PREDICTION OF HIGH TEMPERATURE CREEP FRACTURE LIFE BY HARMONIZING MECHANICAL, MICROSTRUCTURAL AND PHYSICAL METHODOLOGIES

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ABSTRACT

Many constitutive equations for high temperature creep fracture have been proposed until now. Many of them, however, concern macroscopic treatment or particular materials. With respect to materials dependent equation, they have been limited to the smooth specimen. In the present paper, it has been attempted to propose the constitutive equation for predicting of high temperature creep fracture throughout from ductile to brittle materials at high temperatures with different microstructural factors and, furthermore, throughout from smooth, notched and precracked specimens. The study has also been carried out on the crack growth behaviour in various materials.

KEYWORDS

Creep fracture life, high temperature ductile materials, high temperature brittle materials, creep deforamtion curve, creep crack length curve.

INTRODUCTION

Many constitutive equations for high temperature creep fracture have been proposed until now. Many of them, however, concern macroscopic treatment or particular materials. With respect to materials dependent equations, they have been limited to the smooth specimen(Larson and Miller 1952, Monkman and Grant 1956). In the present paper, it has been attempted to propose the constitutive equation for predicting of high temperature creep fracture throughout from ductile to brittle materials at high temperatures with differnet microstructural factors and, furthermore, throughout from smooth, notched and precracked specimens. The study has also been carried out on the crack growth behaviour in various materials.

DUAL VALUE BEHAVIOUR OF HIGH TEMPERATURE CRACK GROWTH RATE

If the logarithm of experimental values of creep crack growth rate, log da/dt at high temperatures is plotted against the logarithm of C^*, the experimental relationship reveals in many cases dual value or the nose like behaviour. A typical example for C_r-M_o-V steel(ferite base alloy) is shown in Fig.1(Yokobori, Jr. et al, 1991). Another typical example is

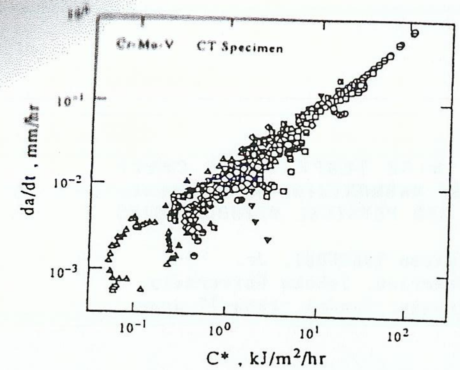

Fig. 1. Creep crack growth rate polotted against C* . Cr-Mo-V steel. Yokobori, Jr. et al, 1991

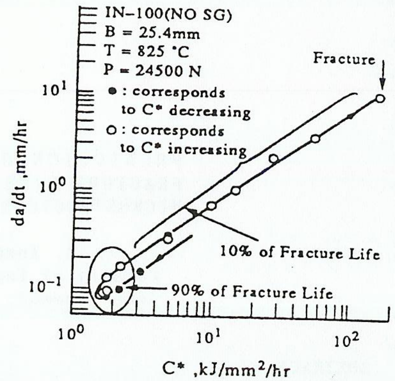

Fig. 2. Creep crack growth rate polotted against C* . IN 100 alloy. Yokobori, Jr. et al, 1996a

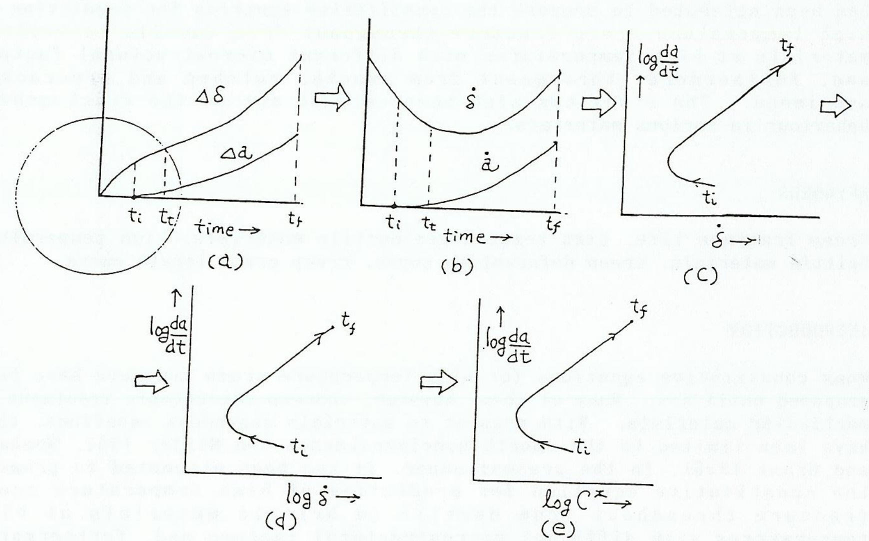

Fig. 3. Schematic illustration of deriving log da/dt vs. Log C* or Log $\dot{\delta}$ projection from Δa vs. t curve and Δδ vs. t curve. For the case $t_i < t_t$. t_r =creep fracture life t_i =time to crack initiation. Yokobori, Jr. and T. Yokobori (1988, 1996a)

shown for IN100 (N_i-base alloy) in Fig. 2. (Yokobori, Jr. et al, 1996a). It was explained by Yokobori, Jr. and Yokobori (1988, 1996a) that this dual behaviour appears when the crack initiates at the tip of the main crack or the crack extension starts during the term of transient creep in the region near by the main crack. (Fig. 3)

Furthermore it has clearly shown by Yokobori, Jr. and Yokobori (1996a) that the various patterns of the dual behaviour, such as the shape of the curve and the range covered, are determined by the mutual relationship of the crack length Δa versus stress applied time t curve (creep crack length curve) to the creep deformation Δδ versus the stress applied time curve (creep deformation curve), where Δa = (crack length, a — initial crack length), and Δδ = (creep deformation (displacement), δ — instantaneous displacement). For instance, it was shown in Fig. 3 that the dual value or or nose type behaviour of da/dt versus C* or $\dot{\delta}$ appears when crack growth occurs during transient creep at the crack tip. It was assumed that C* may be represented by $\dot{\delta}$ in approximately proportional way. (Yokobori, Jr. et al, 1986; Yokobori, Jr. et al, 1991). Furthermore, for this case, many patterns of the nose type occur dependent on the relative value among t_i, t_a, t_t, t_s, and t_b, where, t_i = time to crack initiation, t_a = time to the minimum crack growth rate or time to the inflexion point of crack length Δa versus time curve, t_{ai} = time to the starting of constant rate crack growth, t_t = time to the termination of transient creep or inflexion point of creep curve (Δδ curve), t_s = time to the termination of steady state creep or to the starting of accelerating creep, t_b = time to the termination of constant rate crack growth or the strating of accelerating crack growth at crack length Δa versus time curve, and t_r = fracture time.

A typical experimental relation of log da/dt versus C* for IN100 as shown in Fig. 2 can be very well derived. In Fig. 4 the crack length Δa versus time t/t_r and the creep deformation Δδ versus time t/t_r corresponding to the experimental condition in Fig. 2 is shown, respectively. We can see the relation in Fig. 2 is very well derived graphically from the methodology illustrated in Fig. 3, using Δa - f/f_r and Δδ - t/t_r relation shown in Fig. 4. (Yokobori, Jr. and Yokobori, 1996a).

Comparing Figs. 2 and 4 with Fig. 1 and 5, we can see that for IN100 alloy as high temperature brittle metal, the life corresponding to dual part occupies about 80-90% of the total life, far much larger than that for C_r-M_o-V steel as high temperature ductile metal. This characteristics comes from the crack growth curve for both metals as shown in Fig. 5, in which for IN100 alloy, the uniform velocity part occupies about 80-90% of the total life, whereas for C_r-M_o-V steel the accelerating velocity part occupies about 60% of the total life.

PREDICTION FOR HIGH TEMPERATURE CREEP FRACTURE LIFE THROUGHOUT FROM DUCTILE TO BRITTLE MATERIALS

The Q* parameter proposed by Yokobori et al. is defined as the power coefficient of the exponential in the thermal activation process equation for da/dt. in which the activation energy is expressed in terms of free energy as follows (Yokobori, Jr. and Yokobori, 1989; Yokobori, Jr. et al, 1992):

$$\frac{da}{dt} = A e^{Q^*} \tag{1}$$

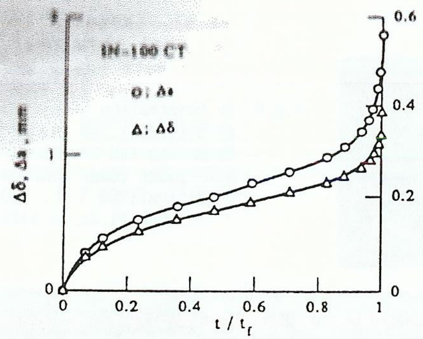

Fig. 4. A typical example of the experimental ralationship between Δa vs. t/t_f and $\Delta\delta$ vs. t/t_f. t_f = creep fracture life. IN 100 (Yokobori, Jr. and Yokobori, 1996a)

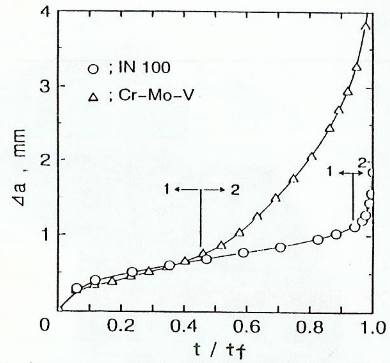

Fig. 5. Comparison of crack length Δa vs. t/t_f curve between Cr-Mo-V steel and IN 100. 1 and 2 correspond to uniform velocity part and acceleration part, respectively. Yokobori, Jr. and Yokobori, 1996a

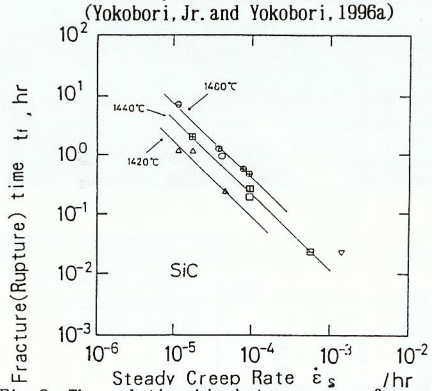

Fig. 6. The relationship between creep fracture life and steady creep rate for SiC as affected by temperature. Yokobori, Jr, et al(1996a)

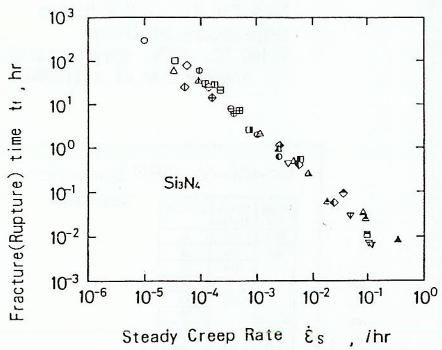

Fig. 8. The relationship between creep fracture life and steady creep rate for Si_3N_4. Yokobori, Jr. and Yokobori(1996a)

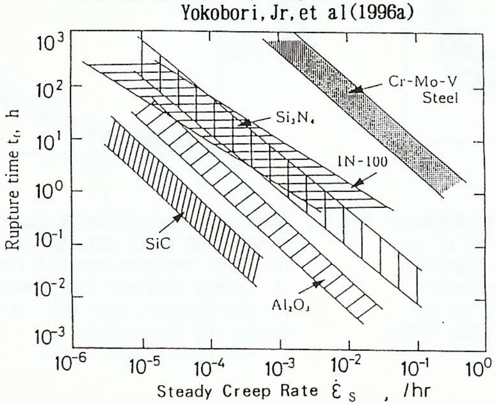

Fig. 7. The experimental relationship between creep fracture life and steady creep rate for various materials. Al_2O_3 800~1100℃, Si_3N_4:1150 ~1330℃, SiC:1400~1480 ℃. Yokobori, Jr. et al(1996c)

where A is a constant independent of temeprature. In eq. (1) Q^* can be written as:

$$Q^* = -\frac{\Delta H_g - \phi_g(\sigma)}{RT} \tag{2}$$

where ΔH_g is the activation free energy for crack growth and $\phi_g(\sigma)$ is a possitive function of applied stress. For the case of high temperature crack growth, Yokobori and colleagues (Yokobori, Jr. and Yokobori, 1989, Yokobori, Jr. et al, 1992) have obtained the following formula in high temperature ductile metals such as 304 stainless steel and Cr-Mo-V steel:

$$\frac{da}{dt} = A_0 a^{m_1/2}\sigma_g^{m_g}\exp\left(-\frac{\Delta H_g}{RT}\right) \tag{3}$$

where $m_1 \equiv \beta_o/RT$, $m_g \equiv m_o + m_1$, $A_o \equiv A_g(W/W_o)^{-\ell_o}(\alpha/\beta^*\sqrt{bG})^{m_1}$, W = specimen width, W_o = reference specimen width, b = Burgers vector, G = modulus of rigidity, β^* = modified coefficient for b, m_o, β_o, ℓ_o and A_g are constants, and α = numerical constant for $K_I = \alpha\sqrt{a}\sigma_g$.

In time dependent fracutre of smooth specimens, final fracture of two types may be realistic. One is the case where one crack which started from the small original defect extends and final fracture is caused by the stress intensity factor of the crack with the critical length due to this one-crack extension. The other is the case where multi-site cracks, say a number of cracks initiated from a number of small defects, will grow and join together(Yokobori; et al, 1968,1969). In the latter case it was shown previously that the fracture time is determined by the time taken for each growing crack to attain the critical length, depending on the distance between each tip of the originally initiated small cracks. (Yokobori; et al, 1968,1969). Thus, for final fracture of both types mentioned above, the creep fracture time t_f can be obtained by integrating da/dt expressed by eq. (3) in terms of Q^* from a_o to a_c, the crack initiation life being assumed as much smaller than the crack growth life. a_o is the initial crack length and a_c is the critical length of the crack which leads to the final fracture when it is reached. That is, creep fracture time t_f will be given as:

$$t_f = \frac{1}{A_0\sigma_g^{m_g}\exp\left[-\frac{\Delta H_g}{RT}\right]}\int_{a_0}^{a_c}\frac{da}{a^{m_1/2}} \tag{4}$$

Since $a_c \gg a_o$, eq. (4) reduces to

$$t_f = \frac{1}{A_f\sigma_g^{m_g}\exp\left[-\frac{\Delta H_g}{RT}\right]} \tag{5}$$

where $A_f \equiv A_o[(m_1-2)/2]a_o^{(m_1-2)/2}$.

On the other hand, with respect to the creep strain rate, many studies have been carried out in literatures in terms of thermal activation process, such as diffusion mechanism(Lange et al, 1980), viscoelastic creep mechanism and cavitational creep mechanism(Lange et al, 1980; Evans and Wiederhorn, 1974). Now, whatever the creep mechanism may be, if we denot denote r_c as the rate of some atomistic rearrangement required for occurrence of time-dependent plastic flow, and we consider that the creep strain ε (for steady creep or minimum creep) will result when this rearrangement occurs, then we get the following relation for the creep strain rate $\dot{\varepsilon}$ as in the usual thermally activated process:

$$\dot{\epsilon} = A_1 \exp\left(-\frac{\Delta H_c - \phi_c(\sigma)}{RT}\right) \tag{6}$$

For smooth specimens, the creep strain rate equation(6) is represented as:

$$\dot{\epsilon} = A_c \sigma_g^{m_c} \exp\left(-\frac{\Delta H_c}{RT}\right) \tag{7}$$

where A_c and m_c are constants.

By multiplaying both sides of eqs.(5) and (7), respectively, we get:

$$t_f \dot{\epsilon} = M\sigma_g^{m} \exp\left[-\frac{\Delta H^*}{RT}\right] \tag{8}$$

where $m \equiv m_c - m_g$, $\Delta H^* \equiv \Delta H_c - \Delta H_g$ and $M \equiv A_o/A_r$.
In general m_c is not equal to m_g and ΔH_c also not equal to ΔH_g. Therefore, the right hand side of eq.(8) is in general a function of applied stress σ_g and temperature T. For instance, with respect to SiC as more creep brittle materials, the relation of the logarithm of creep life, log t_f versus the logarithm of steady creep rate, log $\dot{\varepsilon}_s$ is experimentally expressed by linear line and the line depends on the temperature and applied stress as shown in Fig.6, the relation of which is theoretically suggested by eq.(8). Furthermore, eq.(8) is quite in agreement with the data for aluminum oxide carried out by Wiederhorn et al (1986) and by Yokobori,Jr.(1996b)(Fig.7). On the other hand, for the case of $m_c = m_g$ and $\Delta H_c = \Delta H_g$, then the right hand side of eq.(8) takes the constant value, and the straight line becomes one and the same line independent of applied stress and temperature for Si_3N_4(Yokobori, Jr.,1996b) as rather creep ductile materials as shown in Fig.8. Another example, which we showed is Cr-Mo-V steel as more creep ductile materials. Apparently, the equation is in accord with the formula by Monkman and Grant(1956), but it is to be noted that the right hand side of eq.(8) is different according to different materials, say, it may be called as creep ductility.

In Fig.7 the relation of log t_f versus log $\dot{\varepsilon}_s$ is plotted for various materials.* From Fig.7 it can be seen that for the same fracture life t_f,

* For Cr-Mo-V steel(ferrite base alloy): nothced specimen, for IN100 (Ni base alloy): Precracked specimen, for Al_2O_3, Si_3N_4 and SiC(Ceramics): smooth specimen. The effect of specimen shape may be affected by material, and the study on the effect will be studied as next subject.

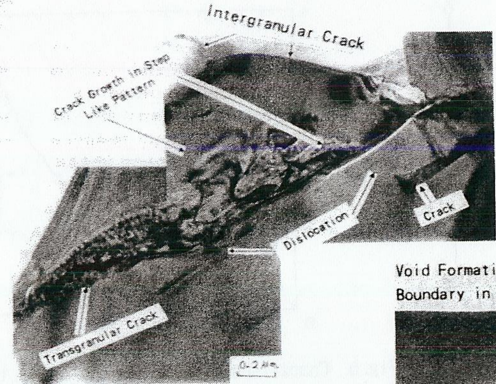

Fig.9. An observation of the microstructure by TEM on creep deformation and fracture for SiC under lower temperature condition(1250 ℃, t_r =30.4h$_r$) Yokobori,Jr.et al(1996d)

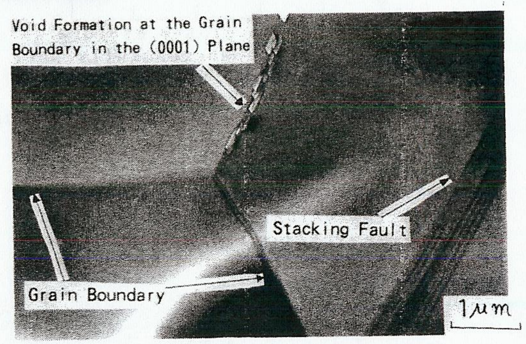

Fig.10. An observation of the microstructure by TEM on creep deformation and fracture surface for SiC under higher temperature condition. (1480 ℃, 490h$_r$, non-fracture) Yokobori,Jr.et al(1996d)

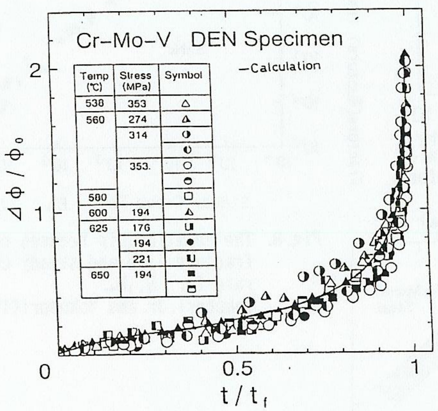

Fig.11. The experimental date on creep deformation $\Delta\phi/\Delta\phi_o$ and the ratio. t/ t_f of stress applied time, t to creep fracture time, t_f for notched (DEN) specimens. The solid curve is calculated one by Eq.(12). Yokobori,Jr.et al(1993,1996b)

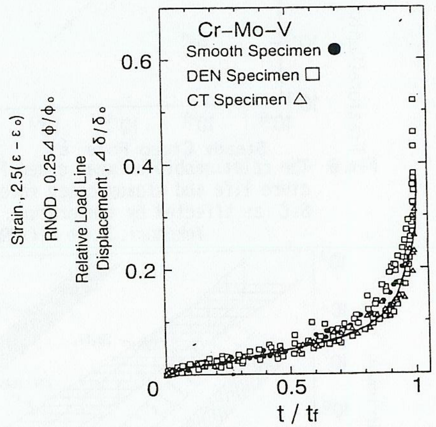

Fig.12. Constitutive equation(master curve) proposed of creep deformation and fracture. t=stress applied time, t_f - creep fracture time. Symbols are experimental date with various stress and temperature. Yokobori,Jr.and Yokobori(1996b)

the steady creep rate, $\dot{\varepsilon}_s$ will decrease, say, become brittle as the creep ductility given by the right hand side of eq.(8) will decrease. Results of TEM observation for S_iC under creep condition in Figs.9 and 10 (Yokobori, Jr. et al 1996d). In lower temperature range(1250° C), there are many cracks which grow straight in the grain. Furthermore, some of cracks show step-like pattern along a different plane. This may be due to the dislocation movement. The brittle behaviour of S_iC at lower temperature may be caused by such mechanism. In higher temperature region(1480° C, 490hr non fracture), voids are formed at a grain boundary along the perpendicular direction to the tensile stress. For this case, log da/dt versus log ε_s curve of S_iC moves upwards and approaches to the data band of S_3N_4 as shown in Figs.6 and 7. These results show that S_iC becomes ductile with increase of temperature. If structural and grain boundary control of S_iC can be successfully performed, the possibility of high ductility is expected for S_iC(Yokobori, Jr. et at 1996d).

CONSTITUTIVE EQUATION(MASTER CURVE) OF CREEP DEFORMATION AND FRACTURE

Based on the similarity law of creep deformation against stress applied time, the following constitutive equation(characteristic function) is proposed by Yokobori,Jr. and Yokobori(1993c) and Yokobori,Jr. et al(1996b) as the master curve for creep deformation and fracture:

$$f=\alpha_1+\alpha_2\left[1-\exp\left(-\alpha_3\frac{t}{t_f}\right)\right]+\alpha_4\left[\exp\left(\alpha_3\frac{t}{t_f}\right)-1\right] \tag{9}$$

where
f = creep deformation, t = elapsed time of stress application, t_f = creep fracture time(life), and $\alpha_1, \alpha_2, \alpha_3$ and α_4 are constants, respectively. α_1 can be neglected as shown in the following. Eq.(9) was proposed by Yokobori, Jr. and Nishiiri(1993) for the creep of solder. Eq.(9) is similar to the creep strain ξ expressed in terms of the stress applied time itself, such type as proposed by Evans and Whilshire(1982,1987) follows:

$$\xi=\beta_1[1-\exp(-\beta_2 t)]+\beta_3[\exp(-\beta_4 t)-1] \tag{10}$$

It, however, is to be noted the form of the proposed equation(9) is different from that by Evans and Wilshire(1982,1987)in that(Yokobori,Jr. et al, 1996b). (1)in the equation, t/t_f is used instead of t, (2)the form of eq.(9) is more simple, and (3)as shown in the following, it can be unified throughout from smooth, notched and precracked specimen.

f corresponds to smooth, notched and precracked specimen, respectively as follow: For smooth specimen: $f\equiv\varepsilon-\varepsilon_0$, where ε = creep strain and ε_0 = the instantaneous strain at the load application. For notched specimen: $f\equiv\Delta\phi/\phi_0$, where $\Delta\phi=\phi-\phi_s-\phi_0$, ϕ and ϕ_s are the notch opening displacement at time t and that at the instant of load application, respectively. ϕ_0 = the initial notch opening value. For precracked specimen: $f\equiv\Delta\delta/\delta_0$, where $\Delta\delta=\delta-\delta_s-\delta_0$, δ and δ_s are the load line displacement at time t and the instantaneous one at the

load application, respectively. δ_0 is the initial distance between upper and lower load pin hole of CT specimen. For the present article, δ_0 = 28mm.

By the analysis of the nonlinear least square method, the constitutive equation(master curve) of creep deformation, f is obtained for smooth, notched(DEN) and precracked(CT) specimen. The constitutive equation is obtained as Eqs.11, 12, and 13, respectively:
For smooth specimen:

$$\varepsilon-\varepsilon_0=1.40\times10^{-2}\left[1-\exp\left(-5.01\frac{t}{t_f}\right)\right]+5.02\times10^{-4}\left[\exp\left(5.01\frac{t}{t_f}\right)-1\right] \tag{11}$$

For notched(DEN) specimen:

$$\frac{\Delta\phi}{\phi_0}=1.49\times10^{-1}\left[1-\exp\left(-5.15\frac{t}{t_f}\right)\right]+4.71\times10^{-3}\left[\exp\left(5.15\frac{t}{t_f}\right)-1\right] \tag{12}$$

For precracked(CT) specimen:

$$\frac{\Delta\delta}{\delta_0}=3.54\times10^{-2}\left[1-\exp\left(-4.92\frac{t}{t_f}\right)\right]+1.20\times10^{-3}\left[\exp\left(4.92\frac{t}{t_f}\right)-1\right] \tag{13}$$

As an example, in Fig.11 the calculated results by eq.12 is shown by the solid line, and the agreement is very well with the experimental results.

The calculated values of α_1 in eqs.11, 12, and 13 are negligibly small as compared with another terms, and, therefore were neglected. Furthermore, it is salient that the values of α_2 and α_4 for notched(DEN) specimens are approximately ten times of those for smooth specimens as can be seen by comparing eq.12 with eq.11 and,those for precracked(CT) specimens are two half times of those for smooth specimens as can be seen by comapring eq.13 with eq.11. It is also to be noted that the values of α_3 in eqs.11, 12, and 13 which correspond to eq.9 are equal each other in each eq.11, 12, and 13, respectively, as can be seen from each equation.

Therefore, from the three characteristics mentioned above, it can be seen that constitutive equation for creep deformation and creep fracture both for notched(DEN) and precracked(CT) specimens can be obtained by multiplying the equation for smooth specimen by each constant proportional value, that is, ten times and two half times, respectively, and vice versa.(Yokobori,Jr. et al 1996b). In Fig.12 the data on $\varepsilon-\varepsilon_0$ for smooth specimen and on $\Delta\phi/\phi_0$ for nothced(DEN) specimen are plotted against t/t_f being multiplied by 2.5 and 0.25 times, respectively. On the other hand, the data on $\Delta\delta/\delta_0$ for precracked(CT) specimen as they stand, are plotted against t/t_f in the same figure. Fig.12 shows the existence of the master curve for creep deformation and fracture covering unifiedly throughout smooth specimen, notched(DEN) specimen and precracked (CT) specimen. Furthermore, eq.9 leading to eqs.11, 12, and 13 for

C_r-M_o-V steel is the constitutive equation for this master curve. For smooth, notched and precracked specimens, by using each master curve respectively, we can predict fracture life t_f, only if the creep deformation is known in creep under any applied stress and temperature.

CONCLUSIONS

The following conclusions are obtained:

(1) The logarithm of experimental values of creep crack growth rate, log da/dt at high temperatures plotted against the logarithm of C^* reveals in many cases the dual value or the nose like behaviour. It was shown that this dual value behaviour appears when the crack initiates at the tip of the main crack or the crack extension starts during the term of transient creep in the region near by the main crack. Furthermore, it was shown that the various patterns of the dual behaviour, such as the shape of the curve and the range covered, are determined by the mutual relationship of the crack length versus time curve to the creep deformation curve, both dependent on the materials.

(2) The formula predicting the creep fracture life was proposed throughout high temperature ductile materials such as C_r-M_o-V steal (ferrite base alloy) to high temperature brittle materials, such as IN100(N_i base alloy) and the ceramics with different chemical bonding type, like $A_{l2}O_3$, $S_{i3}N_4$ and S_iC. In the equation, the microstructure dependent term and the specimen shape factor such as smooth, notched and cracked were suggested. The future study on the expression of the term is needed in terms of microstructures.

(3) The constitutive equation of creep deformation at high temperatures is proposed in terms of the ratio t/t_f of the stress applied time, t to the creep fracture life, t_f. It becomes creep master curve until fracture throughout smooth, nothed and cracked specimens, for ferritic steel such as C_r-M_o-V steel. Moreover, the equation is very simple from the engineering point of view. The future study is desirable on the relationship of the constants contained in the equation to the microstructures.

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