.064	3	With grain	17	20	17	48.5	65.4	21
6	11	24S-T3	.062	2	With grain	17	20	17	51.4	69.6	17.7
6	12	24S-T3	.062	2	With grain	17	20	17	51.4	69.6	17.7
7	9	52S-H32	.064	1	With grain	15	20	20	27.0	34.0	12
8	9	52S-H38	.064	1	With grain	19	19	19	36.0	41.0	7
9	9	61S-T6	.064	1	With grain	25	25	25	40.0	45.0	12
10	13	Alclad 24S-T3	.040	1	Cross grain	20	20	20	47.4	63.0	16.5
11	13	Alclad 24S-T81	.040	1	Cross grain	20	20	25	62.2	66.1	5.7
12	13	Alclad 24S-T86	.040	1	Cross grain	20	20	20	64.0	67.3	5.3
13	13	Alclad 75S-T6	.040	1	Cross grain	20	20	20	67.7	75.5	10.5
14	13	R301-T6 (hardclad)	.040	1	Cross grain	20	20	20	59.9	66.0	9.5
15	14	18S-T61 Forging	-----	1	With grain	20	20	--	47.0	60.6	10.0
16	14	355-T71 Sand casting	-----	1	With grain	25	25	--	32.9	27.5	[a]1.3
17	14	355-T71 Mold casting	-----	1	With grain	25	25	--	31.5	38.6	[a]3
18	15	Alclad 75S-T6 (Heated at 50° to 75° F per sec)	.039		With grain	27		[b]27	67.0	76.0	11.0

[a] Elongation in 4D in percent.

[b] Value is for 2 percent strain.

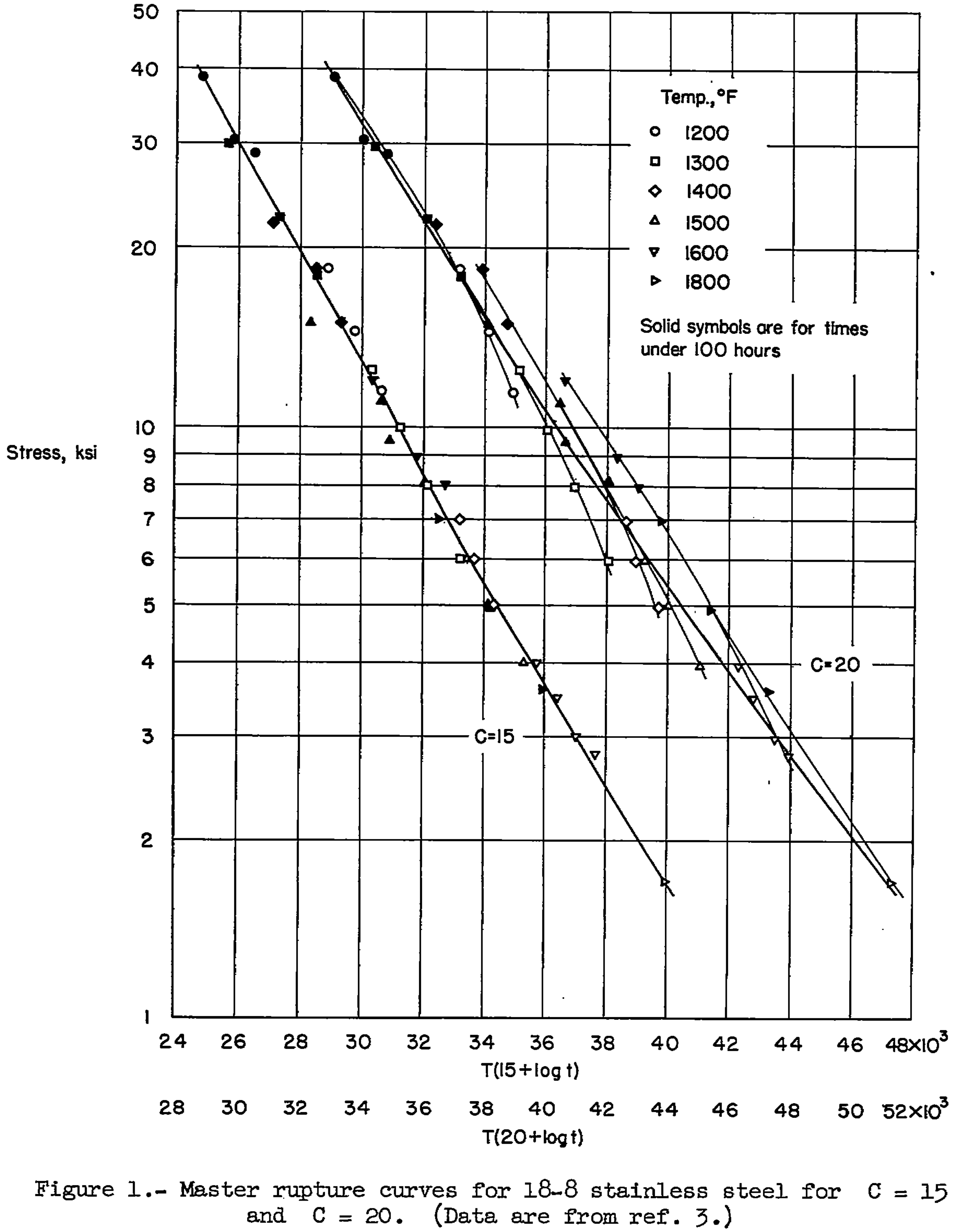

Figure 1.- Master rupture curves for 18-8 stainless steel for $C = 15$ and $C = 20$. (Data are from ref. 3.)

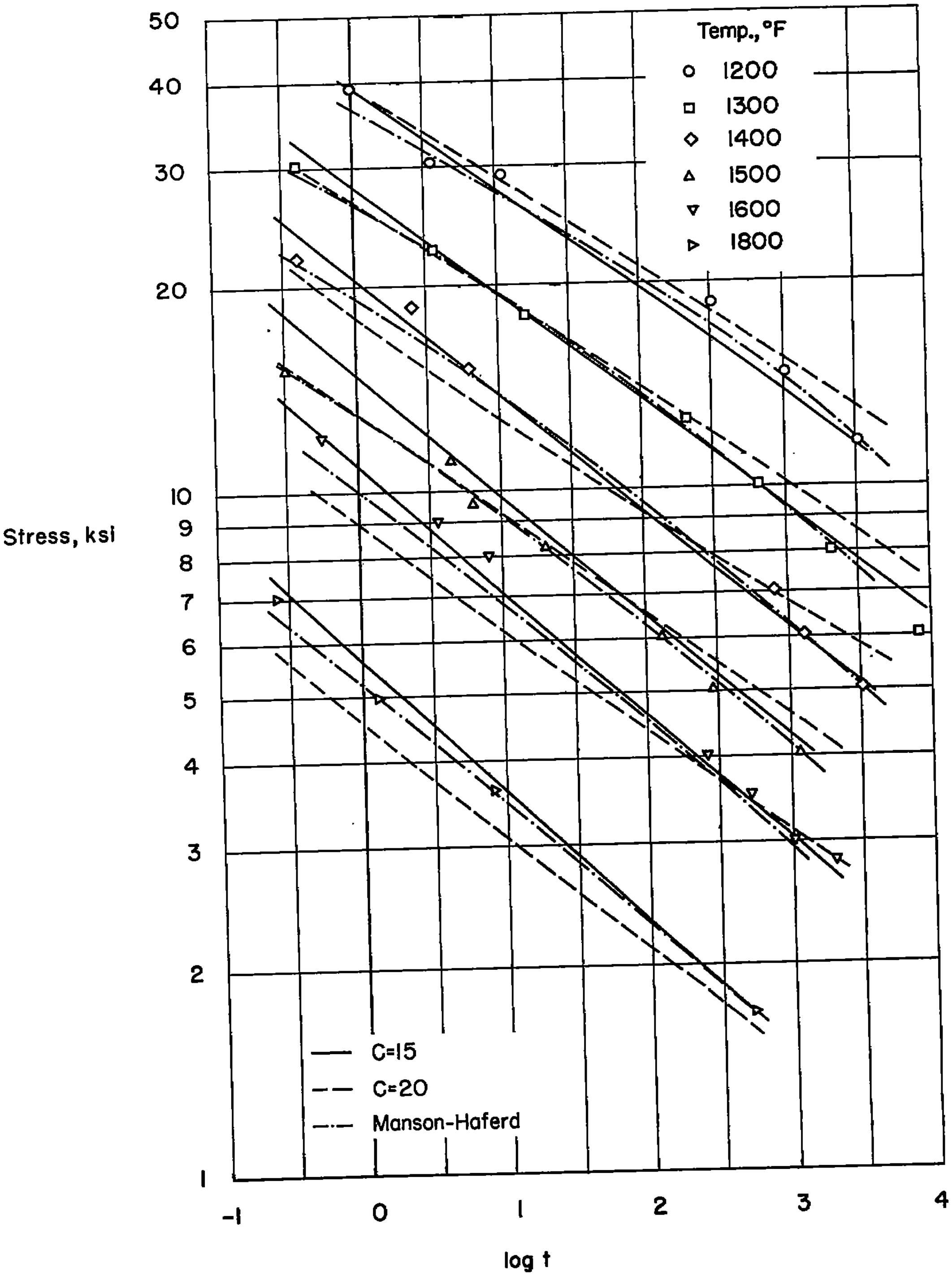

Figure 2.- Rupture curves for 18-8 stainless steel derived from master curves of figure 1 and from figure 7 of reference 3. (Data are from ref. 3.)

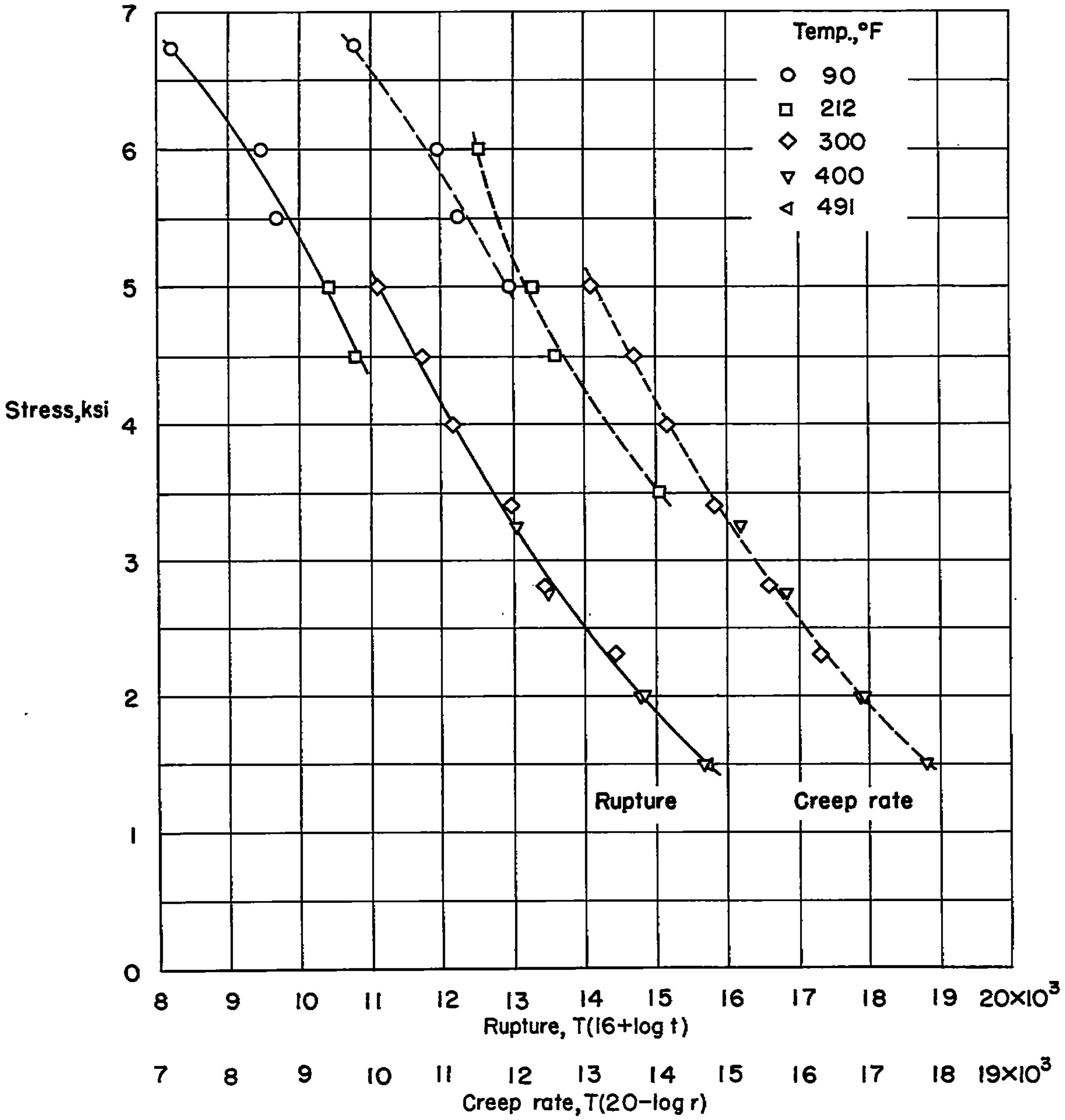

Figure 3.- Master rupture and creep curves for pure aluminum. (Data are from ref. 6.)

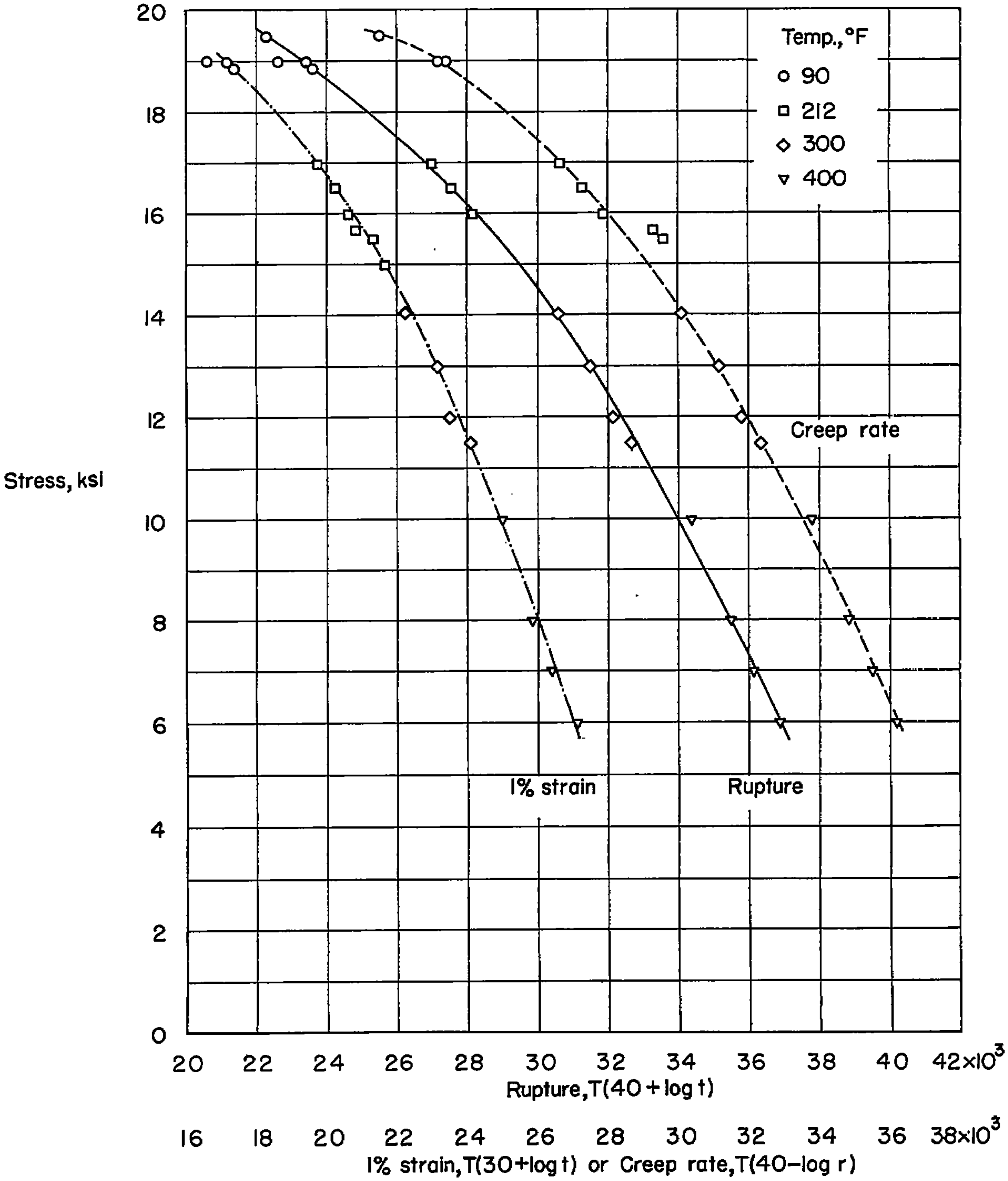

Figure 4.- Master rupture and creep curves for 3S-H12 aluminum alloy. (Data are from ref. 9.)

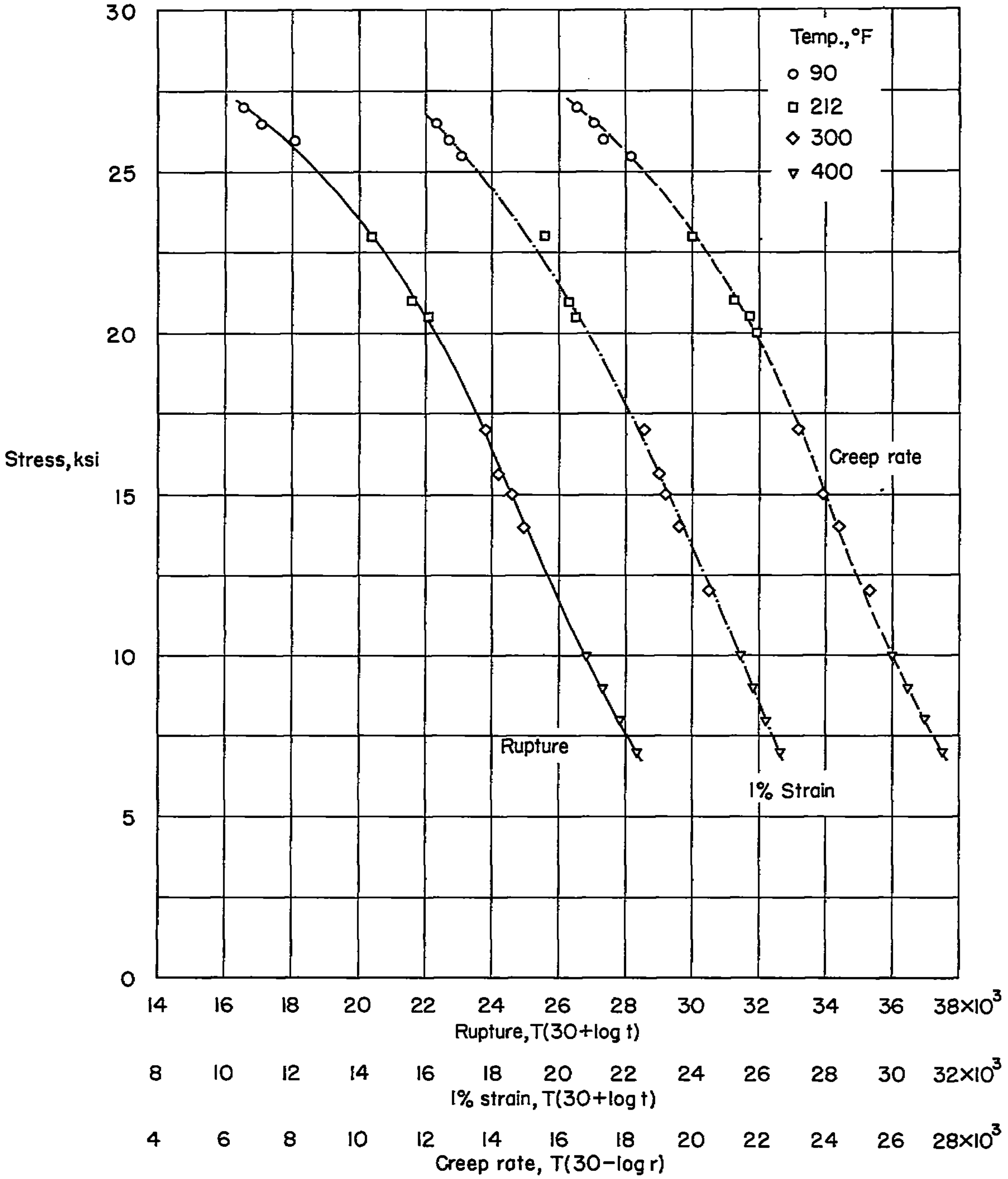

Figure 5.- Master rupture and creep curves for 3S-H18 aluminum alloy. (Data are from ref. 9.)

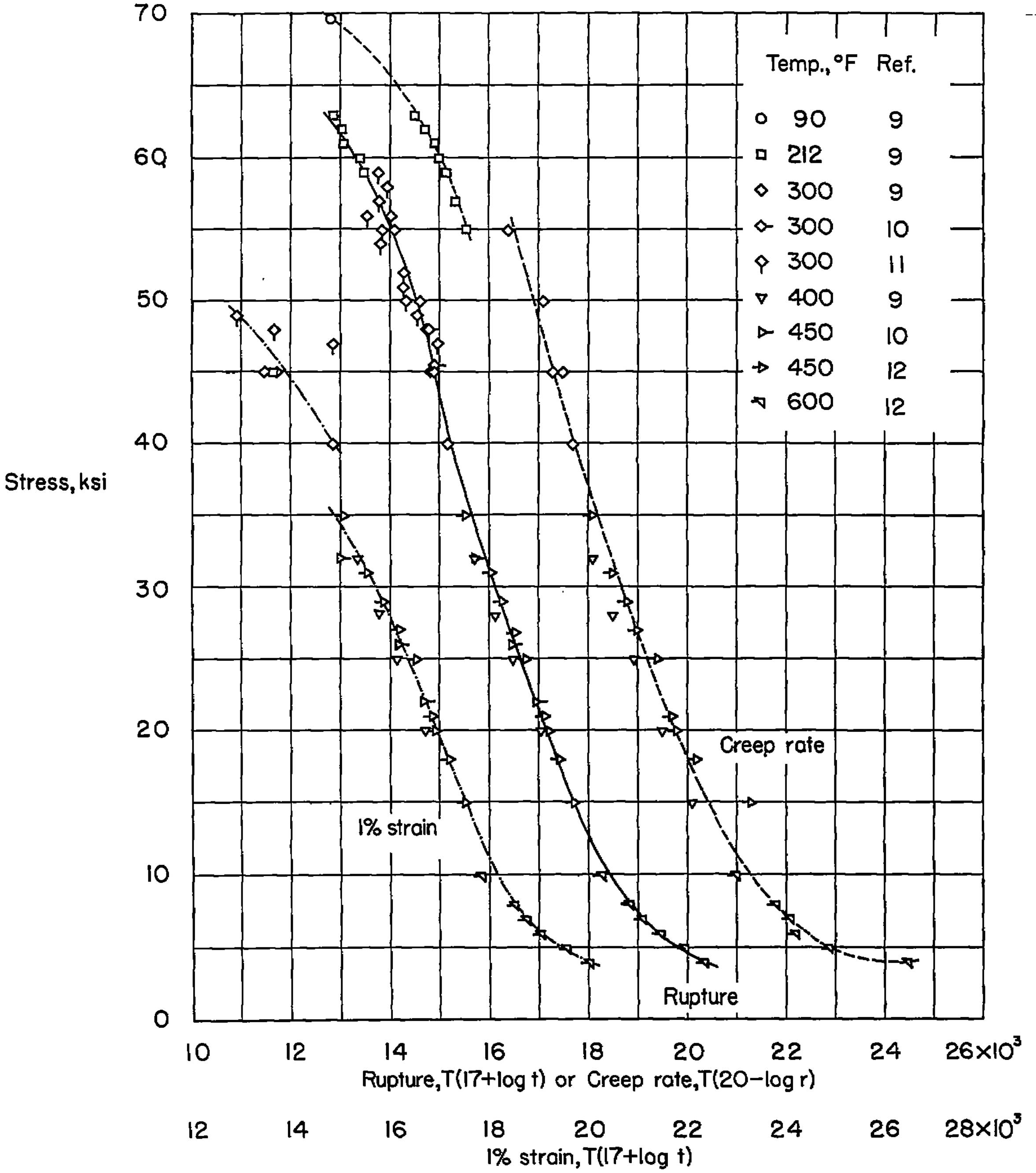

Figure 6.- Master rupture and creep curves for 24S-T3 aluminum alloy.

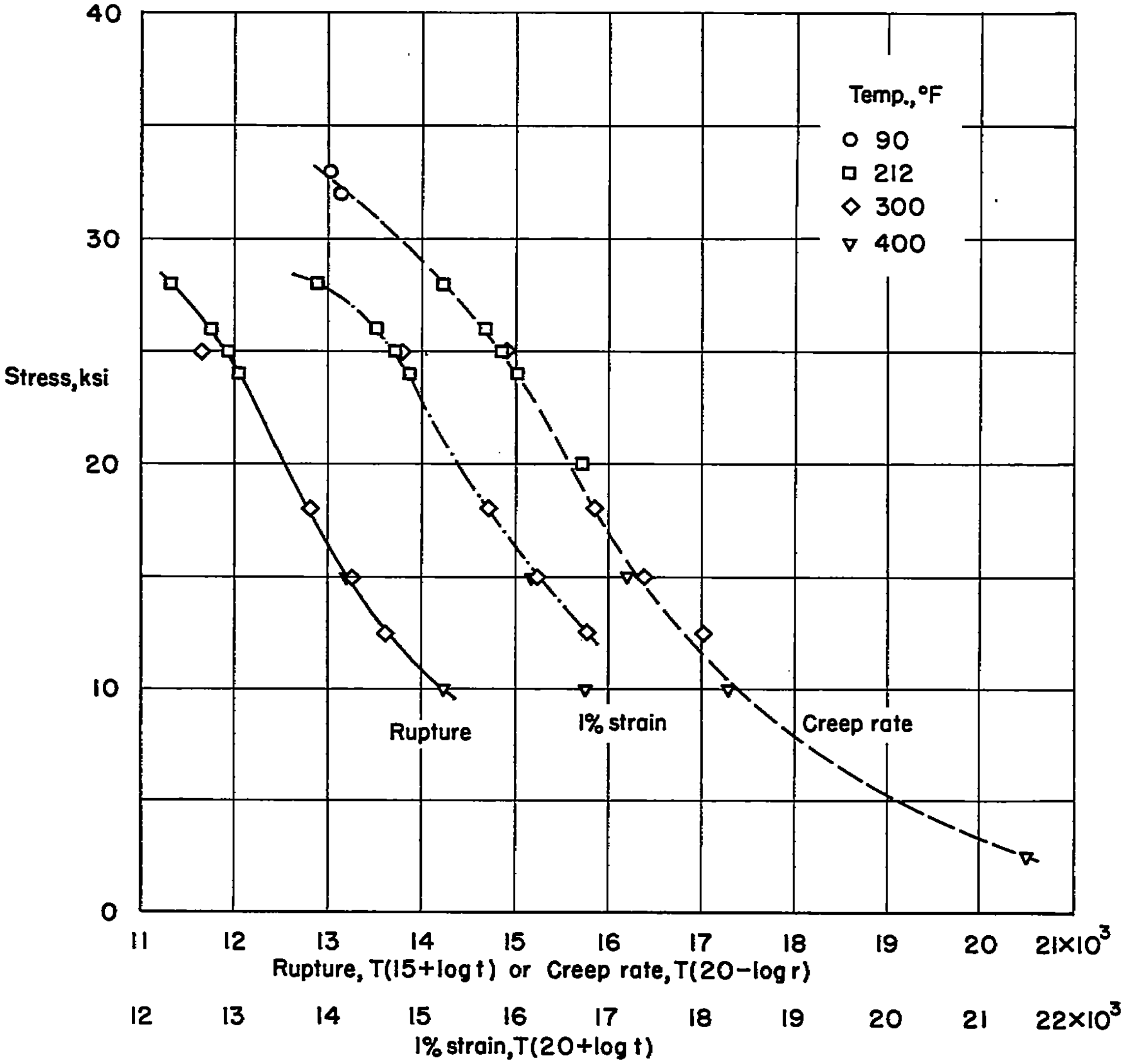

Figure 7.- Master rupture and creep curves for 52S-H32 aluminum alloy. (Data are from ref. 9.)

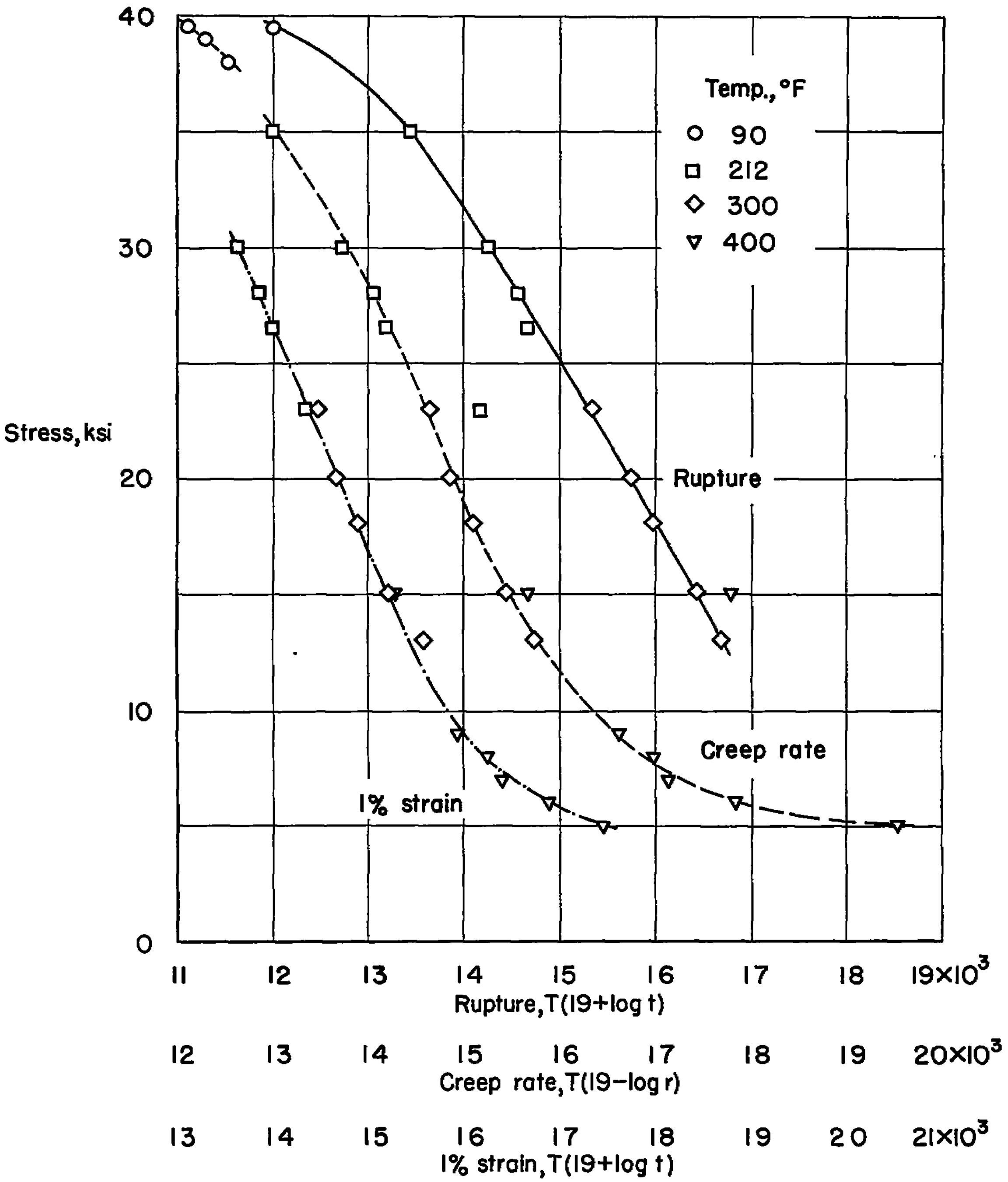

Figure 8.- Master rupture and creep curves for 52S-H38 aluminum alloy. (Data are from ref. 9.)

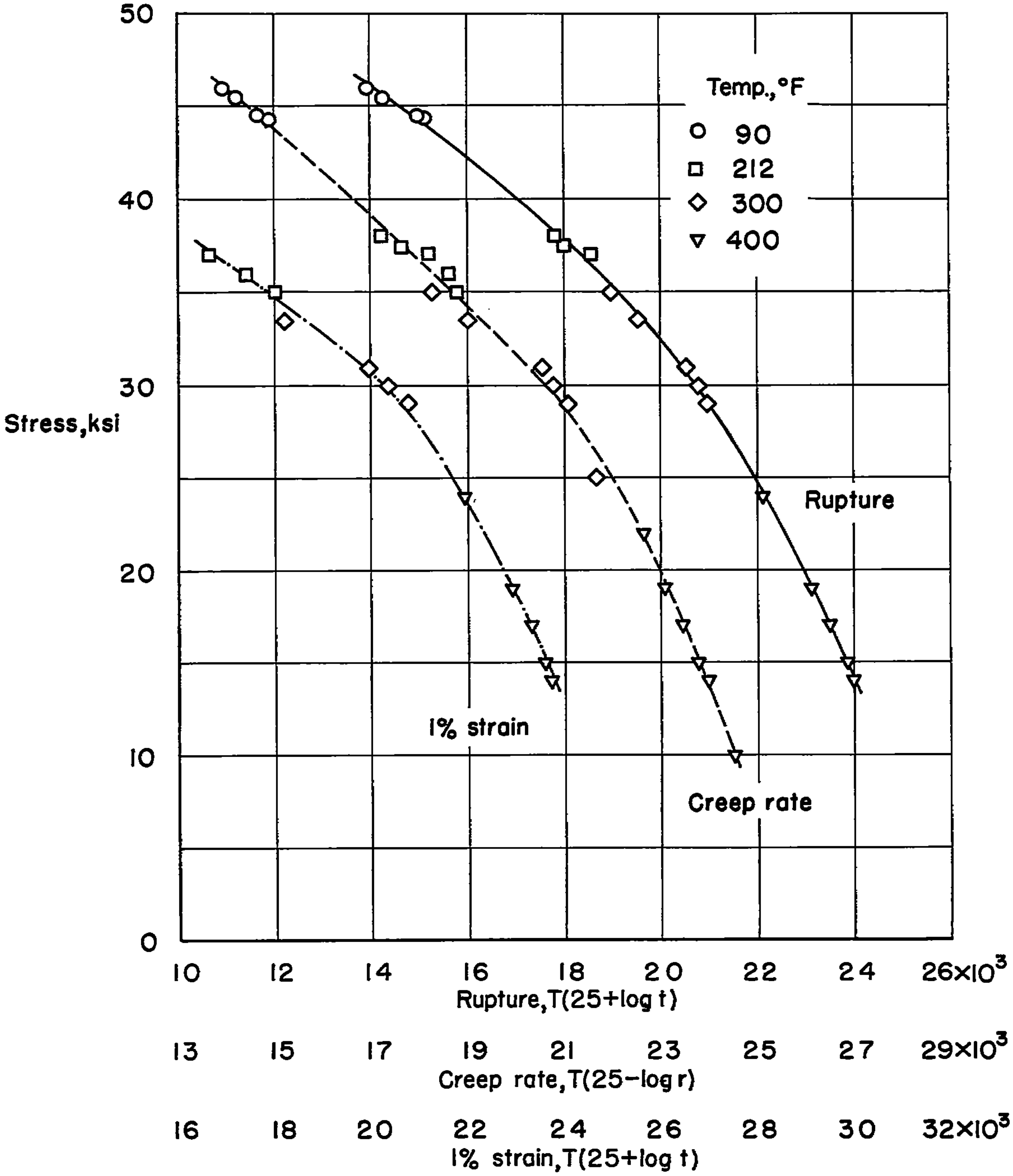

Figure 9.- Master rupture and creep curves for 61S-T6 aluminum alloy. (Data are from ref. 9.)

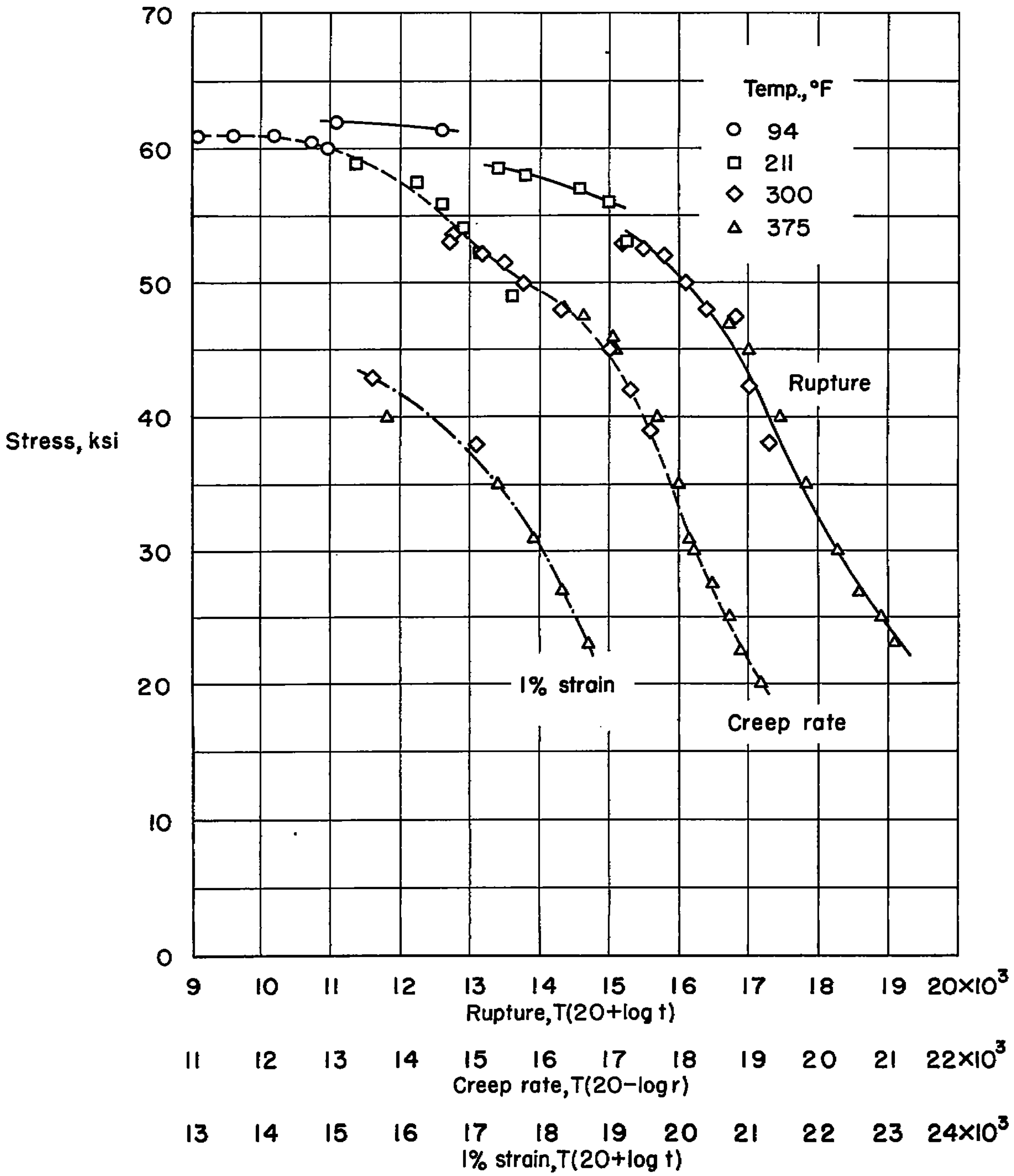

Figure 10.- Master rupture and creep curves for Alclad 24S-T3 aluminum alloy. (Data are from ref. 13.)

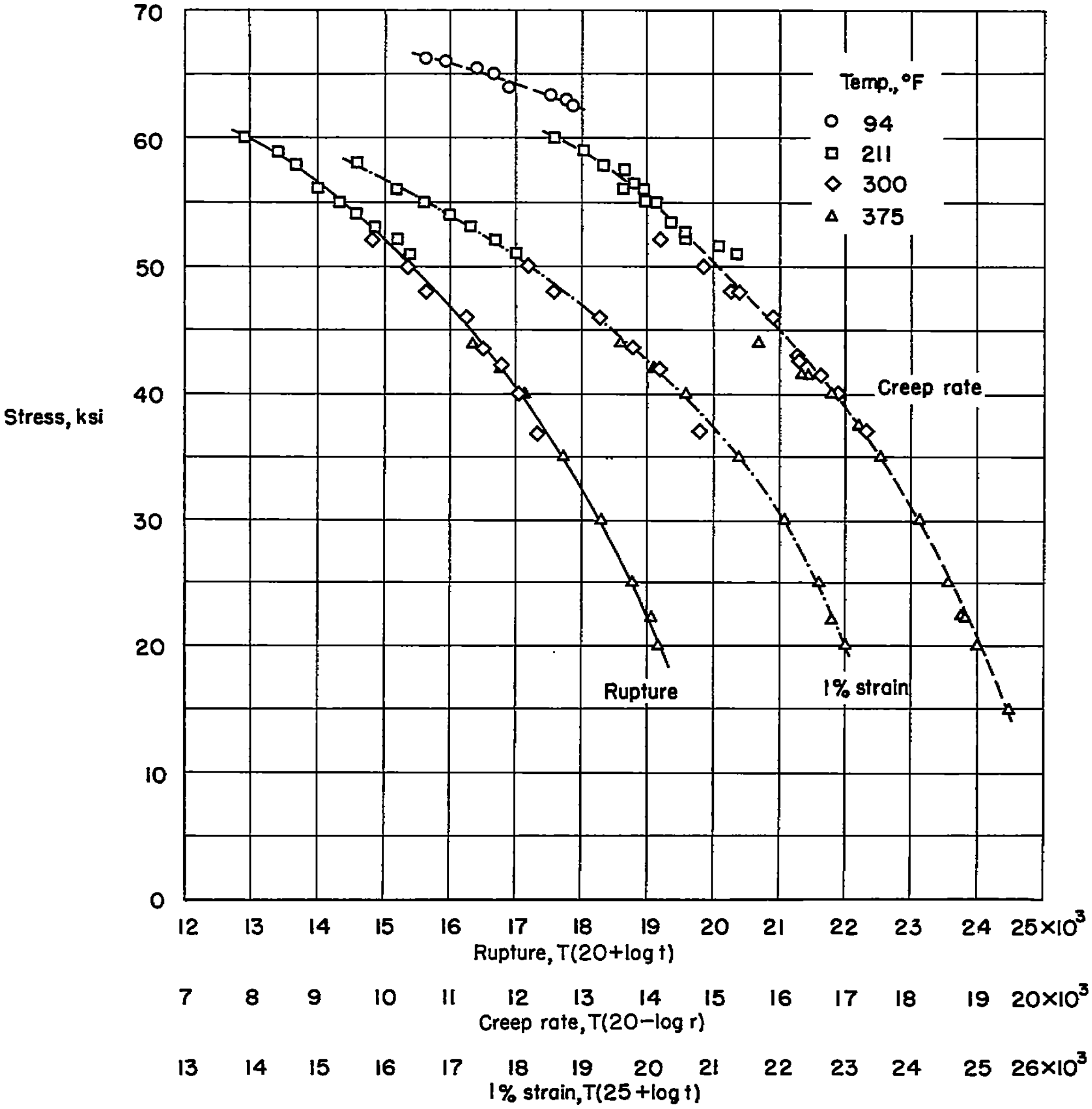

Figure 11.- Master rupture and creep curves for Alclad 24S-T81 aluminum alloy. (Data are from ref. 13.)

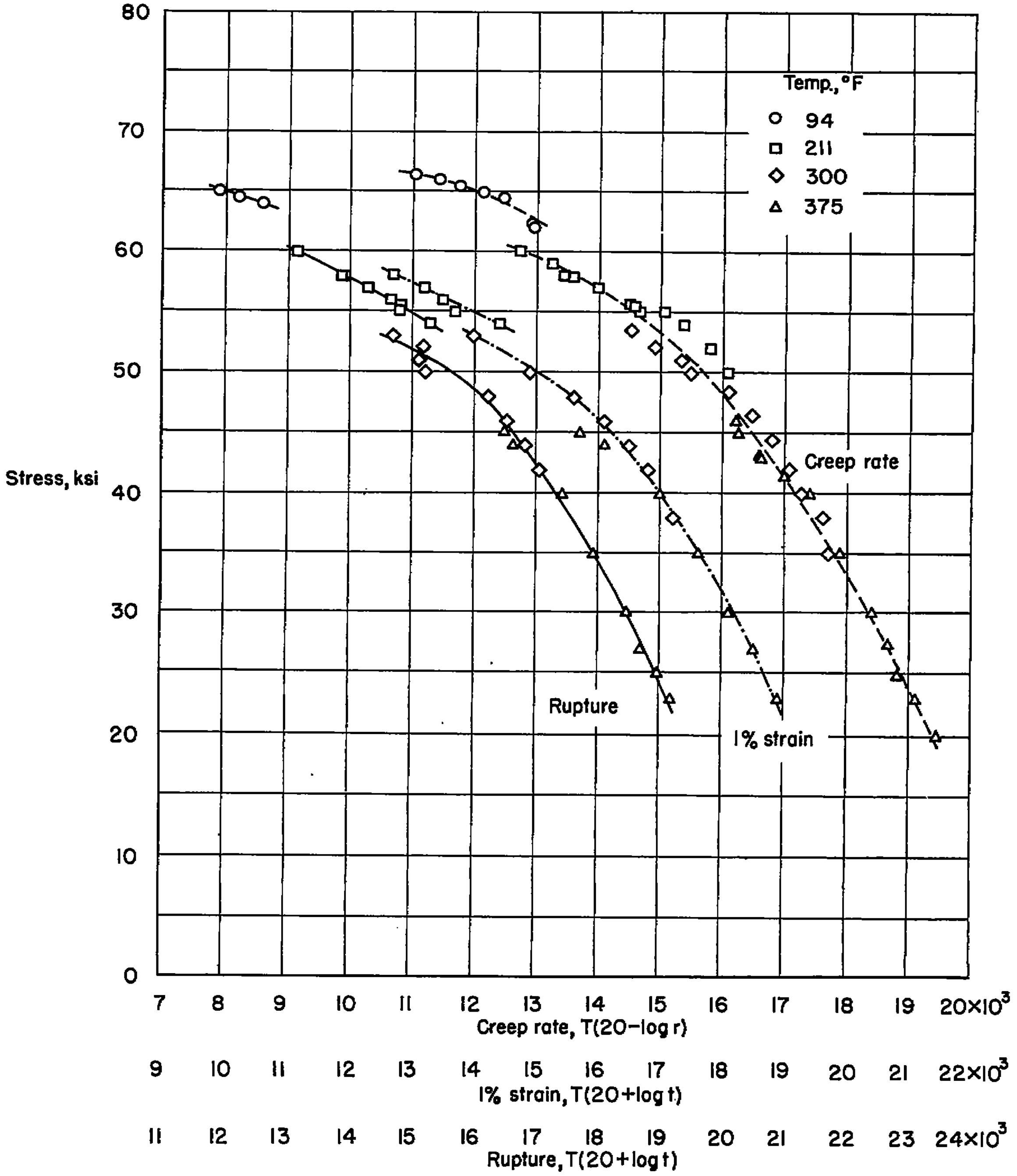

Figure 12.- Master rupture and creep curves for Alclad 24S-T86 aluminum alloy. (Data are from ref. 13.)

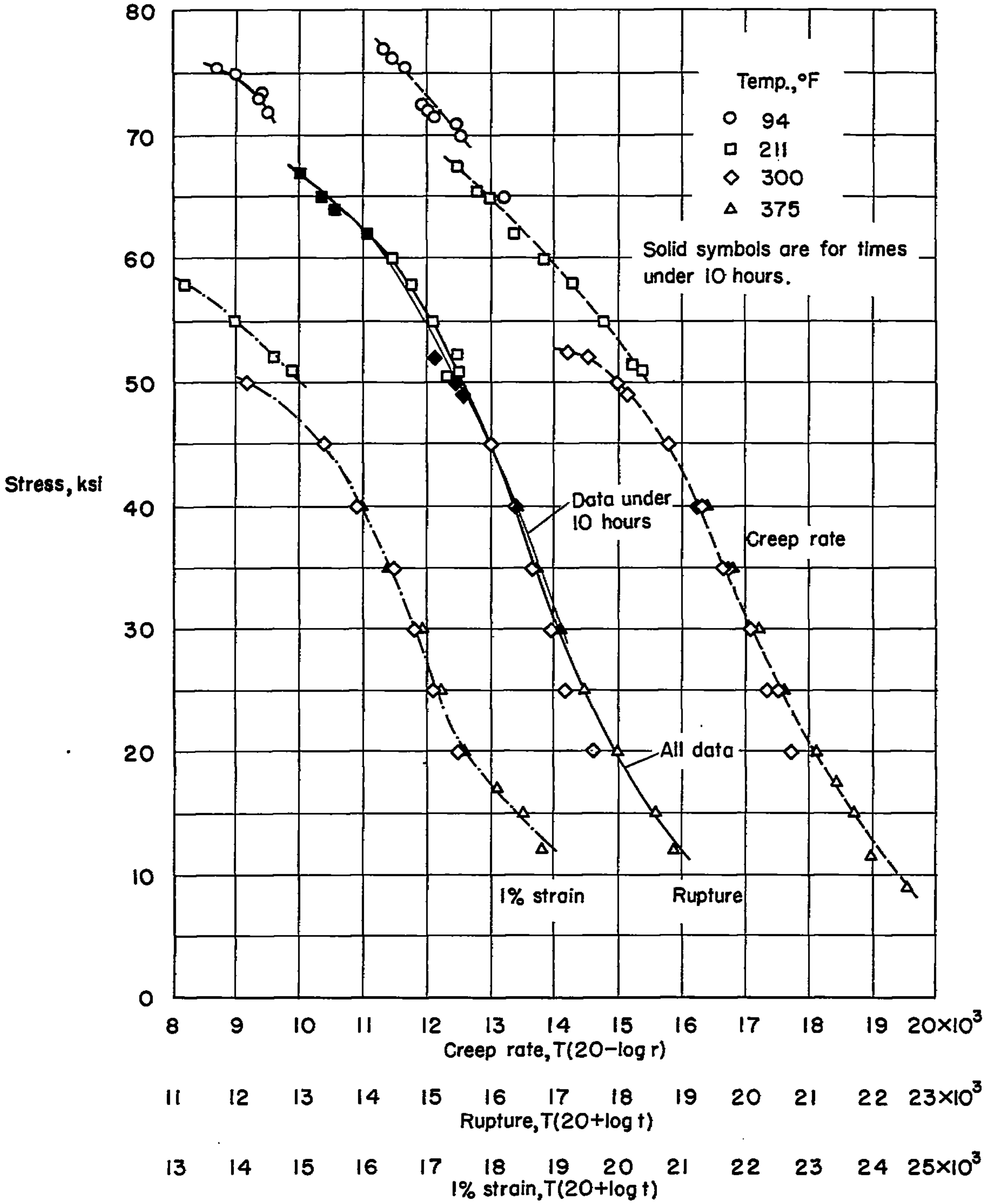

Figure 13.- Master rupture and creep curves for Alclad 75S-T6 aluminum alloy. (Data are from ref. 13.)

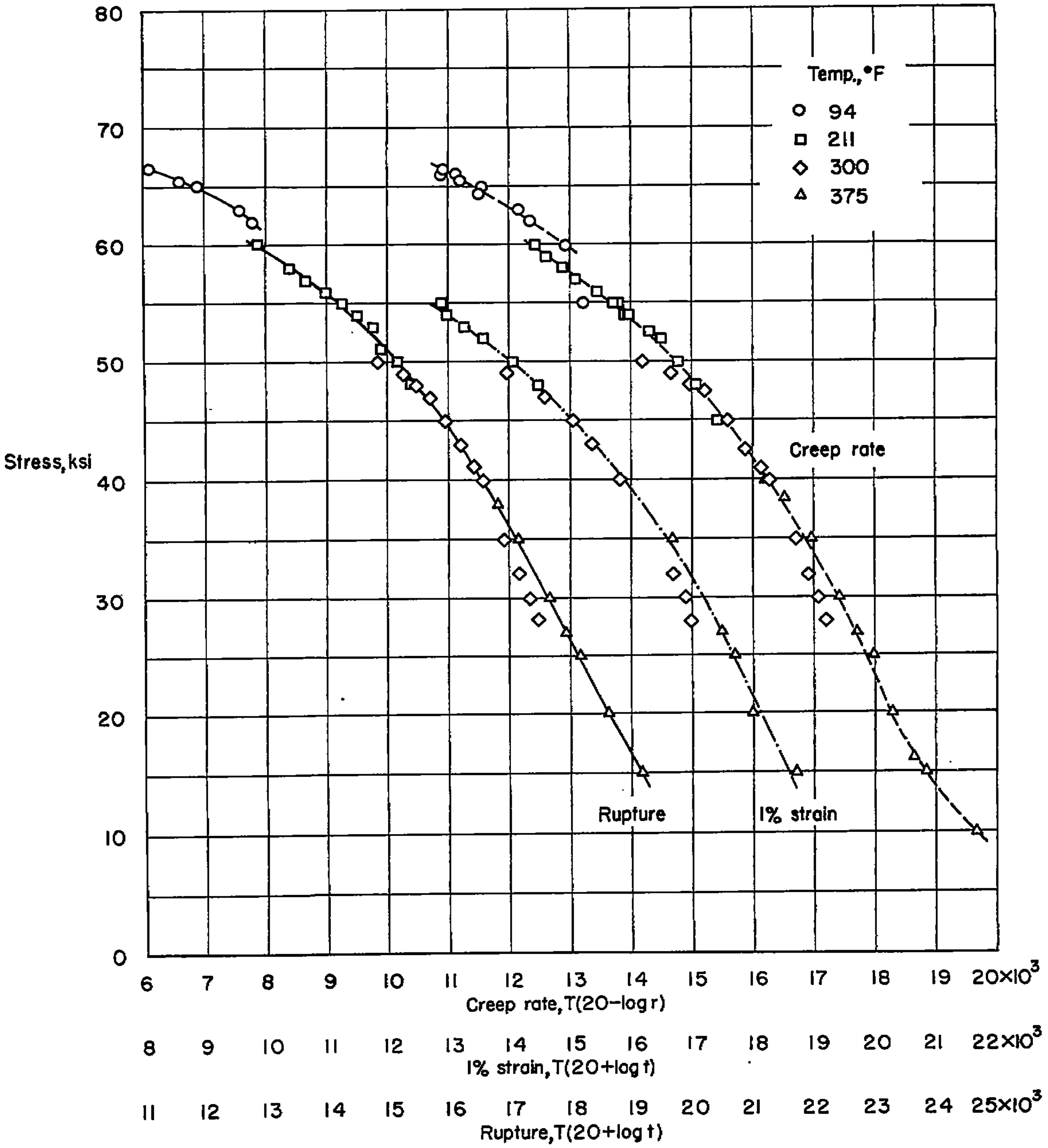

Figure 14.- Master rupture and creep curves for R301-T6 (hardclad) aluminum alloy. (Data are from ref. 13.)

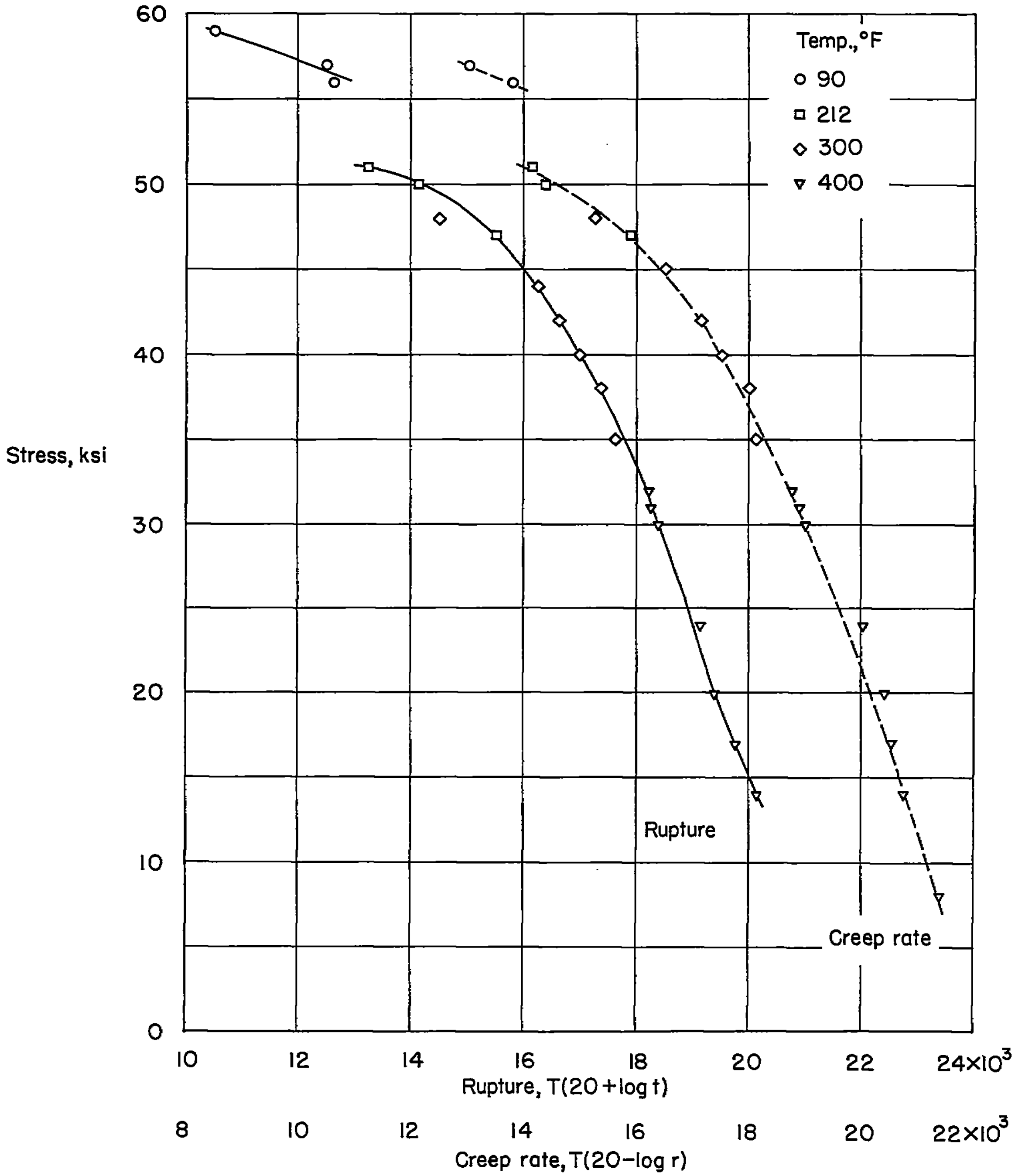

Figure 15.- Master rupture and creep curves for 18S-T61 forging aluminum alloy. (Data are from ref. 14.)

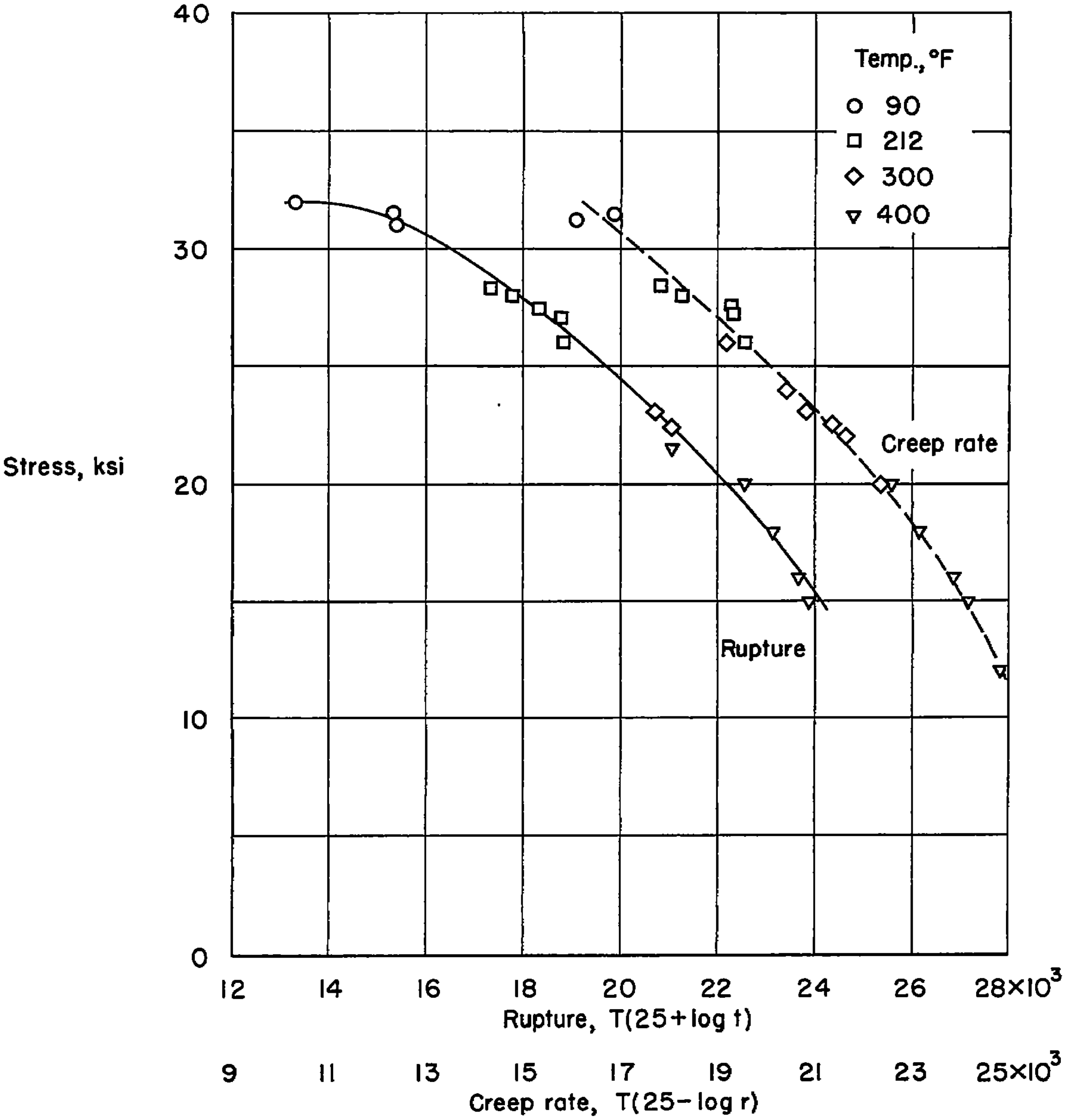

Figure 16.- Master rupture and creep curves for 355-T71 sand casting aluminum alloy. (Data are from ref. 14.)

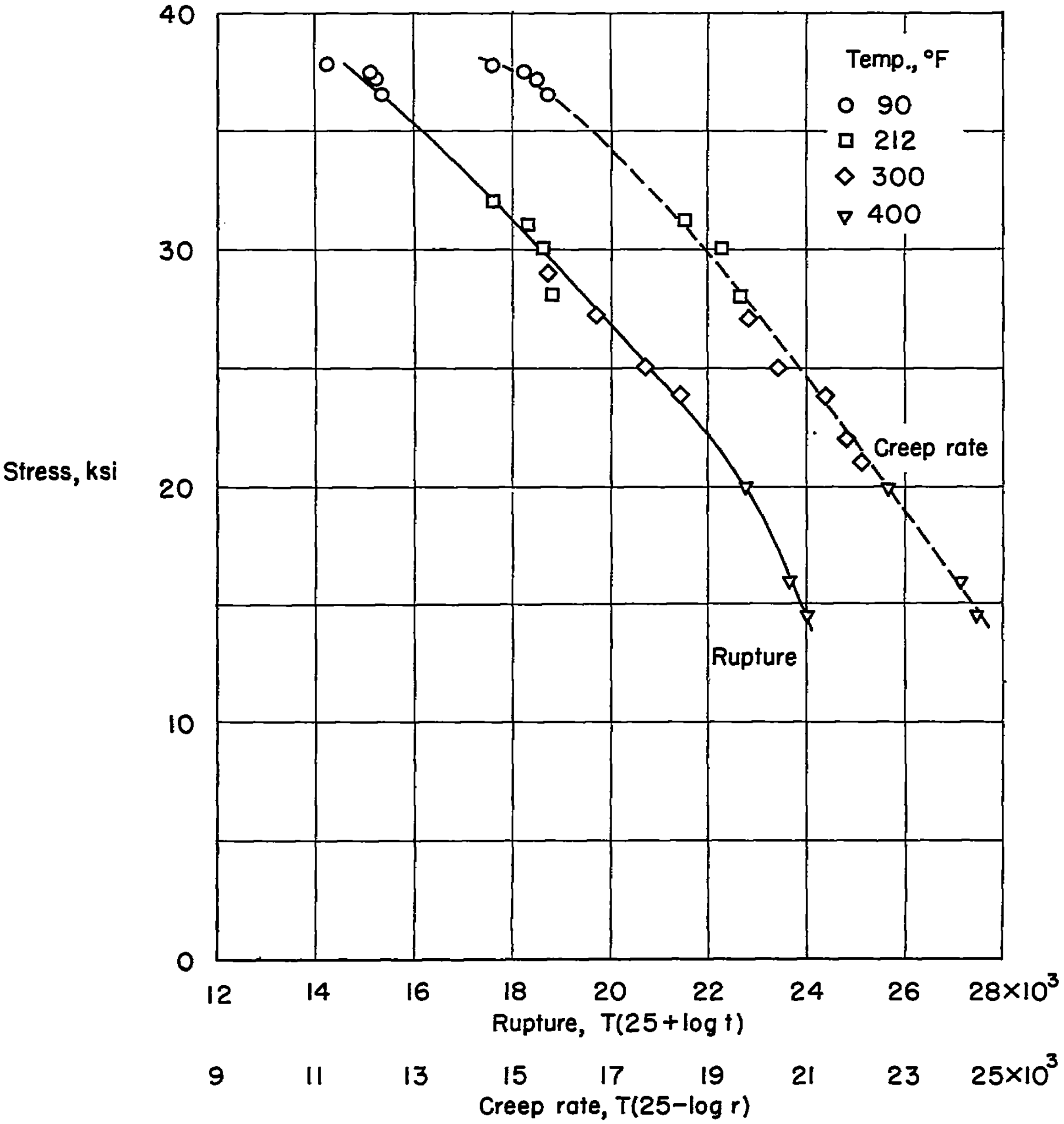

Figure 17.- Master rupture and creep curves for 355-T71 mold casting aluminum alloy. (Data are from ref. 14.)

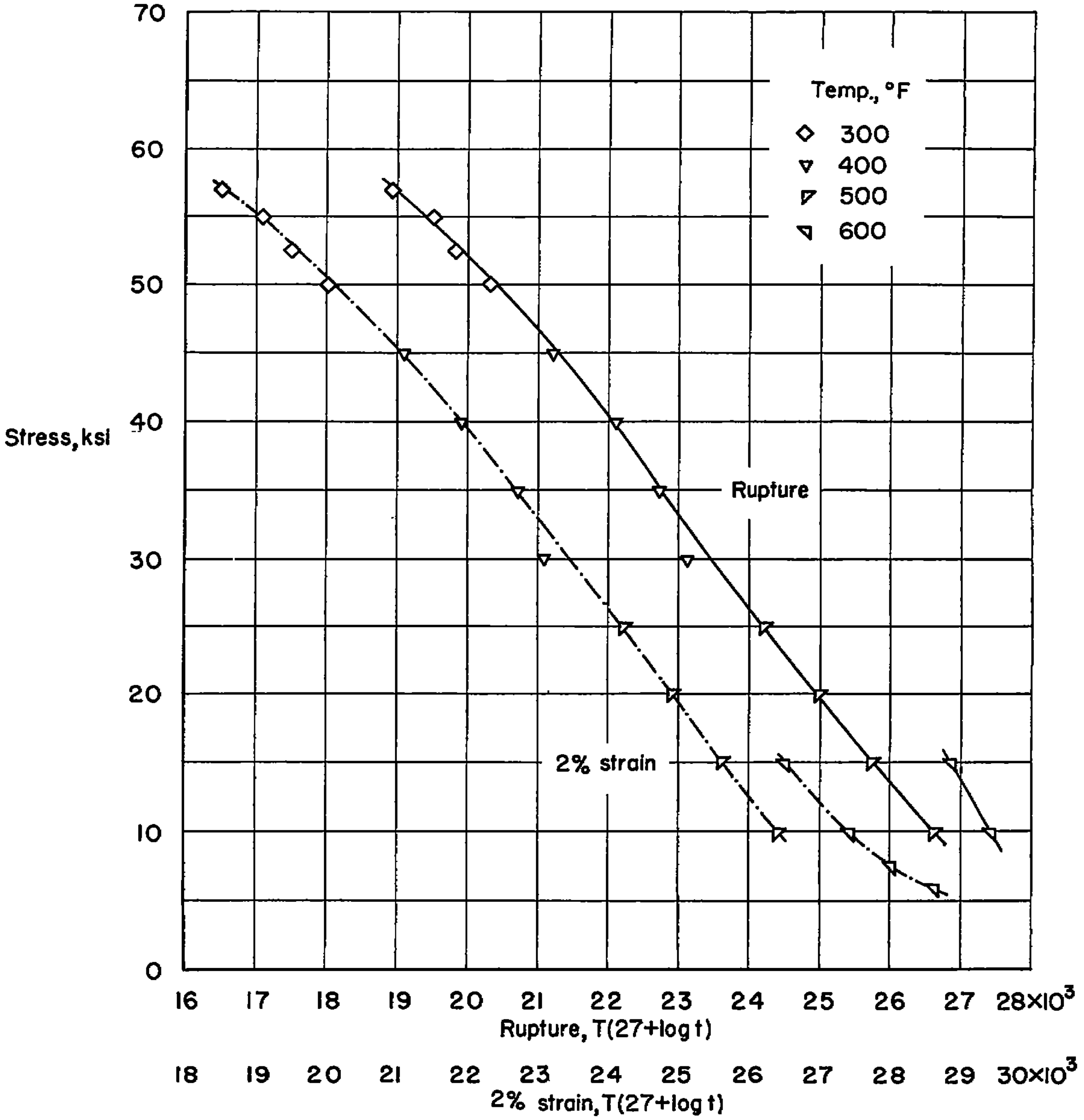

Figure 18.- Master rupture and creep curves for Alclad 75S-T6 aluminum alloy heated at 50° F to 75° F per second. (Data are from ref. 15.)

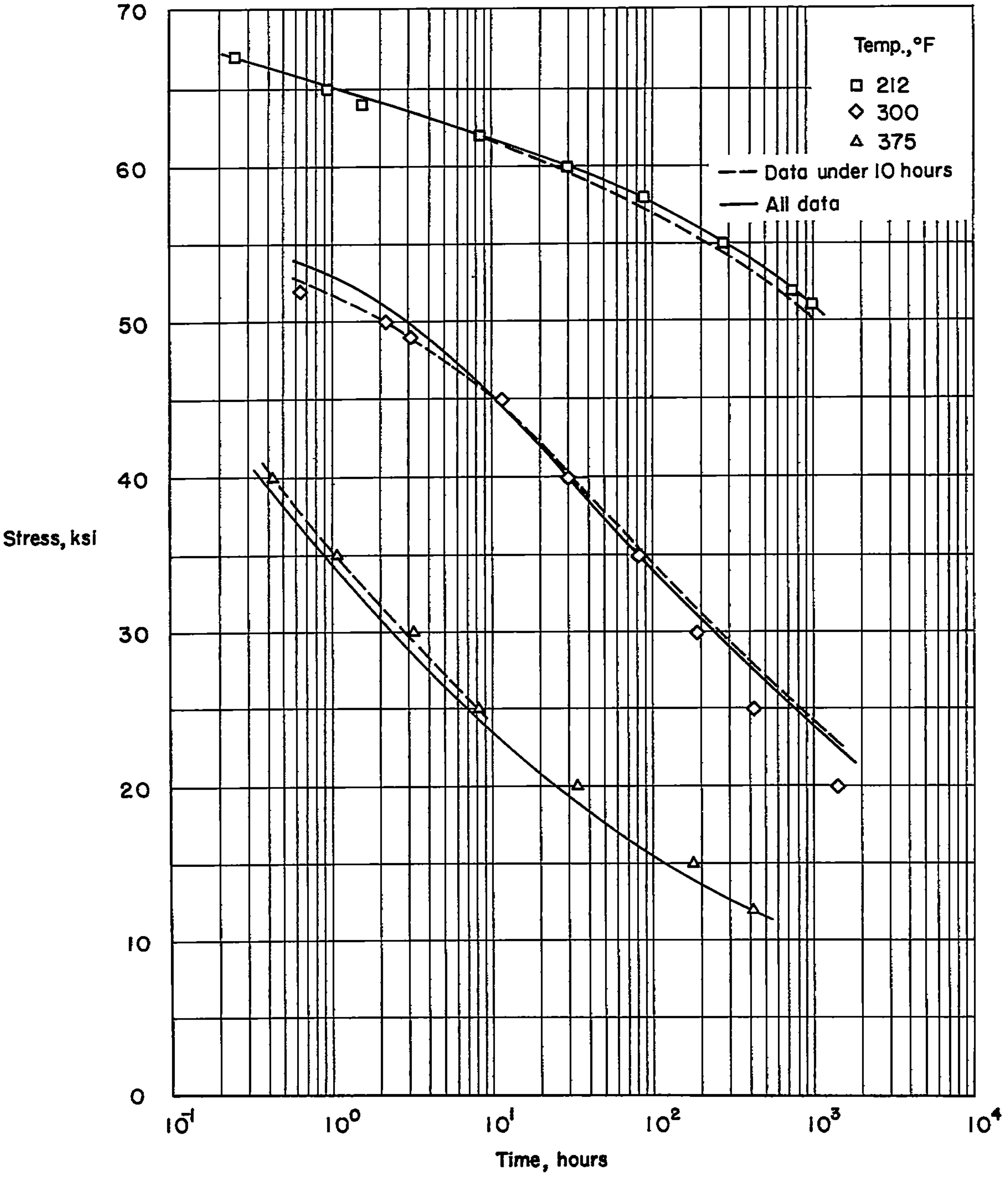

Figure 19.- Rupture curves for Alclad 75S-T6 aluminum alloy derived from master curves of figure 13. (Data are from ref. 13.)

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