

The Relationship Between Minimum Creep Rate and Rupture Time in Cr-Mo Steels

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The Monkman-Grant equation is widely used to relate the minimum creep rate, $\dot{\varepsilon}_{min}$, and the rupture time, t_r, in creep. However, for materials that exhibit large tertiary creep and limited secondary creep, the above equation has not been found to be valid, and a correction in terms of the rupture strain ε_r and the strain at the onset of tertiary stage, ε_{23}, has to be incorporated. The relation is given in the form:

$$\dot{\varepsilon}_{min}\, t_r = 3\sqrt{\varepsilon_{23}^2\, \varepsilon_r}$$

1 Introduction

CREEP-RUPTURE time is an important consideration in the design of many high-temperature components. In many cases, the useful life of the component in service may range from 30,000 to 40,000 hr, and it is costly to carry out creep tests lasting for several thousand hours. Normally, parametric methods are used to predict the long-term creep behavior from short-time tests conducted on the material. One such relation is the Monkman-Grant relation,[1] which is given in the form:

$$\dot{\varepsilon}_{min}\, t_r = C_{MG} \qquad [1]$$

where $\dot{\varepsilon}_{min}$ is the minimum creep rate, t_r is rupture time, and C_{MG} is the Monkman-Grant constant. This relation has been found to be valid for materials that exhibit large secondary stage creep and small tertiary creep. However, there are a number of high-temperature alloys that exhibit a very small secondary stage and a large tertiary stage. In such cases, the above relation is not valid. Dobes and Milicka[2] have introduced a modification to the above equation by incorporating the creep-rupture strain, ε_r, and giving the relation as:

$$\frac{\dot{\varepsilon}_{min}\, t_r}{\varepsilon_r} = C_{MMG} \qquad [2]$$

where C_{MMG} is the modified Monkman-Grant constant.

The creep-rupture strain, ε_r, in many alloy steels and high-temperature materials is dependent on the stress and the exposure time. Structural changes due to high-temperature exposure of the material decrease the rupture strain. Furthermore, when there is large tertiary stage creep, the transition strain, ε_{23}, from Stage 2 to Stage 3 also influences the rupture time.[3] In the following, the above factors are discussed with reference to a Cr-Mo steel that is widely used in power plant applications.

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2 Creep Curve Description

2.1 β-*Envelope Method*

There are a number of empirical relations proposed to describe the creep curves, and one such method is the β-envelope method, in which the creep curve is divided into three segments on the log creep-strain and log time plot, as shown schematically in Fig. 1. The enveloping straight lines are described by equations such as the following:[3,4]

$$\begin{aligned} \varepsilon_1 &= \beta_1\, t^{1/3} \\ \varepsilon_2 &= \beta_2\, t \\ \varepsilon_3 &= \beta_3\, t^3 \end{aligned} \qquad [3]$$

where t is the time, and β_i are the coefficients. The subscripts 1, 2, or 3 denote the first, second, or third stage in creep, respectively. Because each equation describes the data points in each region separately, the coefficients β_i are not influenced by the data points in other regions.

Typical relations between log creep-strain and log time for a 1Cr-0.5Mo steel at 530 and 550 °C are shown in Fig. 2. Only limited data are shown for the sake of clarity. It can be seen that the creep curves can be described by the relations given in Eq 3. At the transition from Stage 1 to Stage 2, note:

$$\beta_1\, t_{12}^{1/3} = \varepsilon_{12} \qquad [4a]$$

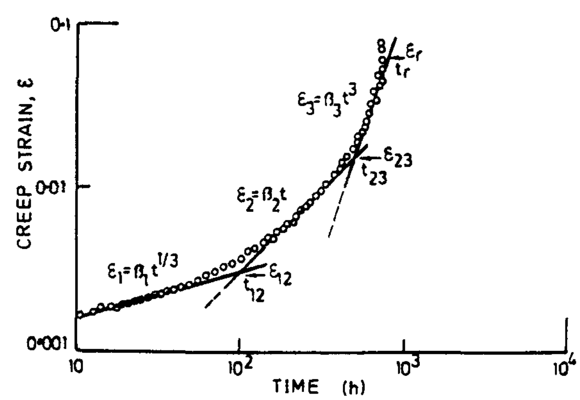

Fig. 1 Schematic representation of creep strain versus time on a log-log plot and the three enveloping straight lines. The transition strains and times at the end of first and second stages are also indicated.

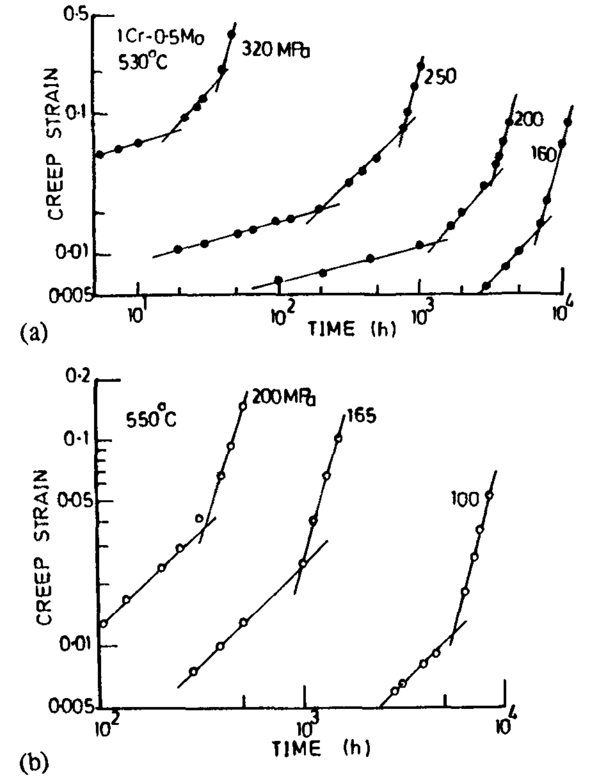

Fig. 2 Relation between creep strain and time for 1Cr-0.5Mo steel at 530 and 550 °C. Note that the creep strain at the end of the second stage, ε_{23}, decreases with decreasing minimum creep rate[3].

and

$$\beta_2 t_{12} = \varepsilon_{12} \tag{4b}$$

where the subscript "12" refers to the point at the intersection of the two lines. Thus, the time, t_{12} corresponds to the end of the first stage and the onset of the second stage, as:

$$t_{12} = \sqrt[3/2]{\beta_1/\beta_2} \tag{5}$$

Similarly, at the transition from Stage 2 to 3:

$$\beta_2 t_{23} \tag{6a}$$

and

$$\beta_3 t_{23}^3 \tag{6b}$$

which lead to

$$t_{23} = \sqrt{\beta_2/\beta_3} \tag{7}$$

Thus, the boundary times of the first and the second stage creep, namely t_{12} and t_{23}, are defined in terms of the coefficients β_1, β_2, and β_3.

2.2 *Relationship Between Rupture Time and Minimum Creep Rate*

Taking the creep-rupture strain and rupture time as ε_r and t_r yields:

$$\beta_3 t_r^3 = \varepsilon_r \tag{8}$$

Noting that the coefficient β_2 represents the minimum creep rate, $\dot{\varepsilon}_{min}$, Eq 6a and 7 yield:

$$\frac{\beta_2^3}{\beta_3} = \varepsilon_{23}^2 = \frac{\dot{\varepsilon}_{min}^3}{\beta_3} \tag{9a}$$

and substituting this into Eq 8 yields:

$$\dot{\varepsilon}_{min} t_r = \sqrt[3]{\varepsilon_{23}^2 \varepsilon_r} \tag{9b}$$

where ε_{23} is the creep-strain at the onset of tertiary stage. Thus, the product $\dot{\varepsilon}_{min} \cdot t_r$ is dependent on ε_{23} and ε_r. If ε_{23} and ε_r are independent of stress or strain rate, $\dot{\varepsilon}_{min}$, then the Monkman-Grant relation is obtained. However, in many cases investigated,[3] both ε_{23} and ε_r decrease with decreasing creep-strain rate, $\dot{\varepsilon}_{min}$ or the applied stress, σ. In such cases, with the above relations following a simple power function, one obtains:

$$\left(\dot{\varepsilon}_{min}\right)^p \cdot t = \text{constant} \tag{10}$$

where the exponent "p" is less than one.

3 Data Analysis

In a recent paper, Phaniraj *et al.*[5] have experimentally shown that for type 304 stainless steel the time at the onset of steady-state creep, namely t_{12}, and the limiting transient creep-strain, namely ε_{12}, are related to the steady-state creep rate, namely $\dot{\varepsilon}_{min}$, in the form:

$$\frac{\dot{\varepsilon}_{min} t_{12}}{\varepsilon_{12}} = \text{constant} \tag{11}$$

Their experimental results are shown in Fig. 3. It can be seen from Eq 4b that the coefficient β_2 represents the minimum creep rate in the second stage, and hence Eq 4b and 11 are similar. Thus, Eq 4b, which is the basis for the β-envelope method developed in Ref 3, stands experimentally verified.

The relations between the applied stress, σ, and the coefficients β_i for the 1Cr-0.5Mo steel investigated are shown in Fig. 4 on a semi-log plot. The time is measured in seconds. Taking the coefficient β_2 to represent the minimum creep rate, $\dot{\varepsilon}_{min}$, the relation between the minimum creep rate and the stress is shown in Fig. 5. It can be seen that the slope of the line, which is given by:

$$\frac{\delta \log \dot{\varepsilon}_{min}}{\delta \log \sigma} = n = A\,\sigma \tag{12a}$$

where A is a constant and n is the stress exponent in the Norton's creep rate equation:

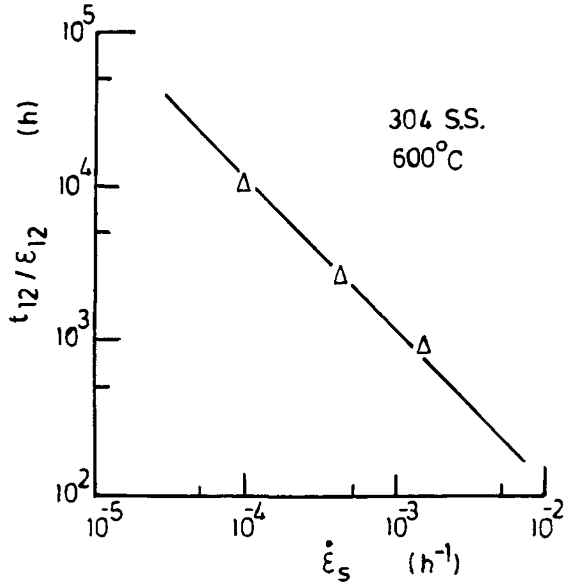

Fig. 3 Relation between the creep strain at the end of the primary stage, ε_{12}, and the product $\dot{\varepsilon}_{min} \cdot t_{12}$, according to Eq 4. The data points are from Ref 5. The material is type 304 stainless steel.

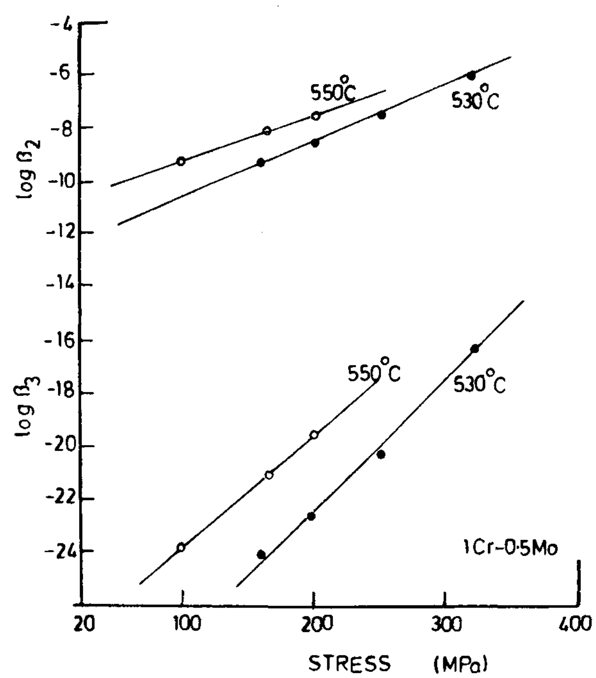

Fig. 4 Relation between the applied stress and the coefficients β_2 and β_3.

$$\dot{\varepsilon}_{min} = K\sigma^n \qquad [12b]$$

The exponent "n" decreases with decreasing stress level. This clearly demonstrates that the stress exponent "n" in the creep rate equation is a function of the stress for the Cr-Mo steel in the temperature range reported.

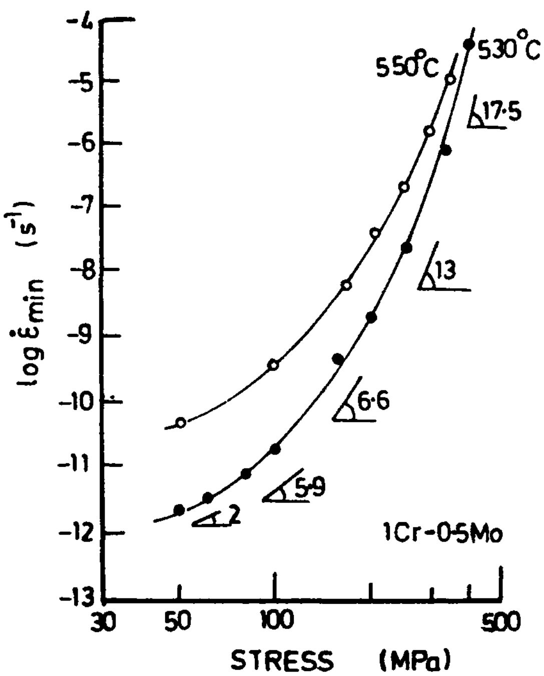

Fig. 5 Variation of the minimum creep rate with applied stress on the semi-log plot. Note the slope that gives the stress exponent "n" in Norton's creep law is dependent on the applied stress.

The relationship between the minimum creep rate and the rupture time is shown in Fig. 6. Data points of limited tests carried out at 600 and 625 °C are also shown in the figure. The relation on the log-log plot is obtained as a straight line according to the equation:

$$\left(\dot{\varepsilon}_{min}\right)^{0.77} t_r = \text{constant} \qquad [13]$$

It can be seen from Fig. 2 that the creep strain at the end of the secondary stage, ε_{23}, and the creep-rupture strain, ε_r, decrease with decreasing minimum creep rate, $\dot{\varepsilon}_{min}$. The relation between the minimum creep rate and the creep strain at the end of the secondary stage and the creep-rupture strain is shown in Fig. 7 on a log-log plot. The relation yields straight lines according to the following equations, for example, at 530 °C:

$$\varepsilon_{23} \propto \left(\dot{\varepsilon}_{min}\right)^{0.34}$$

and

$$\varepsilon_r \propto \left(\dot{\varepsilon}_{min}\right)^{0.08} \qquad [14]$$

Using Eq 14 in Eq 9 yields:

$$\dot{\varepsilon}_{min}\, t_r \propto \left(\dot{\varepsilon}_{min}\right)^{0.25}$$

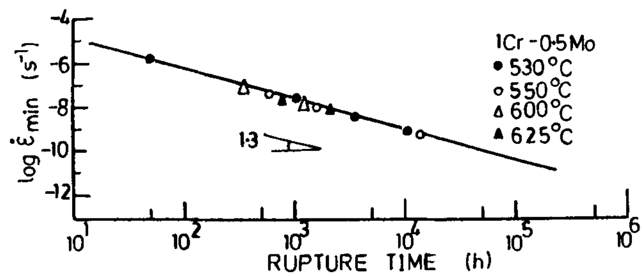

Fig. 6 Relation between minimum creep rate and rupture time for 1Cr-0.5Mo steel.

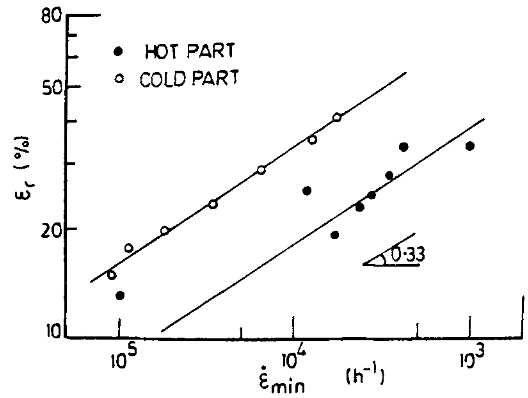

Fig. 8 Relation between minimum creep rate and creep-rupture strain of hot and cold parts of a power plant component. Material was 1Cr-1Mo-0.25V. Raw data points are from Ref 6.

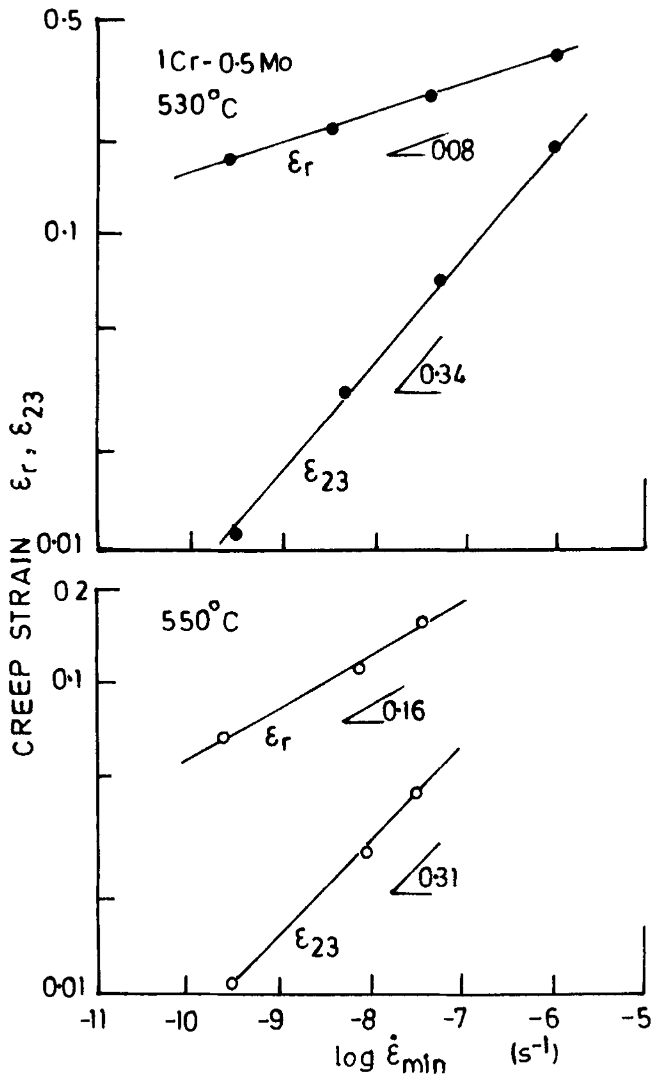

Fig. 7 Relation between the creep strain at the end of the secondary stage, ε_{23}, and the rupture strain, ε_r, and minimum creep rate, $\dot{\varepsilon}_{min}$, for 1Cr-0.5Mo steel.

or

$$\dot{\varepsilon}_{min}^{0.75}\, t_r = \text{constant} \quad [15]$$

The experimental results show that the value of the exponent for Cr-Mo steel is 0.77. Thus, Eq 9b, which is based on the β-envelope method, appears to be valid for the 1Cr-0.5Mo steel investigated in the present study.

4 General Discussion

Molinie *et al.*[6] investigated the creep-rupture properties of service-exposed 1Cr-1Mo-0.25V steel taken from the cold and hot parts of a high-temperature component exposed to 530 °C for about 1.5×10^5 hr. It has been shown that the creep-rupture strain, ε_r, decreases with decreasing $\dot{\varepsilon}_{min}$. The results on the cold part material exhibit a systematic trend, whereas those for the hot part exhibit some scatter. The results are replotted and shown in Fig. 8 on a log-log plot, which yield a straight line relation according to:

$$\varepsilon_r = A2\left(\dot{\varepsilon}_{min}\right)^{0.33} \quad [16]$$

where $A2$ is a constant. The relationship between $\dot{\varepsilon}_{min}$ and t_r was obtained experimentally[6] as:

$$\left(\dot{\varepsilon}_{min}\right)^{0.85} t_r = \text{constant} \quad [17]$$

Now consider the Dobes-Milicka equation given in the form:

$$\frac{\dot{\varepsilon}_{min}\, t_r}{\varepsilon_r} = \text{constant} \quad [18]$$

Substituting for ε_r from Eq 16 yields:

$$\left(\dot{\varepsilon}_{min}\right)^{0.67} t_r = \text{constant} \quad [19]$$

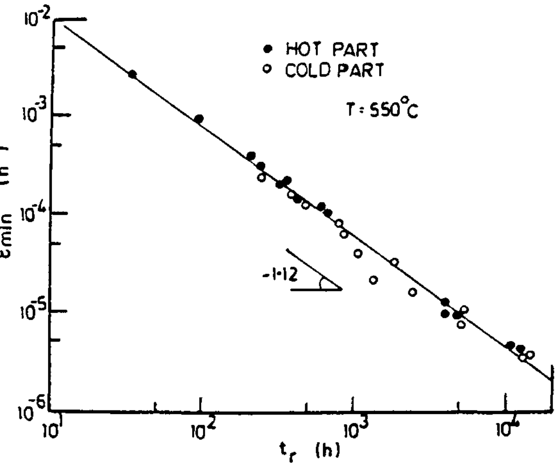

Fig. 9 Relation between the minimum creep rate and the rupture time for the power plant component material. Data are from Ref 6.

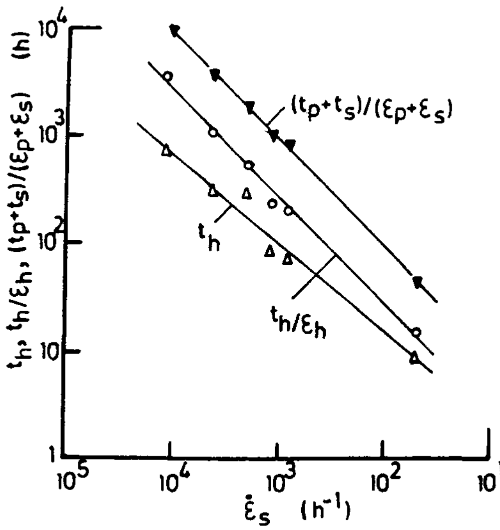

Fig. 10 Relation between the minimum creep rate and the rupture time, t_h, and the normalized times, t_h/ε_h and $(t_p + t_s)/(\varepsilon_p + \varepsilon_s)$. The data points are from Ref 7. Notations are as used in the reference. The material is a 2.25Cr-1Mo weld.

The exponent 0.67 is different from the experimentally obtained value, namely, 0.85. Now consider the relation obtained based on the β-envelope method, namely:

$$\frac{\dot{\varepsilon}_{min}\, t_r}{\sqrt[3]{\varepsilon_{23}^2\, \varepsilon_r}} = \text{constant} \quad [20]$$

The variation of the creep strain, ε_{23}, either with stress or with minimum creep rate has not been reported by Molinie *et al.* Hence, taking ε_{23} to be not very strongly dependent on minimum creep rate, the above relation yields:

$$\frac{\dot{\varepsilon}_{min}\, t_r}{\sqrt[3]{\varepsilon_r}} = \text{constant} \quad [21]$$

Using Eq 16 in the above relation yields:

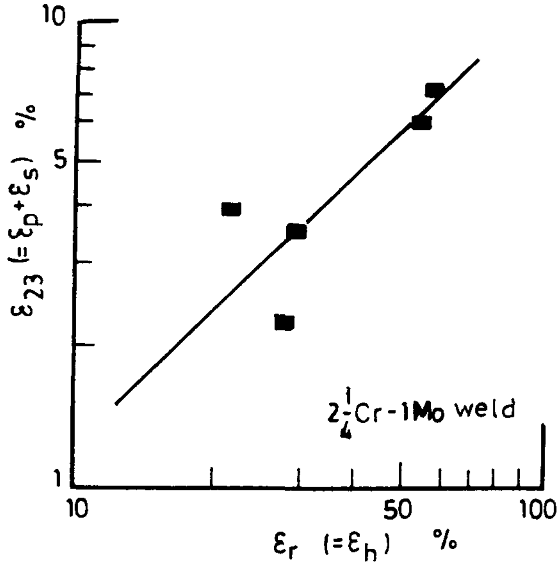

Fig. 11 Relation between the creep strain at the end of the secondary stage, ε_{23}, and the creep-rupture strain, ε_r.

$$\left(\dot{\varepsilon}_{min}\right)^{0.89} t_r = \text{constant} \quad [22]$$

This relation is shown in Fig. 9 on a log-log plot with the data points of Molinie *et al.* The results are well described by the above relation. The difference between the value of the exponent reported by Molinie *et al.* (0.85) and the present value (0.89) may be due to the dependence of the strain ε_{23} on $\dot{\varepsilon}_{min}$. Because this relationship is not known, it was not taken into consideration in the present discussion.

Now consider the results of the service-exposed 2.25Cr-1Mo weld material reported by Liaw *et al.*[7] Typical relations between the minimum creep rate and the rupture time t_r (the variable used in Fig. 10 is t_h) and the normalized rupture time are shown in Fig. 10, reproduced from Ref 6. The relationships of the lines shown are (from bottom to top)

$$t_r\left(\dot{\varepsilon}_{min}\right)^{0.825} = \text{constant} \quad [23]$$

$$\frac{t_r\left(\dot{\varepsilon}_{min}\right)^{0.983}}{\varepsilon_r} = \text{constant} \quad [24]$$

$$\frac{t_{23}\left(\dot{\varepsilon}_{min}\right)^{1.004}}{\varepsilon_{23}} = \text{constant} \quad [25]$$

The terminologies used in Fig. 10 are those used in Ref 7.

Thus, $t_r = t_h$, $\varepsilon_r = \varepsilon_h$, $t_{23} = t_p + t_s$, and $\varepsilon_{23} = \varepsilon_p + \varepsilon_s$. Equation 25 clearly shows that the relation of the type

$$t_{23}\, \beta_2 = \varepsilon_{23}$$

assumed in the β-envelope method (Eq 6a) is valid.

Equation 24 is the modified Monkman-Grant relation (Eq 2) in the form:

$$\frac{t_r \dot{\varepsilon}_{min}}{\varepsilon_r} = \text{constant}$$

Now consider the relation obtained by the β-envelope method.

The relation (Eq 9b) is given as:

$$\frac{t_r \dot{\varepsilon}_{min}}{\sqrt[3]{\varepsilon_{23}^2}\,\sqrt[3]{\varepsilon_r}} = \text{constant}$$

The reported data of the variation of the creep strain, ε_{23}, with the rupture strain, ε_r, are plotted on the log-log scale and are shown in Fig. 11. A straight line relation with a slope equal to unity can be best fitted with the data. Thus

$$\log \varepsilon_{23} = \log \varepsilon_r + \log \text{constant} \qquad [26]$$

The strain, ε_{23}, decreases with minimum creep rate much in the same way as does the rupture strain, ε_r, for the weld material investigated by Liaw *et al.* Thus

$$\frac{\dot{\varepsilon}_{min} t_r}{\sqrt[3]{\varepsilon_{23}^2 \varepsilon_r}} = \frac{\dot{\varepsilon}_{min} t_r}{\varepsilon_r} = \text{constant} \qquad [27]$$

This is what has been obtained in Eq 24. Thus, the general relationship between the minimum creep rate and the rupture time given in Eq 9b is able to adequately describe the experimental findings of Molinie *et al.*[6] and Liaw *et al.*[7] for Cr-Mo steels and their welds.

5 Concluding Remarks

From the investigation carried out on the creep-rupture characteristics of Cr-Mo steels, the following conclusions exist. The creep strain-time relation can be best described by three segments on the log-log plot, each given by a power law equation of time. This approach defines the transition times and the transition creep strains from Stage 1 to Stage 2 and also from Stage 2 to Stage 3.

The minimum creep rate, $\dot{\varepsilon}_{min}$, and the rupture time, t_r, are related by:

$$\dot{\varepsilon}_{min} t_r = \sqrt[3]{\varepsilon_{23}^2 \varepsilon_r}$$

where ε_{23} and ε_r are the creep strains at the end of Stage 2 and creep-rupture strain, respectively. The Monkman-Grant relation and the Dobes-Milicka relation are particular forms of the above general equation.

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