Creep Life Prediction of Low-Alloy Steels Based on the β-Envelope Method

V.M. Radhakrishnan, P.J. Ennis, and H. Schuster

The creep life of low-alloy steels has been analyzed based on the β-envelope method. A parameter that compensates both the stress and the time axes is proposed involving the coefficients of the creep strain-time relations.

1. Introduction

IN a recent report,[1-3] a simple graphical procedure known as the β-envelope method was developed, in which the creep strain-time relation has been partitioned into three regions, each of which has been enveloped by a straight line on the log-log plot and given by the equations:

$$\varepsilon_1 = \beta_1 t^{1/3}$$
$$\varepsilon_2 = \beta_2 t$$
$$\varepsilon_3 = \beta_3 t^3 \quad [1]$$

The subscripts 1, 2, and 3 refer to the three stages of creep strain on the time variation. It has been shown that the coefficients β_i are functions of stress, σ, and temperature, *T*. In the case of Cr-Mo steels, the coefficients β_1, β_2, and β_3 have been found to depend on the applied stress in the form:

$$\beta_1 = \beta_{o1} \exp (B_1 \cdot \sigma) \quad [2]$$

Nomenclature	
B_1, B_2, B_3	Constants
C, C_1	Constants
G	Slope in stress-log rupture time relation
P_R	Creep-rupture parameter
q	Exponent
T	Temperature
T_r	Reference temperature
t	Time
t_r	Rupture time
$\beta_1, \beta_2, \beta_3$	Coefficients
β_{2o}	β_2 at σ_o
β_{o2}	β_2 at $\sigma = 0$
β_{2or}	β_{2o} at reference temperature T_r
β_{o2r}	β_{o2} at reference temperature T_r
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	Creep strains in the first, second, and third stages
ε_r	Creep-rupture strain
σ	Stress
σ_o	Creep strength at short time
σ_{or}	Creep strength at short time at the reference temperature

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$$\beta_2 = \beta_{o2} \exp (B_2 \cdot \sigma) \quad [3]$$

$$\beta_3 = \beta_{o3} \exp (B_3 \cdot \sigma) \quad [4]$$

where β_{o1}, β_{o2}, and β_{o3} are temperature-dependent constants. Typical relations between the applied stress and the coefficients β_2 and β_3 are shown in Fig. 1 for 1Cr-0.5Mo steel on a semi-log plot at 530 and 550 °C.[1] The coefficient β_2 represents the minimum creep rate, $\dot{\varepsilon}_{min}$. It has also been found that the relation between the minimum creep rate, $\dot{\varepsilon}_{min}$, and the rupture time, t_r, can be given by a relation of the type:

$$\dot{\varepsilon}_{min} \cdot (t_r)^q = C \quad [5]$$

where the exponent q has a value of 1.3, and C is a constant. The typical relation between the minimum creep rate and the rupture time is shown in Fig. 2.[1]

At fracture, we have the relation:

$$\beta_3 t_r^3 = \varepsilon_r \quad [6]$$

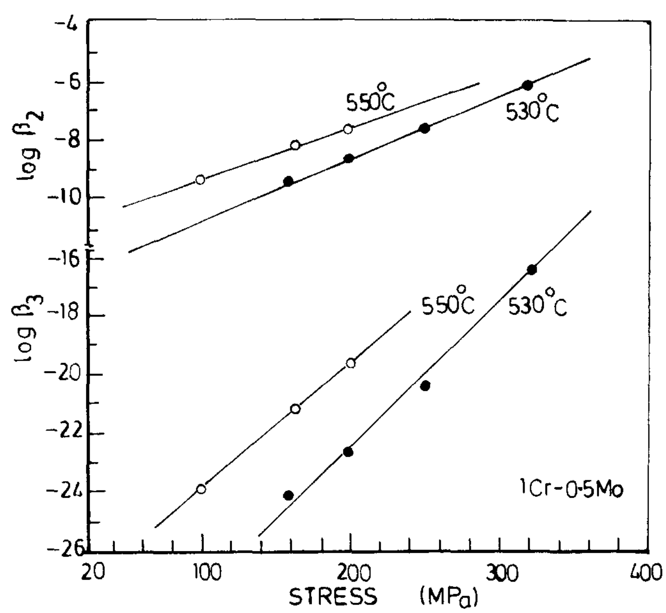

Fig. 1 Relationship between stress and the coefficients β_2 and β_3 for 1Cr-0.5Mo steel.[1]

$$t_r = \frac{\varepsilon_r^{1/3}}{\beta_{o3}^{1/3} \exp(B_3 \cdot \sigma/3)} \quad [7]$$

From the above relations, it can be shown that:

$$\exp(B_2 \cdot \sigma - B_3 \cdot \sigma \cdot q/3) = C/\varepsilon_r^{q/3} \quad [8]$$

where ε_r is the creep fracture strain. Creep fracture strain is dependent on the applied stress in general. In the case of service-exposed material, its dependence is significant. In the case of fresh materials, it is not.[4] If it is taken as minimal, then we get:

$$B_2 = B_3 \cdot q/3 \quad [9]$$

If the Monkman-Grant relation is valid, then $q = 1$ and $B_2 = B_3/3$.

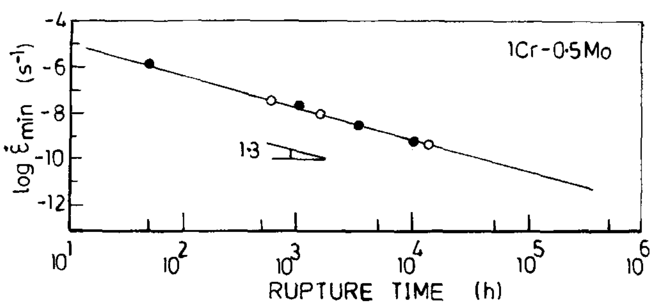

Fig. 2 Relationship between minimum creep rate and rupture time.[1]

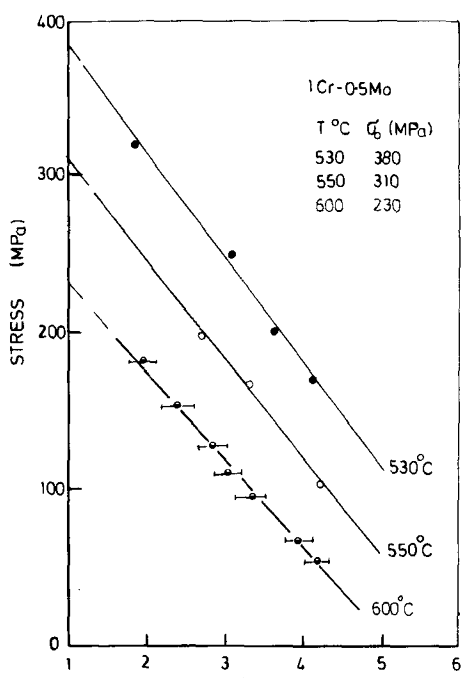

Fig. 3(a) Relationship between applied stress and rupture life on semi-log plot for 1Cr-0.5Mo. The points shown are mean rupture values.[1,4]

The aim of the present investigation is to analyze the creep-rupture behavior of low-alloy chromium-molybdenum steels that are widely used in the industrial power plants and to char-

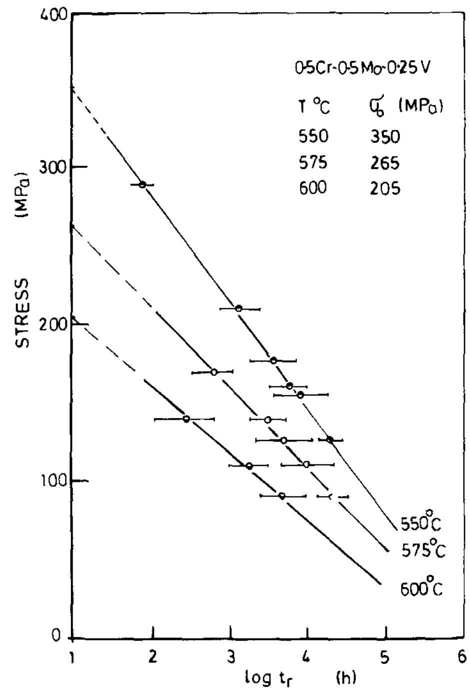

Fig. 3(b) Relationship between applied stress and rupture life on semi-log plot for 0.5Cr-0.5Mo-0.25V. The points shown are mean rupture values.[4]

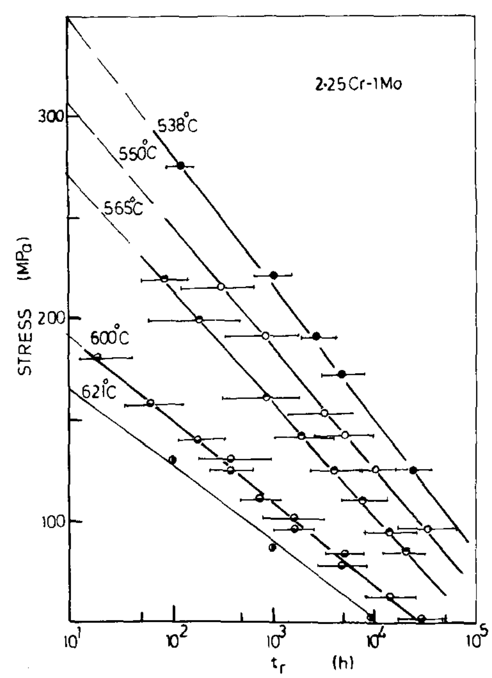

Fig. 3(c) Relationship between applied stress and rupture life on semi-log plot for 2.25Cr-1Mo. The points shown are mean rupture values.[4,5]

acterize these steels by a suitable parameter based on the basic creep strain-time relations.

2. Materials

The materials analyzed for the life prediction in this study were low-alloy chromium-molybdenum and chromium-molybdenum-vanadium steels with the following nominal designations:

- 1Cr-0.5Mo steel
- 0.5 Cr-0.5Mo-0.25 V steel
- 2.25Cr-1Mo steel
- 0.5Cr-0.25Mo-0.25 V
- 0.5Cr-0.25V
- 12Cr-Mo-V

The creep-rupture data for the 1Cr-0.05Mo material have been obtained from the data bank of IRW, KFA, Julich, Germany and are given in Ref [1]. The base data for the other materials have been taken from Ref 4 through 7. In each case, there is large scatter. The mean data points are taken for the analysis. The data generated are based on constant-load tests.

3. Rupture Life

Typical relations between the applied stress and the rupture time for the materials studied are shown in Fig. 3(a) through (f) on a semi-log plot. For many of the low-alloy steels, the stress-rupture time relation can be given by a relation of the type:

$$t_r \cdot \exp(G\sigma) = C_1 \quad [10]$$

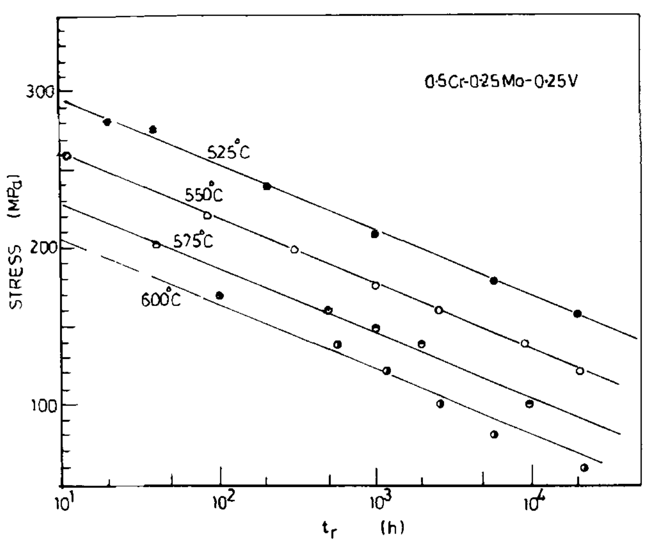

Fig. 3(d) Relationship between applied stress and rupture life on semi-log plot for 0.5Cr-0.25Mo-0.25V. The points shown are mean rupture values.[6]

where $(-1/G)$ is the slope of the line stress-log rupture time, and C_1 is a constant. The rupture time can also be written at a given temperature such that:

$$t_r \cdot \exp(B_3 \cdot \sigma/3) = \text{constant} \quad [11]$$

Considering Eq. 10 and 11, we see that:

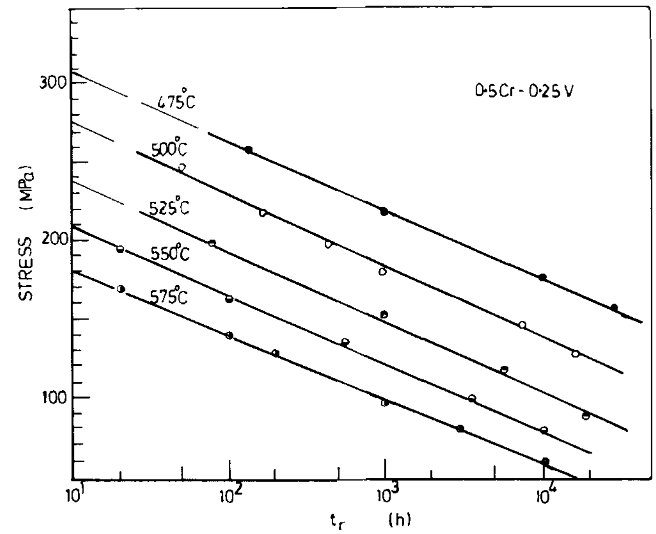

Fig. 3(e) Relationship between applied stress and rupture life on semi-log plot for 0.5Cr-0.25V. The points shown are mean rupture values.[6]

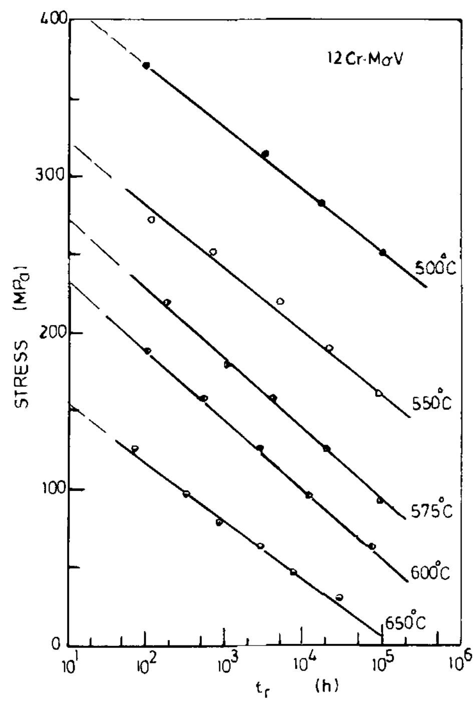

Fig. 3(f) Relationship between applied stress and rupture life on semi-log plot for 12Cr-Mo-V. The points shown are mean rupture values.[7]

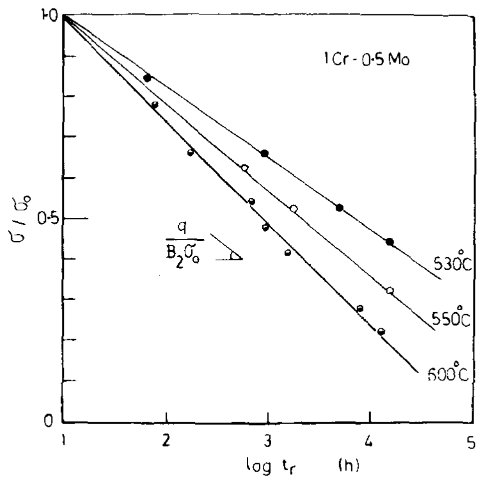

Fig. 4(a) Relationship between normalized stress and rupture time for 1Cr-0.5Mo.

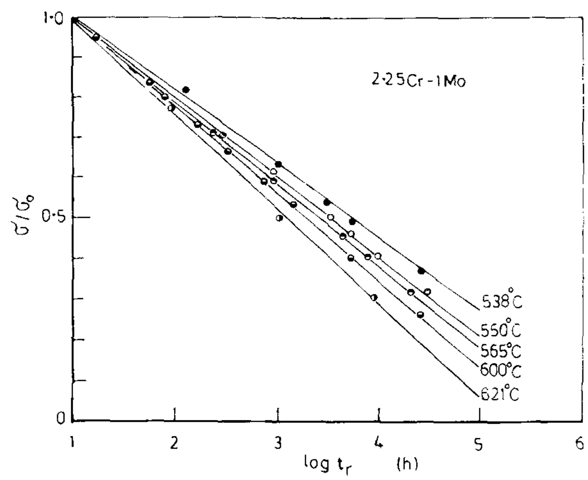

Fig. 4(c) Relationship between normalized stress and rupture time for 2.25Cr-1Mo.

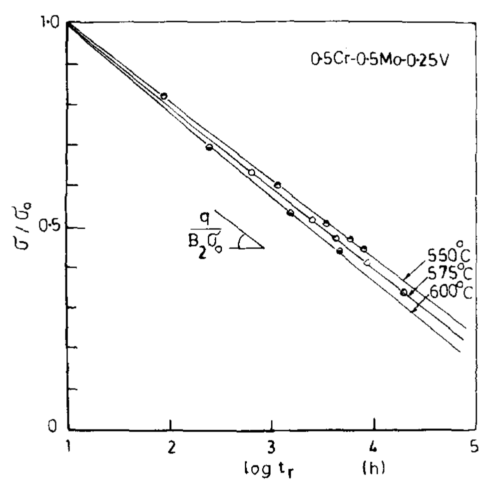

Fig. 4(b) Relationship between normalized stress and rupture time for 0.5Cr-0.5Mo-0.25V.

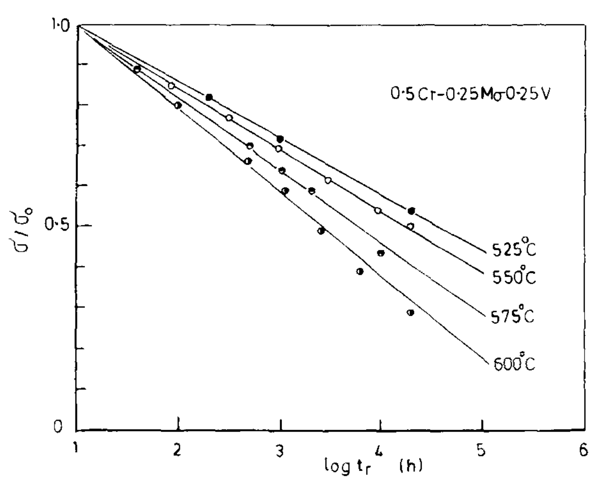

Fig. 4(d) Relationship between normalized stress and rupture time for 0.5Cr-0.25Mo-0.25V.

$$G = B_3/3$$

or with Eq 9:

$$G = B_2/q \tag{12}$$

Thus, the slope of the lines representing stress versus log rupture time is given as q/B_2. In case the Monkman-Grant relation is valid, then the value of q = 1, and hence the slope will be given by $(1/B_2)$.

4. Normalized Stress-Rupture Time Relation

It would be better to express the working stress σ in terms of short-time strength of the material, such as the ultimate strength or creep strength of short duration, say 10 hr. This will give us an idea about the factor of safety. The ASME Boiler and Pressure Vessel Code[8,9] makes use of the maximum stress theory in Section 1, Section IV, and Section VIII, Division I. In the creep-rupture range, design criteria are based on the stress to produce rupture in 100,000 hr and the stress to produce a specified creep rate in 100,000 hr, with a suitable factor of safety. Working stress values of one third of ultimate stress and one half of ultimate stress are recommended for particular structures. Thus, for designers, it would be easier to consider that the component has to work at a given fraction of the ultimate stress at the temperature of operation. Up to around 10 hr of creep-rupture time, the reduction in creep strength is not very much. Hence, it is taken in the present analysis that the working stress σ will be normalized by the short-time creep strength, σ_o, and

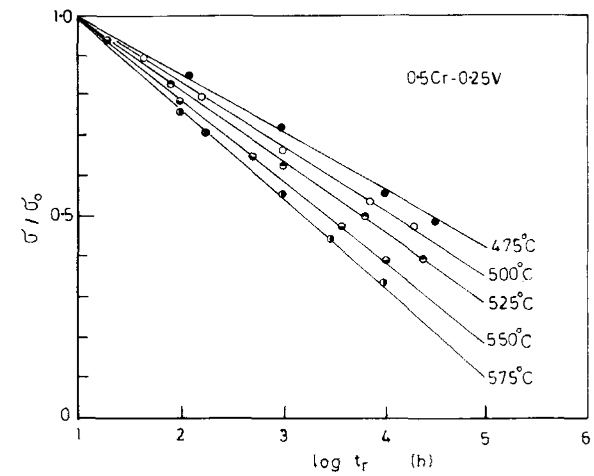

Fig. 4(e) Relationship between normalized stress and rupture time for 0.5Cr-0.25V.

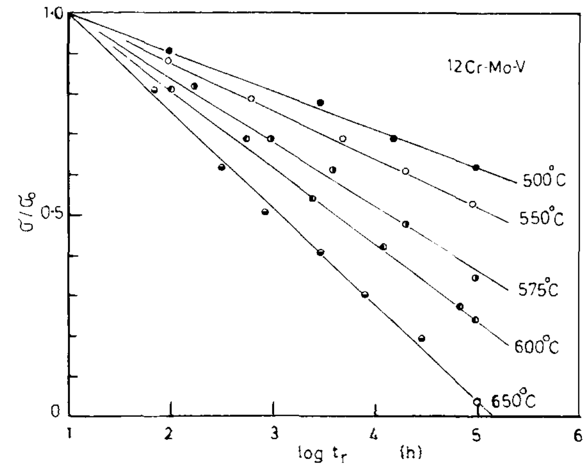

Fig. 4(f) Relationship between normalized stress and rupture time for 12Cr-Mo-V.

that the short-time creep strength referred to is the creep-rupture stress at a rupture time of 10 hr.

Thus, expressing the working stress as a fraction of the short-time creep-rupture stress, the creep stress-rupture time relation can be drawn with the stress axis normalized by the short-time creep strength, σ_o. This will result in all the (σ/σ_o) – log t_r lines starting from the same point, namely, $\sigma/\sigma_o = 1$ on the normalized stress axis at log $t_r = 1$. Typical relations between the normalized stress and the rupture life for the steels investigated are shown in Fig. 4(a) through (f).

Considering Fig. 3 and 4, the governing relations are

$$\log t_r + G \cdot \sigma = C_1$$

At $\sigma = \sigma_o$, we have $t_r = 10$. So:

$$1 + G \cdot \sigma_o = C_1$$

that is

$$\log t_r + G \cdot \sigma = G \cdot \sigma_o + 1 \qquad [13]$$

or

$$\frac{\sigma}{\sigma_o} = 1 - \frac{1}{G \cdot \sigma_o} \log t_r + \frac{1}{G \cdot \sigma_o} \qquad [14]$$

Time is given in hours and G in MPa^{-1}. The slope of the normalized stress versus log rupture time $(- \frac{1}{G} \cdot \sigma_o)$.

5. Rupture Time Parameter Based on â2

The data points of the normalized stress versus rupture time relation at different temperatures can be transferred and plotted on a master curve with the reference temperature T_r and the corresponding short-time creep strength σ_{or}. The parameter can be given, in general, by a relation of the type:[10,11]

$$P_R = [t_r]\, G_r \cdot \sigma_o r/G \cdot \sigma o \qquad [15]$$

where G_r and σ_{or} refer to the values corresponding to the reference temperature.

Because $G = B_2/q$ and $\beta_2 = \beta_{o2} \exp(\sigma B_2)$, we have:

$$\frac{G_r}{G} = \frac{B_{2r}}{B_2} \qquad [16]$$

With Eq 16 in Eq 15, we get:

$$P_R = [t_r] \log(\beta_{2or} / \beta_{o2r}) / \log\beta_{2o} / \beta_{o2}) \qquad [17]$$

where β_{2o} and β_{o2} refer to the value of the coefficient β_2 at the short-time creep stress and at stress levels equal to zero, respectively. The subscript r refers to the values at the reference temperature. The parameter can thus be obtained in terms of the short-time creep strength and the coefficient β_2. The values of the short-time creep strength at different temperatures for the materials analyzed and the values of other constants, such as G, $B_{2r}\, \sigma_{or} / B_o\, \sigma_o$, are given in Table 1.

In the present analysis where the origin on the time scale is taken as $t_r = 10$ hr, Eq 17 can be written in the following form to shift the origin. Equation 15 and 17 are thus:

$$P_R = 1 + \log(t_r / 10) G_r \cdot \sigma_{or} / G \cdot \sigma_o \qquad [18]$$

and

$$P_R = 1 + \log(t_r / 10) \log(\beta_{2or} / \beta_{o2r}) / \log(\beta_{2o} / \beta_{o2}) \qquad [19]$$

The relations between the normalized stress (σ/σ_o) and the parameter P_R for the materials analyzed in this study are shown in Fig. 5(a) through (f). The reference temperature, T_r, chosen

Table 1 Values of the Constants

Material	T, °C	σ_o, MPa	$1/G$, MPa	$\sigma_o G$	$B_{2r}\sigma_{or} / B_2\sigma_o$
1Cr-0.5Mo	530	380	65.0	5.85	0.830
	550(a)	310	63.75	4.86	1.000
	600	230	55.0	4.18	1.623
0.5Cr-0.5Mo-0.25V	550	350	67.5	5.185	0.998
	575(a)	265	51.2	5.175	1.000
	600	205	42.5	4.823	1.073
2.25Cr-1Mo	538	350	66.25	5.283	0.962
	550(a)	305	60.00	5.083	1.000
	565	270	55.00	4.91	1.035
	600	190	40.00	4.75	1.070
	621	165	36.5	4.52	1.124
0.5Cr-0.25Mo-0.25V	525	295	42	7.024	0.881
	550(a)	260	42	6.19	1.000
	575	230	42	5.476	1.13
	600	210	45	4.666	1.327
0.5Cr-0.25V	475	310	46	6.74	0.906
	500(a)	275	45	6.11	1.000
	525	240	45	5.33	1.146
	550	210	44	4.77	1.281
	575	180	41	4.39	1.392
12Cr-Mo-V	500	410	40	10.25	0.507
	550	320	40	8.00	0.65
	575	270	44	6.14	0.847
	600(a)	230	44	5.20	1.000
	650	155	37.5	4.10	1.268

(a) Corresponds to the reference temperature to the base line of which the rupture times of other temperatures are transferred.

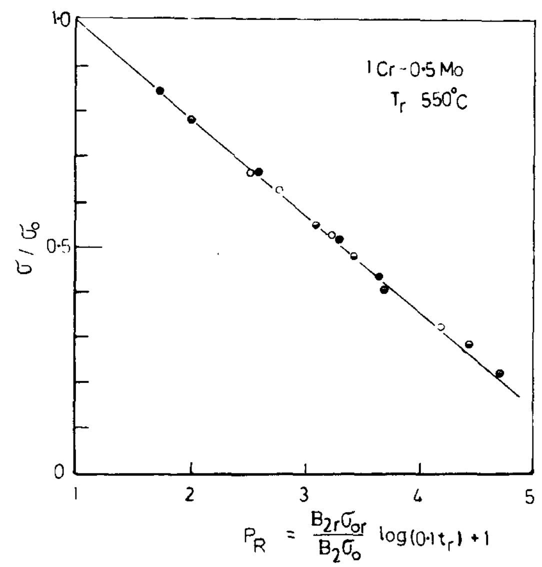

Fig. 5(a) Relationship between normalized stress and the parameter for 1Cr-0.5Mo. Reference temperatures are indicated in the figure. The points shown are mean values.

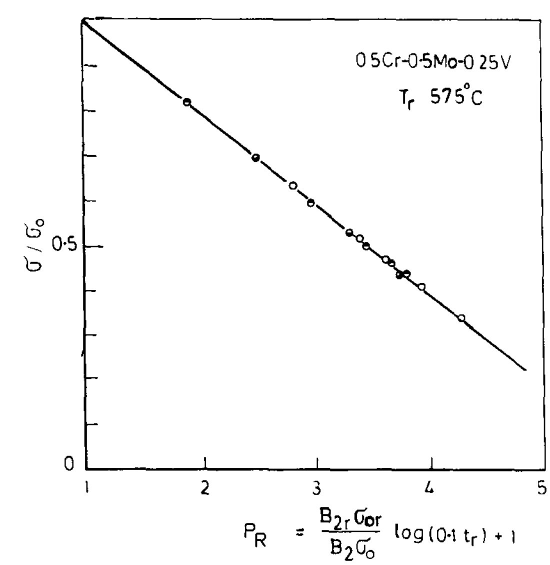

Fig. 5(b) Relationship between normalized stress and the parameter for 0.5Cr-0.5Mo-0.25V. Reference temperatures are indicated in the figure. The points shown are mean values.

to be such that rupture lines are obtained below and above that temperature, is indicated by each master curve.

6. Discussion

The parameter suggested and given in the form

$$P_R = [t_r]\, B_{2r}\sigma_{or} / B_2\sigma_o [t_r]^{B}{}_{2r}\,\sigma_{or}/B_2\,\sigma_o \quad [20]$$

essentially depends on the slope B_2 of the relation

$$\beta_2 = \beta_{o2} \exp{(B_2\,\sigma)} \quad [21]$$

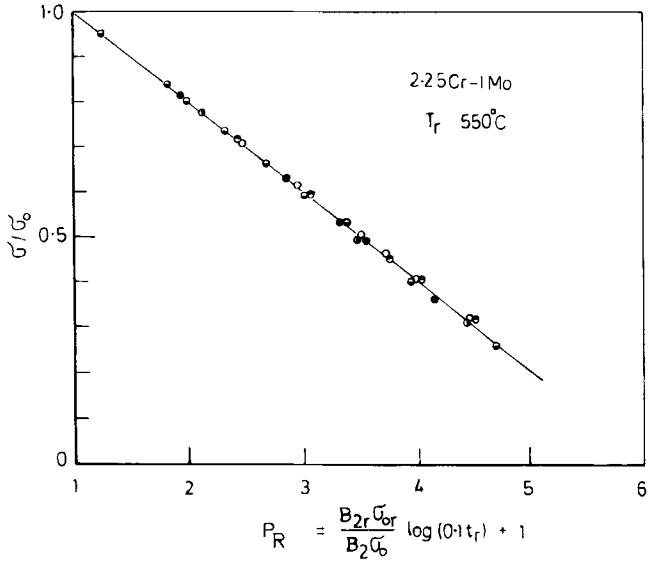

Fig. 5(c) Relationship between normalized stress and the parameter for 2.25Cr-1Mo. Reference temperatures are indicated in the figure. The points shown are mean values.

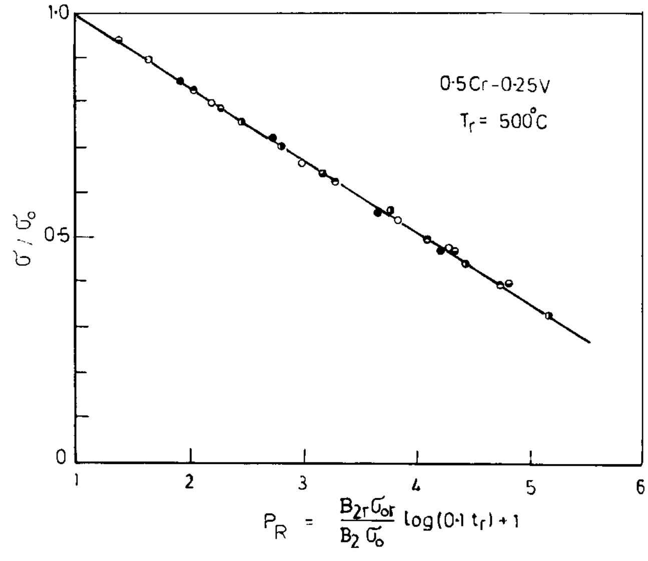

Fig. 5(e) Relationship between normalized stress and the parameter for 0.5Cr-0.25V. Reference temperatures are indicated in the figure. The points shown are mean values.

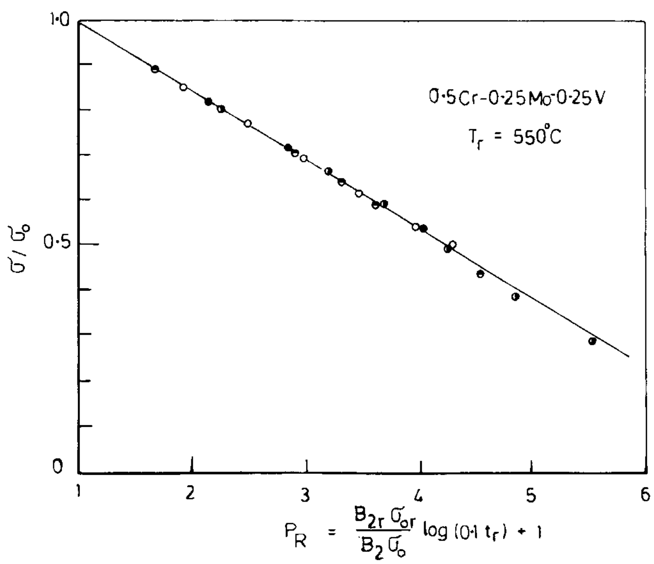

Fig. 5(d) Relationship between normalized stress and the parameter for 0.5Cr-0.25Mo-0.25V. Reference temperatures are indicated in the figure. The points shown are mean values.

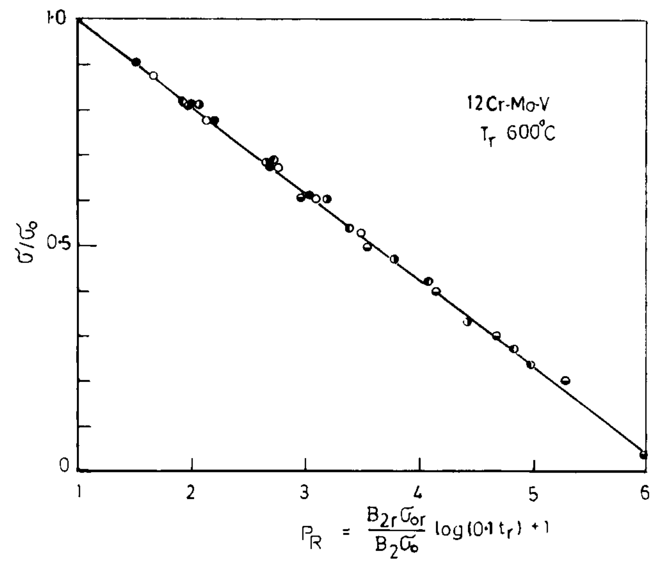

Fig. 5(f) Relationship between normalized stress and the parameter for 12Cr-Mo-V. Reference temperatures are indicated in the figure. The points shown are mean values.

Thus, the temperature dependence of the parameter is through the variation of B_2 with temperature. The short-time creep strength, σ_o, is also dependent on temperature. Both these quantities, in general, will increase with increasing temperature. If both these quantities can be expressed in terms of temperature, then the exponent in Eq 20 can be given in terms of temperature.

It has been pointed out that, in some materials, there is no steady-state creep and the minimum creep rate (or β_2 in the present analysis) will be very difficult to determine. In such cases, the above parameter will also be valid because the ratio

$$\frac{B_{2r}}{B_2}=\frac{G_r}{G}=\frac{B_{3r}}{B_3}$$

can be easily determined if only the tertiary stage is present in the creep deformation. The main advantage in the above parametric approach is that the steady-state values of creep deformation and its associated constants need not be known for evaluating the long-time rupture life.

A detailed discussion of different extrapolation methods is given in Ref 12. It can be noted that, in almost all the parametric relations for creep life prediction, the time axis alone is compensated by temperature. Thus, a temperature-modified time function is used in all the cases. The only exception is the oblique translation method,[13] which is a graphical method. In the present analysis, it can be seen that both the stress axis and the time axis are compensated by temperature. The temperature effect is introduced through the term σ_o in the stress axis by the normalized stress term (σ/σ_o). In the time axis, the temperature effect is introduced through the term B_2. Thus, in the parameter introduced in the present investigation, both the stress and the time axes are compensated by temperature.

The present study indicates that the approach gives a good prediction up to 10^5 hr or up to a working stress level of one fourth of the ultimate strength at the operating temperature. Hence, this approach can be used effectively for design purposes. There will be scatter in the data. However, if the data points are contained by two upper and lower bound lines in the σ/σ_u versus log t_r relation, the same will get reflected in the master curve as well. Hence, the same scatter band can be used for the life prediction.

7. Conclusions

From the analysis carried out in the present study on low-alloy steels, the following conclusions are developed. The coefficients β_i in the β-envelope method follow an exponential function with the applied stress in the form:

$$\beta_i = \beta_{oi} \exp (B_i \sigma)$$

where i takes the value of 1, 2, or 3 depending on the first, second, or the third stage of creep.

The stress-logarithmic rupture time relation yields straight line relations suggesting equations of the type

$$t_r = \text{constant} \cdot \exp(-G \cdot \sigma)$$

to be valid. The constant G is related to the constants in the β_i relations such that:

$$G = B_3 / 3$$
$$= B_2 / q$$

where q is the exponent in the Monkman-Grant relation.

Based on the above relations, a parameter P_R in the form

$$P_R = [t_r]^{B_{2r}\sigma_{or} / B_2\sigma_o}$$

is suggested. This parameter is plotted against the normalized stress (σ/σ_o), and the experimental data points obtained on low-alloy steels have been found to yield a very good fit with the parameter suggested.

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