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The master curve and the constitutive equation for creep deformation and fracture for Cr–Mo–V steel throughout smooth, notched and precracked specimens

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It has been shown experimentally that the master curve for creep deformation versus the ratio of time to fracture time, can be obtained for smooth, notched and precracked specimens of Cr–Mo–V steel, a high-temperature ductile material. A simple unified constitutive equation, i.e. a master curve equation, has been proposed. It is suggested that there is some correlation between the creep deformation fracture curve and the creep damage size master curve. Although the range of the applicability of methodology might be rather limited, the development of this concept is needed for improved long-term creep lives and for other creep ductile materials.

1. Introduction

The θ methodology has been proposed by Wilshire as a new model-based approach to creep and creep fracture. This methodology enables a creep deformation curve to be obtained as a function of stress and temperature and to predict creep fracture (rupture) life [1, 2]. Among the major advantages of the θ methodology, the capability of prediction of long-term creep lives and the possibility of relating the micro-mechanisms, are salient. Thus several attempts have been made to modify the θ methodology [3, 4].

On the other hand, from the standpoint of micro- and macro-mechanisms and also, for practical use, it is desirable to have a methodology for not only smooth specimens (without notch or crack), but also notched and cracked specimens, by correlating the crack initiation and growth behaviour to the creep fracture, and for the methodology to be more simpler.

In the present paper, a simple unified estimation methodology is proposed for the creep fracture life of not only smooth, but also notched and cracked specimens, noting the similarity law of the creep deformation curve versus time. Although the range of applicability of this methodology might be rather limited, the development of this unified concept may be needed for improved long-term creep lives. It is also suggested that there is the correlation between the creep deformation and fracture master curve and the creep damage size master curve.

2. Experimental procedure

2.1. Material and specimen

A test block from turbine-rotor 1Cr–Mo–V steel, made by Nippon Steel Works, was used. Material samples were taken from the test block at the end of the rotor. The chemical composition of the material is shown in Table I, and the mechanical properties are given in Table II.

For the smooth specimen, the round bar type was used with diameter of 10 mm, and gauge length of 50 mm. For notched and precracked specimens, double-ended V-notch (DEN) type and CT specimens were used as shown in Figs 1 and 2, respectively.

2.2. Test methods and testing conditions

For the smooth and notched specimens, a servo-hydraulic creep testing machine and a lever-type creep testing machine were used. For the notched specimen, the tests were carried out in a vacuum of 1.33 MPa. Notch-opening displacements were measured continuously during the tests without stopping, by use of a high-temperature microscope through an observation window with × 100 magnification. The specimen temperature was continuously monitored with a thermo-couple spot-welded near the notch in the specimen surface. The temperatures were kept constant to within ± 1 °C, whereas for the smooth specimen they were kept constant to within ± 2 °C.

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TABLE I Chemical composition (wt %)

C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Sn	As
0.27	0.07	0.69	0.003	0.0021	1.19	1.13	0.38	0.24	< 0.005	0.008	0.005

TABLE II Mechanical properties

Temp. (%)	0.2% yield stress (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction of area (%)
Room temp.	655.9	804.6	22.0	63.9
538	453.7	512.1	19.5	83.1
594	371.9	430.7	24.8	87.7

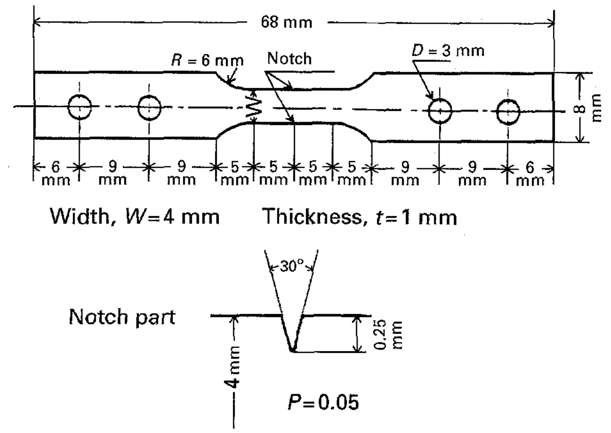

Figure 1 Shape and dimensions of the DEN specimen

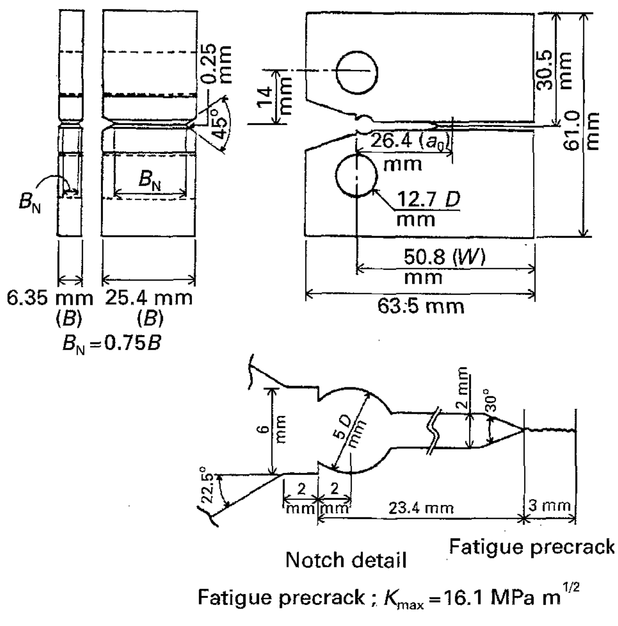

Figure 2 Shape and dimensions of the CT specimen

For the CT specimen, the tests were performed in atmospheric conditions. Load-line displacements were measured with a precision of less than 0.1 mm. The specimen was heated with an electrical resistance heater furnace. During the test, the temperature of the specimen was kept constant to within $\pm 2\,°C$.

The testing conditions for smooth, notched and pre-cracked specimens are shown in each figure.

2.3. Representation of creep deformation

For the smooth specimen, creep deformation was represented by $\varepsilon - \varepsilon_0$, where ε is the creep strain, and ε_0 the instantaneous strain at the instant of load application.

For the notched (DEN) specimen, creep deformation was represented by the relative notch-opening displacement, $\Delta\phi/\phi_0$ [5], where ϕ and ϕ_s are the notch-opening displacement at time t and the instantaneous one at the instant of load application, respectively. ϕ_0 is the initial notch-opening displacement, and

$$\Delta\phi = \phi - \phi_s - \phi_0 \tag{1}$$

For the pre-cracked (CT) specimen, creep deformation was represented by the relative load-line displacement, $\Delta\delta/\delta_0$, where δ and δ_s are the load-line displacement at time t and the instantaneous one at the instant of load application, respectively. δ_0 is the initial distance between upper and lower load pin hole of the CT specimen, and

$$\Delta\delta = \delta - \delta_s - \delta_0 \tag{2}$$

That is, in all cases mentioned above, the instantaneous deformation at the instant of load application was subtracted from the total creep deformation and the value was taken as the creep deformation.

3. Results

3.1. The representation method by non-dimensional time, t/t_f

Figs 3 and 4 show the creep deformation versus the time of applied stress, t, as the usual plot, for example, for notched and CT specimens, respectively. Instead, here the data are plotted by the non-dimensional time of stress application, t/t_f, where t is the time of stress application and t_f is the creep fracture time (life) for each specimen. In Figs 5–7, the creep deformation, $\varepsilon - \varepsilon_0$, $\Delta\phi/\phi_0$ and $\Delta\delta/\delta_0$, are plotted against the non-dimensional time of stress application. t/t_f, for smooth, notched and pre-cracked specimens, respectively.

All of the results, as shown in Figs 5–7, show that creep curves are independent of stress and temperature from smooth, notched and precracked specimens, respectively. That is, it was shown that the creep deformation and fracture master curve can be obtained for smooth, notched to precracked specimens, by the representation method proposed here. Furthermore, this characteristic shows the existence of a similarity law of creep deformation against time of stress application.

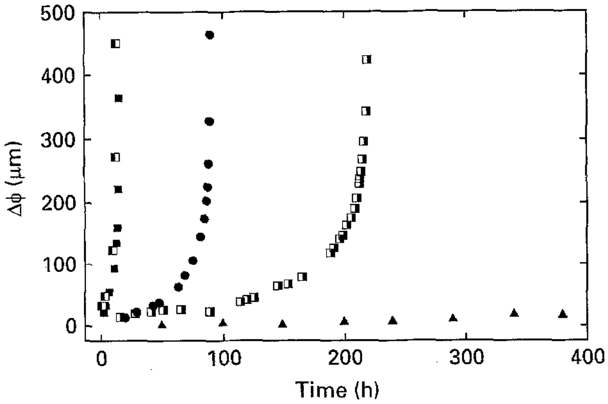

Figure 3 Typical examples of the creep deformation curve for DEN specimens. (▲) 600 °C, 194 MPa; (◨) 625 °C, 176 MPa; (●) 625 °C, 194 MPa; (◧) 625 °C, 221 MPa; (■) 650 °C, 194 MPa.

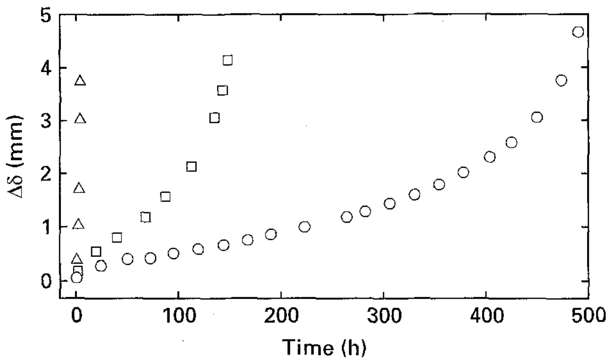

Figure 4 Typical examples of the creep deformation curve for CT specimens. (○) 538 °C, 4.9 kN, 6.35mm thick; (□) 560°C, 19.6 kN, 25.4 mm thick; (△) 594 °C, 5.39 kN, 6.35 mm thick.

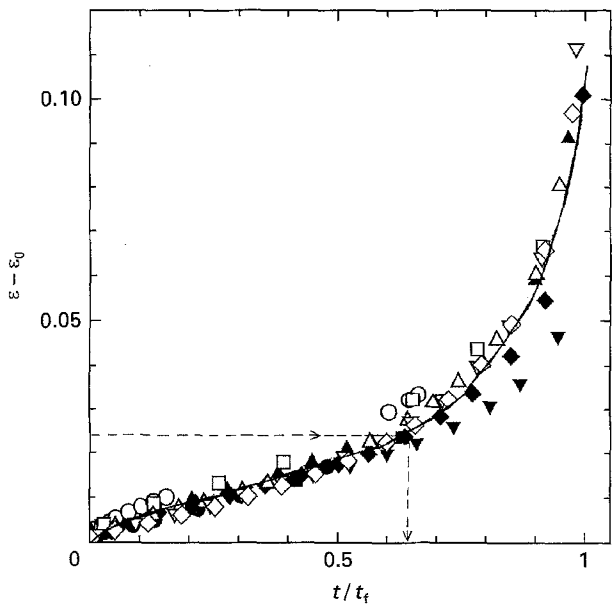

Figure 5 The experimental data on creep deformation, $\varepsilon - \varepsilon_0$, against the ratio, t/t_f, of stress applied time, t, to creep fracture life, t_f for smooth specimens. (——) The curve calculated from Equation 14. 538 °C: (●) 392 MPa, (■) 343 MPa (▲) 304 MPa, (▼) 275 MPa, (◆) 235 MPa. 594 °C: (○) 275 MPa, (□) 235 MPa, (△) 196 MPa, (▽) 157 MPa, (◇) 118 MPa.

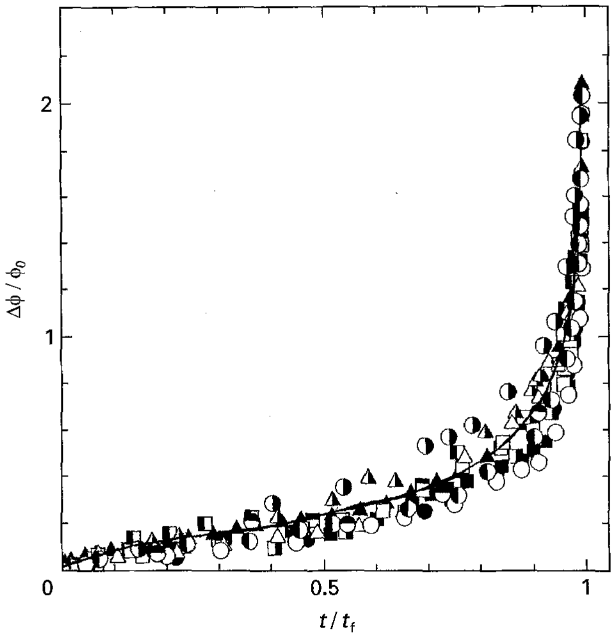

Figure 6 The experimental data on creep deformation, $\Delta\phi/\phi_0$, against the ratio t/t_0 of stress applied time, t, to creep fracture life, t_f, for notched (DEN) specimens. (——) The curve calculated from Equation 15. 538 °C: (△) 353 MPa. 560 °C: (◭) 274 MPa, (◑, ◐) 314 MPa, (○, ◒) 353 MPa. 580 °C: (□) 353 MPa. 600 °C: (◭) 194 MPa. 625 °C: (◨) 176 MPa, (●) 194 MPa. (◧) 221 MPa. 650 °C: (□, ⬒) 194 MPa.

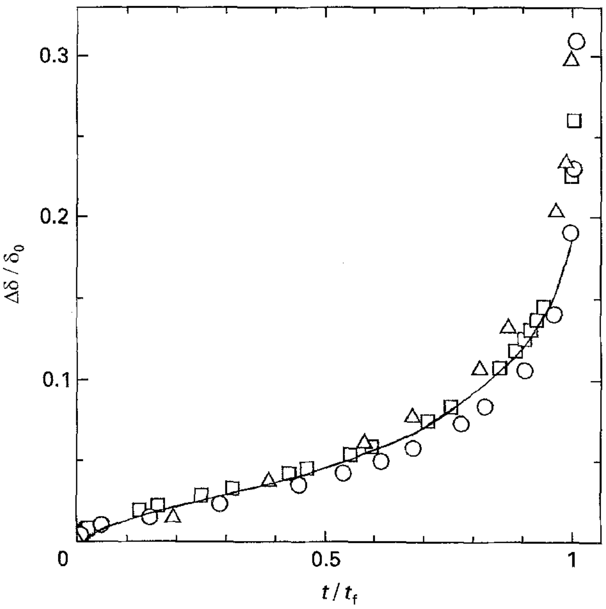

Figure 7 The experimental data on creep deformation, $\Delta\delta/\delta_0$, against the ratio t/t_f of stress applied time, t, to creep fracture life, t_f, of precracked (CT) specimens. (——) The curve calculated from Equation 16. (○) 538 °C, 4.9 kN, B = 6.35 mm; (□) 560 °C, 19.6 kN, B = 25.4 mm; (△) 594 °C, 5.39 kN, B = 6.35 mm.

3.2. Derivation of constitutive equation (master curve) of creep deformation and fracture

Based on the similarity law of creep deformation against the time of applied stress, the following constitutive equation (characteristic function) can be proposed as the master curve for creep deformation and fracture

$$f = \alpha_1 + \alpha_2\left[1 - \exp\left(-\alpha_3\frac{t}{t_f}\right)\right] + \alpha_4\left[\exp\left(\alpha_3\frac{t}{t_f}\right) - 1\right] \qquad (3)$$

where f is the creep deformation (the expression for f will be described below), t the elapsed time of stress application. t_f the creep fracture time (life), and α_1, α_2, α_3 and α_4 are constants.

Equation 3 is similar to the creep strain, ξ, expressed in terms of the time of applied stress itself, as proposed by Wilshire and co-workers [1,2] as follow

$$\xi = \beta_1[1 - \exp(-\beta_2 t)] + \beta_3[\exp(-\beta_4 t) - 1] \qquad (4)$$

where β_1, β_2, β_3 and β_4 are constants, respectively.

Taking the first order of the Taylor expansion of the constitutive Equation 3, each value of α_1, α_2, α_3 and α_4 can be determined by analysis by the non-linear least square method, so that the difference between the curve calculated and experimental data becomes minimum. That is, the procedure is as follows.

Taking the first order of the Taylor expansion of Equation 3 we get,

$$\begin{aligned} f^* = {} & \alpha_{10} + \alpha_{20}\left[1 - \exp\left(-\alpha_{30}\frac{t}{t_f}\right)\right] \\ & + \alpha_{40}\left[\exp\left(\alpha_{30}\frac{t}{t_f}\right) - 1\right] \\ & + \frac{\partial f}{\partial \alpha_1}\Big|_{\alpha_{io}}(\alpha_1 - \alpha_{10}) + \frac{\partial f}{\partial \alpha_2}\Big|_{\alpha_{io}}(\alpha_2 - \alpha_{20}) \\ & + \frac{\partial f}{\partial \alpha_3}\Big|_{\alpha_{io}}(\alpha_3 - \alpha_{30}) + \frac{\partial f}{\partial \alpha_4}\Big|_{\alpha_{io}}(\alpha_4 - \alpha_{40}) \\ & \qquad i = 1\text{–}4 \end{aligned} \qquad (5)$$

Let us define the following function as Equation 6

$$g_j = f^* - y_j \qquad (6)$$

where y_j corresponds to the experimental value of creep deformation.

Substituting experimental data into y_j, we perform the analysis of the non-linear least square method by following Equations 7 and 8

$$I = \sum_{j=1}^{n} g_j^2 \qquad (7)$$

$$\frac{\partial I}{\partial \alpha_i} = 2\sum_{j=1}^{n} g_j \frac{\partial f^*}{\partial \alpha_i}\Big|_{t_j, y_j, \alpha_{io}} = 0 \qquad (i = 1\text{–}4) \qquad (8)$$

That is, values of α_i are obtained from Equation 8, and the condition of minimizing I is denoted by Equation 7.

Equation 8 is represented by the following simultaneous equations

$$A_1 + A_2(\alpha_1 - \alpha_{10}) + A_3(\alpha_2 - \alpha_{20}) + A_4(\alpha_3 - \alpha_{30}) + A_5(\alpha_4 - \alpha_{40}) = 0 \qquad (9a)$$

$$B_1 + B_2(\alpha_1 - \alpha_{10}) + B_3(\alpha_2 - \alpha_{20}) + B_4(\alpha_3 - \alpha_{30}) + B_5(\alpha_4 - \alpha_{40}) = 0 \qquad (9b)$$

$$C_1 + C_2(\alpha_1 - \alpha_{10}) + C_3(\alpha_2 - \alpha_{20}) + C_4(\alpha_3 - \alpha_{30}) + C_5(\alpha_4 - \alpha_{40}) = 0 \qquad (9c)$$

$$D_1 + D_2(\alpha_1 - \alpha_{10}) + D_3(\alpha_2 - \alpha_{20}) + D_4(\alpha_3 - \alpha_{30}) + D_5(\alpha_4 - \alpha_{40}) = 0 \qquad (9d)$$

where A_i, B_i, C_i and D_i (i = 1–5) are presented by Equations 10–13

$$A_1 = \sum_j\left\{-y_j + \alpha_{10} + \alpha_{20}\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] + \alpha_{40}\left[\exp\left(\alpha_{30}\frac{t_j}{t_f}\right) - 1\right]\right\} \qquad (10a)$$

$$A_2 = n \qquad (10b)$$

$$A_3 = \sum_j\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] \qquad (10c)$$

$$A_4 = \sum_j\left\{\frac{t_j}{t_f}\left[\alpha_{20}\exp\left(-\alpha_{30}\frac{t_j}{t_f}\right) + \alpha_{40}\exp\left(\alpha_{30}\frac{t_j}{t_f}\right)\right]\right\} \qquad (10d)$$

$$A_5 = \sum_j\left[\exp\left(\alpha_{30}\frac{t_j}{t_f}\right) - 1\right] \qquad (10e)$$

$$B_1 = \sum_j\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right]\left\{-y_j + \alpha_{10} + \alpha_{20}\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] + \alpha_{40}\left[\exp\left(\alpha_{30}\frac{t_j}{t_f}\right) - 1\right]\right\} \qquad (11a)$$

$$B_2 = \sum_j\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] \qquad (11b)$$

$$B_3 = \sum_j\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right]^2 \qquad (11c)$$

$$B_4 = \sum_j\left\{\frac{t_j}{t_f}\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] \times \left[\alpha_{20}\exp\left(-\alpha_{30}\frac{t_j}{t_f}\right) + \alpha_{40}\exp\left(\alpha_{30}\frac{t_j}{t_f}\right)\right]\right\} \qquad (11d)$$

$$B_5 = \sum_j\left\{\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right]\left[\exp\left(\alpha_{30}\frac{t_j}{t_f}\right) - 1\right]\right\} \qquad (11e)$$

$$C_1 = \sum_j\left(\frac{t_j}{t_f}\left[\alpha_{20}\exp\left(-\alpha_{30}\frac{t_j}{t_f}\right) + \alpha_{40}\exp\left(\alpha_{30}\frac{t_j}{t_f}\right)\right] \times \left\{-y_j - \alpha_{10} + \alpha_{20}\left[1 - \exp\left(-\alpha_{30}\frac{t_j}{t_f}\right)\right] + \alpha_{40}\left[\exp\left(\alpha_{30}\frac{t_j}{t_f}\right) - 1\right]\right\}\right) \qquad (12a)$$

$$C_2 = \sum_j\left\{\frac{t_j}{t_f}\left[\alpha_{20}\exp\left(-\alpha_{30}\frac{t_j}{t_f}\right) + \alpha_{40}\exp\left(\alpha_{30}\frac{t_j}{t_f}\right)\right]\right\} \qquad (12b)$$

$$C_3 = \sum_j \left\{ \frac{t_j}{t_f} \left[\alpha_{20} \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) + \alpha_{40} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) \right] \times \left[1 - \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) \right] \right\} \quad (12c)$$

$$C_4 = \sum_j \left\{ \frac{t_j}{t_f} \left[\alpha_{20} \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) + \alpha_{40} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) \right] \right\} \quad (12d)$$

$$C_5 = \sum_j \left\{ \frac{t_j}{t_f} \left[\alpha_{20} \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) + \alpha_{40} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) \right] \times \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \right\} \quad (12e)$$

$$D_1 = \sum_j \left\{ \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \left[-y_j + \alpha_{10} + \alpha_{20} \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) + \alpha_{40} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \right\} \quad (13a)$$

$$D_2 = \sum_j \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \quad (13b)$$

$$D_3 = \sum_j \left\{ \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \left[1 - \exp\left(-\alpha_{30} \frac{t_j}{t_f} \right) \right] \right\} \quad (13c)$$

$$D_4 = \sum_j \left\{ \frac{t_j}{t_f} \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right] \left[\alpha_{20} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) + \alpha_{40} \exp\left(\alpha_{30} \frac{t_j}{t_f} \right) \right] \right\} \quad (13d)$$

$$D_5 = \sum_j \left[\exp\left(\alpha_{30} \frac{t_j}{t_f} \right) - 1 \right]^2 \quad (13e)$$

The initial value α_{i0} is assumed to be arbitrary, say, zero, and α_i is obtained by Cramer's formula. The value of α_i thus obtained is assumed to be the value of α_{i0} as the next initial value, and the calculation is iterated in succession until $\alpha_i - \alpha_{i0}$ becomes less than 10^{-5}.

By this analysis mentioned, the constitutive equation (master curve) of creep deformation, f, is obtained. f is represented for smooth, notched and precracked specimens, respectively, as follows:

for a smooth specimen, $f \equiv \varepsilon$

for a notched specimen, $f \equiv \Delta\phi/\phi_0$

for a precracked specimen, $f \equiv \Delta\delta/\delta_0$

Explanations for ε, $\Delta\phi/\phi_0$ and $\Delta\delta/\delta_0$ were given above. Thus, for smooth, notched (DEN) and precracked (CT) specimens the constitutive equation is obtained as equations 14–16, respectively.

For a smooth specimen

$$\varepsilon - \varepsilon_0 = -6.22 \times 10^{-5} + 1.40 \times 10^{-2} \times \left[1 - \exp\left(-5.01 \frac{t}{t_f} \right) \right] + 5.02 \times 10^{-4} \left[\exp\left(5.01 \frac{t}{t_f} \right) - 1 \right] \quad (14)$$

For a notched (DEN) specimen

$$\frac{\Delta\phi}{\phi_0} = 2.12 \times 10^{-4} + 1.49 \times 10^{-1} \left[1 - \exp\left(-5.15 \frac{t}{t_f} \right) \right] + 4.71 \times 10^{-3} \left[\exp\left(5.15 \frac{t}{t_f} \right) - 1 \right] \quad (15)$$

For a precracked (CT) specimen

$$\frac{\Delta\delta}{\delta_0} = -7.93 \times 10^{-5} + 3.54 \times 10^{-2} \times \left[1 - \exp\left(-4.92 \frac{t}{t_f} \right) \right] + 1.20 \times 10^{-3} \left[\exp\left(4.92 \frac{t}{t_f} \right) - 1 \right] \quad (16)$$

In Figs 5–7, the results calculated from Equations 14–16 are shown by the solid lines, respectively, and agreement with the experimental results is very good.

The values of α_1 in Equations 14–16 are negligibly small compared with other terms. These equations are similar to the constitutive Equation 4 proposed by Wilshire and co-workers [1, 2]. Furthermore, it is salient that the values of α_2 and α_4 for notched (DEN) specimens are approximately 10 times those for smooth specimens, as can be seen by comparing Equation 15 with Equation 14, and those for precracked (CT) specimens are 2.5 times those for smooth specimens, as can be seen by comparing Equation 16 with Equation 14.

It should be noted that the values of α_3 in Equations 14–16 which correspond to Equation 3 are equal to each other in each Equations 14–16, respectively, as can be seen from each equation.

Therefore, from the three characteristics mentioned above, it can be seen that the constitutive equation for creep deformation and creep fracture both for notched (DEN) and precracked (CT) specimens can be obtained by multiplying the equation for the smooth specimen by each constant proportional value, that is, 10 times and 2.5 times, respectively, and *vice versa*. In Fig. 8 the data on $\varepsilon - \varepsilon_0$ for a smooth specimen and on $\Delta\phi/\phi_0$ for a notched (DEN) specimen are plotted against t/t_f, being multiplyed by 2.5 and 0.25 times, respectively. On the other hand, the data on $\Delta\delta/\delta_0$ for a precracked (CT) specimen as they stand, are plotted against t/t_f in the same figure.

Fig. 8 shows the existence of the master curve for creep deformation and fracture covering uniformly smooth, notched (DEN) and precracked (CT) specimens. Furthermore, Equation 3 leading to Equations 14–16 for 1Cr–Mo–V steel is the constitutive equation for this master curve. For smooth, notched and precracked specimens, by using each master curve, we can predict the fracture life, t_f, only if the creep deformation is known in creep under any applied stress and temperature. For instance, a schematic illustration for the smooth specimen is shown in Fig. 5.

4. Discussion

Creep damage size around the notch tip versus t/t_f for a notched specimen is expressed by the master curve,

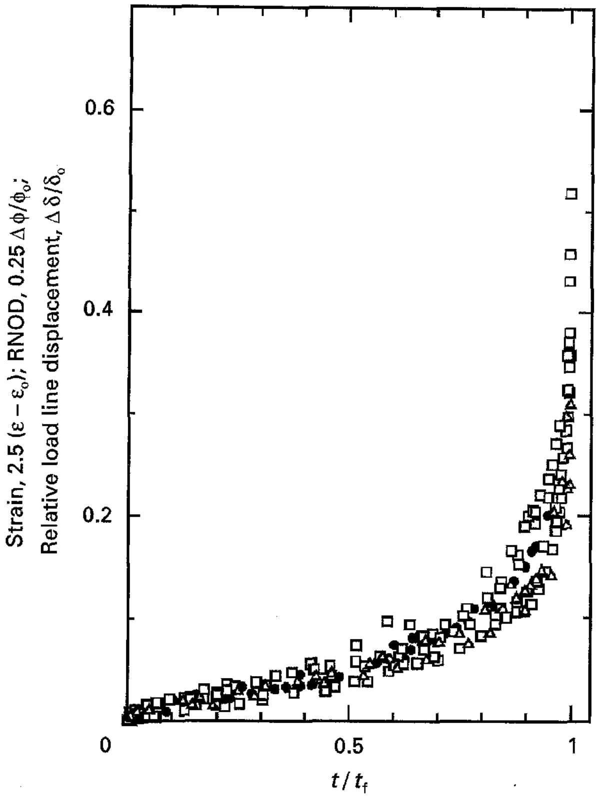

Figure 8 All of the experimental data on (○) smooth, (□) notched (DEN) and (△) precracked (CT) specimens plotted against the ratio t/t_f of stress applied time, t, to creep fracture life, t_f. In this figure, the data for $\varepsilon - \varepsilon_0$ for smooth specimens and for $\Delta\phi/\phi_0$ for notched specimens (DEN) are multiplied by 0.4 and 4 times, respectively. The data $\Delta\delta/\delta_0$ for precracked (CT) specimens are plotted against t/t_f in the same figure.

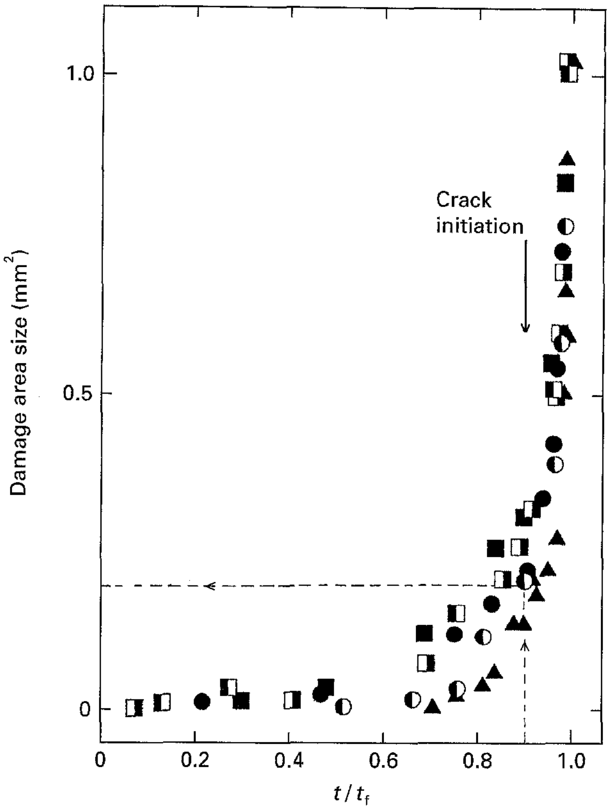

Figure 9 The data on creep damage area size against t/t_f. The figure shows the existence of the creep damage area size master curve similar to the creep deformation and fracture master curve. 600 °C: (▲) 194 MPa. 625 °C: (◨) 176 MPa, (●) 194 MPa, (◧) 221 MPa. 650 °C: (■) 194 MPa. 560°C: (◐) 314 MPa.

independent of temperature and applied gross stress, as shown in Fig. 9 [6]. On comparing Fig. 9 with Fig. 6, it is suggested that there is a correlation between creep deformation and the fracture master curve and the creep damage size master curve. Furthermore, there is an approximately linear relation [6] between $\Delta\phi/\phi_0$ and the creep damage. On the other hand, creep crack initiation occurs when $\Delta\phi/\phi_0$ attains some critical value [5]. Therefore, it may be inferred that a creep crack initiates when creep damage amounts to some critical value. In fact, Fig. 9 shows this is the case. That is, for creep ductile materials such as 1Cr–Mo–V steel, creep crack initiation will occur at $t/t_f = 0.9$. From the argument mentioned above, for a notched specimen, the crack initiation life occupies the main part of fracture life. For a smooth specimen, this respect may be similar [7]. On the other hand, for a precracked (CT) specimen of creep ductile materials, crack growth life will occupy a larger part of the fracture life.

Previously it has been shown that the constitutive equations proposed can be well applied to solder joint materials [8] as high-temperature ductile materials. The application of this concept to high-temperature brittle materials remains a problem.

5. Conclusions

1. The existence of a master curve for creep deformation and the fracture curve versus the ratio of time of applied stress to fracture time was found to cover uniformly smooth, notched (DEN) and precracked (CT) specimens for high-temperature ductile materials, such as Cr–Mo–V steel.

2. A simple prediction methodology, including a macroscopic factor such as specimen shape, and the possibility of relating it to micro-mechanisms is proposed in terms of the constitutive equation of creep deformation and fracture (the master curve equation).

3. By using the master curve proposed, fracture life can be predicted only if the creep deformation is known in creep under any applied stress and temperature.

4. It is suggested that there is some correlation between creep deformation and the fracture curve and the creep damage area size master curve.

5. Although the range of applicability of the methodology might be rather limited, the development of this concept is needed for more long-term creep lives and for other high-temperature ductile materials.

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References

1. R. W. EVANS, J. D. PARKER and B. WILSHIRE, in "Recent Advances in Creep and Fracture of Engineering Materials and Structures", edited by B. Wilshire and D. R. J. Owen (Pineridge Press, 1982) p. 135.
2. R. W. EVANS and B. WILSHIRE, in "Creep and Fracture of Engineering Materials and Structures" edited by B. Wilshire and R. W. Evans (Institute of Metals, London, 1987) p. 59.
3. K. MARUYAMA, C. HARADA and H. OIKAWA, *J. Mater. Soc. Jpn* **34** (1985) 34 (in Japanese).
4. K. KOBAYASHI and H. KAMBAYASHI, *Trans. Jpn Soc. Mech. Eng.* **58**(546) (1992) 268 (in Japanese).
5. A. T. YOKOBORI Jr, T. YOKOBORI, T. KURIYAMA and T. KAKO, in "Proceedings of the 6th ICF", edited by S. R. Vallvri et al., Vol. 3 (Pergamon Press, New Delhi, India, 1984) p. 2181.
6. A. T. YOKOBORI Jr, T. YOKOBORI, T. NISHIHARA and T. YAMAOKU, in "Proceedings of the Japanese 3rd International SAMPE Symposium", "Advanced Materials, NPR", Vol. 2 (1993) 2019.
7. A. T. YOKOBORI Jr, T. YOKOBORI and T. NISHIHARA, *Engng. Frac. Mech.* **40**(4/5) (1991) 737.
8. A. T. YOKOBORI Jr, and T. NISHIRA, *J. Jpn. Soc. Strength Fract. Mater.* **27**(4) (1993) 95 (in Japanese).

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