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Recent Methodologies for Creep Deformation Analysis and Its Life Prediction

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1. Introduction

Generation-IV (Gen-IV) reactor systems such as a very high temperature reactor (VHTR) and a sodium-cooled fast reactor (SFR) is designed to be used for a 60 year lifetime at the elevated temperatures reaching 550 ^{o}C in SFR and 950^{o}C in VHTR. Since their components suffer from creep damage during the long service life at the elevated temperatures, "creep" is one of the most critical properties, because creep life (or strength) is gradually reduced under the severe conditions of the high temperatures and long duration [1-2].

To design the high-temperature creeping materials, various creep data are needed for codification, as follows: i) stress vs. creep rupture time for base metals and weldments (average and minimum), ii) stress vs. time to 1% total strain (average), iii) stress vs. time to onset of tertiary creep (minimum), and iv) constitutive eqns. for conducting time- and temperature- dependent stress-strain (average), and v) isochronous stress-strain curves (average). Also, elevated temperature components such as those used in modern power generation plant are designed using allowable stress under creep conditions. The allowable stress is usually estimated on the basis of up to 10^5 h creep rupture strength at the operating temperature.

In ASME PVP Code Section III, Division 1 Subsection NH Class 1 Components in Elevated Temperature Service, for each specific time, t, the S_t (a temperature and time-dependent stress intensity limit) values are less: i) 100% of the average stress to produce a creep rate of 0.01%/1000h, ii) 80% of the minimum stress to cause rupture at the end of 10^5h, and iii) 67% of the average stress to cause rupture at the end of 10^5 h. To experimentally obtain the long-term data reaching 10^5h is difficult as time-consuming works and not economical as well. Therefore, one of the main challenges in the design process of such components is the prediction of long-term creep strength. In addition, the creep constants or parameters in various creep constitutive equations which will be used in creep design of the components should be provided to designers.

In this study, various methodologies for analyzing creep rupture data are introduced using various creep laws, and recently improved methodology for creep life-prediction is proposed using the data based on author's experimental creep data.

2. Results and Discussion

2.1 Various presentation methodologies

"Creep" of materials is classically regarded as the irreversible and time-dependent deformation of materials. Although creep can take place at all temperatures above absolute zero, traditionally creep refers to the time-dependent plastic deformation at elevated temperatures, often higher than roughly 0.4T_m (T_m is material melting temperature). Textbooks generally consider three stages in a typical creep curve: the first stage (primary or transient creep), the second stage (secondary or stationary creep), and the third stage (tertiary or accelerated creep). During the primary creep stage, the creep rate decreases with time due to strain hardening until it reaches a certain value (minimum or steady creep rate, $d\varepsilon/dt$). In the secondary creep stage, there is a balance between the strain hardening and thermal softening and the creep rate remains approximately constant at $d\varepsilon/dt$. During the tertiary stage, the creep rate increases and finally at the end of the tertiary stage creep rupture of the specimen occurs. The increase in creep rate with time in the tertiary creep stage can arise from increasing stress (due to cross-section reduction in constant tensile loading) or from microstructure evolution including damage formation.

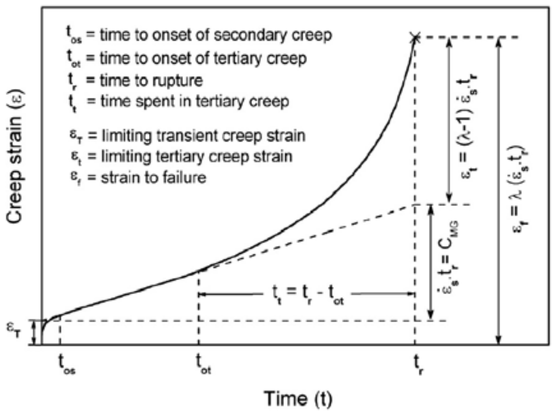


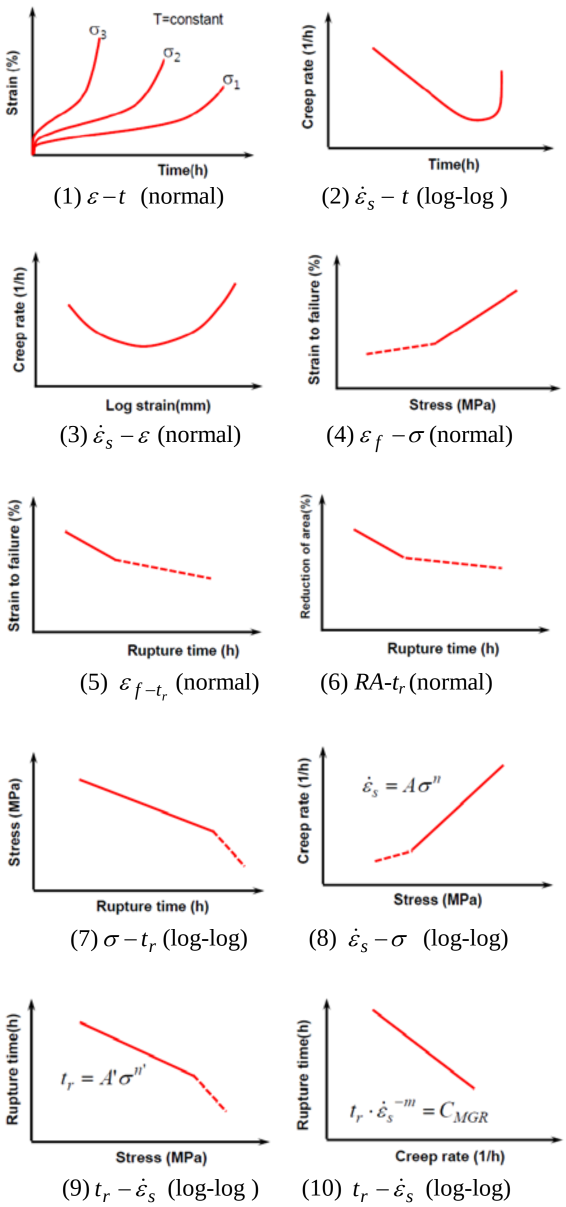
Fig. 1. Typical creep curve showing various parameters used for defining tertiary creep behavior of 9Cr–1Mo ferritic steel.

Creep strain-time curve can be defined by seven terminologies of ε_T, ε_t, ε_f, t_{os}, t_{ot}, t_r, and t_t, as shown in Fig. 1, which shows a typical creep curve for 9Cr–1Mo steel depicting evaluation of various parameters used to describe the creep behavior of 9Cr–1Mo steel. The transient creep strain (ε_T) exhibits very small contribution towards overall creep strain to failure. The secondary creep strain contribution is shown as Monkman–Grant (M-G) strain $\dot{\varepsilon}_s \cdot t_r$, the product of steady state creep rate and rupture life. In the figure, λ is the creep damage tolerance factor, as given by [3,4]

$$\lambda = \varepsilon_f / t_r \cdot \dot{\varepsilon}_s = \dot{\varepsilon}_{avg} / \dot{\varepsilon}_s \, . \qquad (1)$$

Eq. (1) means that the ratio of total strain (ε_f) to secondary creep strain.

The shape of the creep curve and the duration of creep stages for a material depend strongly on creep testing conditions, namely stress and temperature. We can obtain material information of rupture time, secondary creep rate (or minimum creep rate), rupture elongation, and reduction of area at the given applied stress and temperature conditions. From the tested data, we can observe in detail creep behavior in terms of 14 kinds of various plotting methods, as shown in Fig. 2.



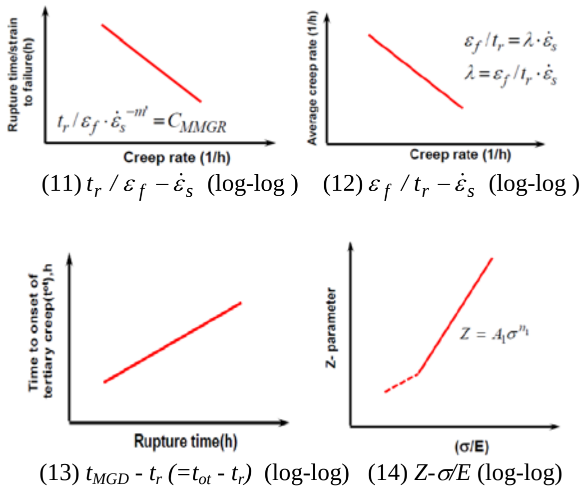
(1) $\varepsilon - t$ (normal) (2) $\dot{\varepsilon}_s - t$ (log-log)

(3) $\dot{\varepsilon}_s - \varepsilon$ (normal) (4) $\varepsilon_f - \sigma$ (normal)

(5) ε_{f-t_r} (normal) (6) RA-t_r (normal)

(7) $\sigma - t_r$ (log-log) (8) $\dot{\varepsilon}_s - \sigma$ (log-log)

(9) $t_r - \dot{\varepsilon}_s$ (log-log) (10) $t_r - \dot{\varepsilon}_s$ (log-log)



(11) $t_r / \varepsilon_f - \dot{\varepsilon}_s$ (log-log) (12) $\varepsilon_f / t_r - \dot{\varepsilon}_s$ (log-log)

(13) t_{MGD} - t_r (=t_{ot} - t_r) (log-log) (14) Z-σ/E (log-log)

Fig. 2. Various plots (14 kinds) of creep rupture data.

As given in various plotting methods above, the plot of No. 8 is for Norton's power law. When secondary creep dominates, creep deformation follows the Norton's power law well. The equation gives:

$$\dot{\varepsilon}_s = A\sigma^n \qquad (2)$$

Creep is also thermally activated process and its temperature dependency can be expressed with an Arrehenius equation:

$$\dot{\varepsilon}_s = A exp\left(\frac{-Q_c}{RT}\right) \qquad (3)$$

Combination of Eqs. (2) and (3) gives:

$$\dot{\varepsilon}_s = A\sigma^n \, exp\left(\frac{-Q_c}{RT}\right) \qquad (4)$$

Plots of log $\dot{\varepsilon}_s$ vs. log σ for the majority of advanced heat resistance steels show at least one transition of creep exponent, n , depending on the level of stress. The change of n corresponds to a transition in dominant creep deformation mechanism. In general, plots of log $\dot{\varepsilon}_s$ vs. log σ (and/or log $\dot{\varepsilon}_s$ vs. 1/T) provide useful information about the dominant creep mechanism and its changes due to change of creep condition.

Plots of No. 10 and No 11 show the plots of Monkman-Grant Relationships (MGR) and Modified Monkman-Grant Relationships (MMGR). The equations of MGR and MMGR are given by [3,5]

$$log \, t_r + m \, log \, \dot{\varepsilon}_s = C_{MGR} \qquad (5)$$

$$log \, t_r / \varepsilon_f + m' \, log \, \dot{\varepsilon}_s = C_{MMGR} \quad . \qquad (6)$$

The MMGR equation has better agreement to experimental data than MGR one, because the data of rupture elongation (ε_f) is involved. It is close to unity as $m' \cong 1$.

The plot of No. 12 indicates creep damage tolerance factor, λ, which provides a measure of the susceptibility of a material to localized cracking at stress and strain concentrations. It is considered to be a material performance characteristic. Based on a continuum creep damage mechanics approach, λ is defined as the ratio of ε_f to the secondary creep strain, as given in Eq. (1)

Finally, the plot of No. 14 is for "Zener-Hollomon parameter". The creep strain rate can be expressed by a power-law relation of Eq. (7) describing the relationship with stress and temperature [6].

$$\dot{\varepsilon}_s = A_1 \sigma^{n'} \exp(-Q/RT) \quad (7)$$

$$Z = \dot{\varepsilon}_s \exp(Q/RT) \quad (8)$$

$$Z = A_1 \sigma^{n_1} \quad (9)$$

With Eq. (6), the parameter A_1, stress exponent n_1, and the apparent activation energy Q are themselves functions of stress and temperature. The Z parameter of Eq. (8) is referred to as a temperature-modified strain rate. Eq. (9) from the relation of Eq. (8) and Eq. (9) can be finally derived by the power law form of $Z = f(\sigma)$. This equation is frequently used to describe creep behavior. As for an example for Alloy 617, a straight line was seen well with a slope regardless of temperature conditions if a same mechanism is operative in test temperature ranges, as shown in Fig. 3.

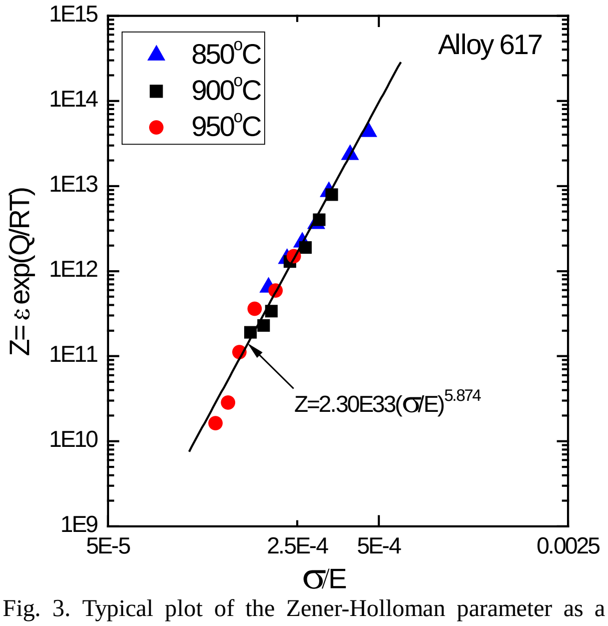
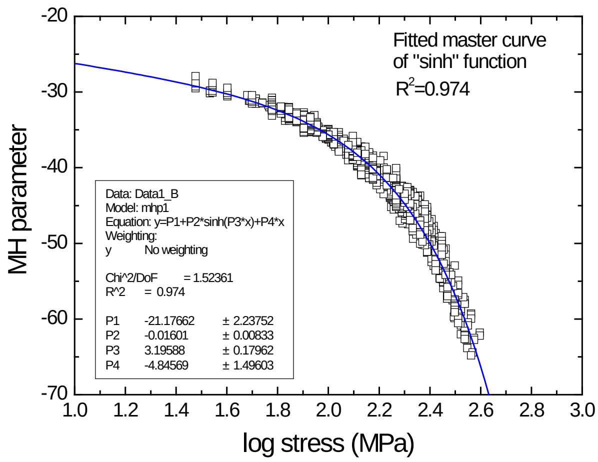


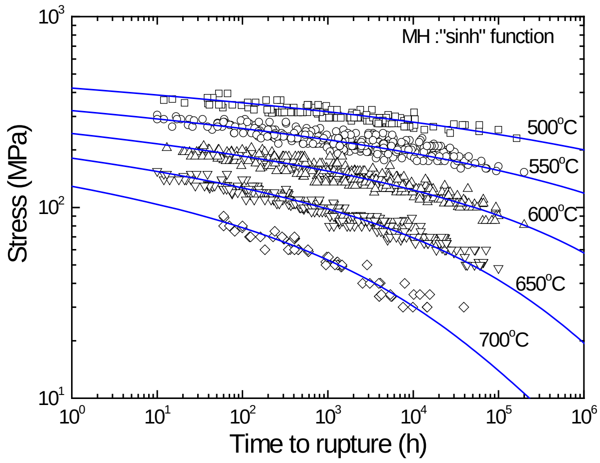
Fig. 3. Typical plot of the Zener-Holloman parameter as a function of stress (σ/E) at 850, 900, and 950°C of Alloy 617.

2.2 Recent life-prediction methodology

Many attempts have been made to formulate dependency of creep life to operating temperature and stress. A promising approach has been the use of time-temperature parameters (TTP). All of the various developed TTPs consist of a combination of time, temperature and suitable constants. With such parameters and for a given material, a single master curve of stress against the parameter can be obtained and this is of a great value for extrapolating test results.



(a) A master curve fitted by the "sinh" function



(b) Life prediction curves

Fig. 4. Plots of (a) a master curve and (b) the rupture stress curves predicted for the "sinh" function in the MH parameter for Grade 91 steel.

To accurately achieve the long-term life extrapolation, a "master rupture curve" (hereafter referred to as "master curve") describing the relationships between log (stress) and parameter (P) should be suitably determined. So far, a polynomial equation, as the master curve in the TTP methods such as the Larson-Miller (LM), Orr-Sherby-Dorn (OSD), and Manson-Harferd (MH) parameters, has been conventionally used well. However, the equations of a polynomial form give the convex or concave curves in the extrapolation of the low stress ranges beyond experimental creep durations. The reason for this is due to intrinsic characteristics of polynomials. As the results, the predicted curve is unstable in the low stress region beyond experimental data. In particular, the predicted life was overestimated or underestimated according to the degree of orders of polynomial forms. To overcome this problem, a "sinh" function instead of the polynomial form is newly proposed herein, as follows.

$$P(t_r, T) \Rightarrow f(\sigma) \quad (10)$$

$$P = b_1 \log(\sigma) - b_2 \log(\sigma)^2 - b_3 \log(\sigma)^3 + ... b_n \log(\sigma)^n \quad (11)$$

$$P = b_1 + b_2 \sinh(b_3 \log \sigma) - b_4(\log \sigma) \quad (12)$$

In the above equations, the time-temperature parameter (*P*) is expressed as a function of stress as Eq. (10). The parameter is given as the polynomial form of Eq. (11). The “sinh” function of Eq. (12) was used instead of Eq. (11). It was identified that Eq. (12) was stable prediction without a sharp bent of the master curve in the extrapolation of the low stress ranges beyond the experimental test durations. Typical results applied for the MH method in the TTP methods for Grade 91 steel are shown in Fig. 4.

In addition, a constant *C* in the LM method is unique for a given set of creep rupture data to be analyzed. Temperature dependency of a rupture life, $d\log t_r / d(1/T)$, should not change in the data set. However, this assumption is not always valid, because the *C* for the rupture life changes from a high value of the short-term creep to a low value of the long-term creep. A change in $d\log t_r/d(1/T)$ was a major cause of the resultant overestimation. Thus, to avoid overestimation, a multi-constant method for the *C* in the LM parameter was newly demonstrated herein.

Fig. 5 shows a comparison of the creep strength curves predicted by the unique-*C* and multi-*C* methods with an application of the LM parameter at 950°C of Alloy 617. The unique *C* method has a higher value in the predicted curve than the multi *C* one with *C*=20 and *C*=10 for 10^5 h and 10^6 h. In particular, the strength gap between the two curves becomes larger as the time is extended from 10^5 to 10^6 h. It is believed that this multi-constant method can be used to accurately predict creep strength of Gen-IV nuclear materials which will be designed for life span of 60 years.

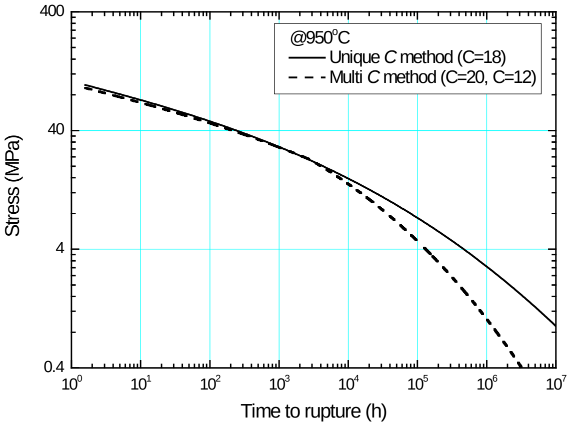


Fig. 5. Typical result of creep strength curves predicted by the unique -*C* and multi-*C* methods at 950°C for Alloy 617.

3. Conclusions

Various methodologies for analyzing creep rupture data were introduced using various creep laws such as Norton’s power law, Monkman-Grant relation, Modified Monkman-Grant relation, and Zener-Hollomon parameter. In addition, recently improved methodologies for creep life-prediction were proposed using author’s experimental creep data. The master curve of the “sinh” function was found to have a wider acceptance with good flexibility in the low stress ranges beyond the experimental data. The proposed multi-*C* method in the LM parameter revealed better life prediction than a single-*C* method. These improved methodologies can be utilized to accurately predict the long-term creep life or strength of Gen-IV nuclear materials which are designed for life span of 60 years.

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REFERENCES

[1] W.G. Kim, S.N. Yin, G.G. Lee, Y.W. Kim and S.J. Kim, Creep Oxidation Behavior and Creep Strength Prediction for Alloy 617, Int. J. of Pressure Vessels and Piping, Vol. 87, pp. 289~295, 2010.
[2] J.H. Chang, et al., A Study of a Nuclear Hydrogen Production Demonstration Plant, Nuclear Eng. and Tech., Vol. 39, No.2, pp. 111~122, 2007.
[3] B.K. Choudhary, and E. Isaac Samuel, Creep Behavior of Modified 9Cr–1Mo Ferritic Steel, Journal of Nuclear Materials, Vol. 412, pp. 82~89, 2011.
[4] W.G. Kim, J.Y. Park, I.M.W. Ekaputra, S.J. Kim, M.H. Kim and Y.W. Kim, Creep Deformation and Rupture Behavior of Alloy 617, Engineering Failure Analysis, Vol. 58, pp. 441~451, 2015.
[5] C. Phaniraj, B.K. Choudhary, K. Bhanu Sankara Rao and B. Rai, Relationship Between Time to Reach Monkmon-Grant Ductility and Rupture Life, Scripta Materialia, Vol. 48, pp. 1313~1318, 2003.
[6] G.E. Deter, and D. Bacon, Mechanical Metallurgy, McGraw-Hill Book Co. pp. 306~307, 1988.