Damage Modelling: the current state and the latest progress on the development of creep damage constitutive equations for high Cr steels

Qiang Xu[1], Zhongyu Lu[2] and Xue Wang[2]

[1]Doctor, School of Computing and Engineering, Huddersfield University, Huddersfield, HD1 3BA, UK
[2]Professor, Doctor, School of Computing and Engineering, Huddersfield University, Huddersfield, HD1 3BA, UK
[3]Professor, Doctor, School of Power and Mechanics, Wuhan University, China
[1]Q.Xu2@hud.ac.uk, [2]Z.Lu@hud.ac.uk, [3] wxue2008163@163.com

Abstract: This paper summarizes and presents research progress on the fundamentals of the development of creep damage constitutive equations for high Cr steels including 1) a brief summary of the characteristics of creep deformation and creep damage evolution and their dependence on the stress level and the importance of cavitation for the final fracture; 2) a critical review of the state of art of creep damage equation for high Cr steels; 3) some discussion and comments on the various approaches; 4) consideration and suggestion for future work. It emphasizes the need for better understanding the nucleation, cavity growth and coalesces and the theory for coupling method between creep cavity damage and brittle fracture and generalization.

Keywords: high Cr steels, creep damage constitutive, creep damage mechanism, stress level dependence, creep cavity

1. Introduction

Demands on the thermal efficiency and reduction of CO_2 emissions for fossil plants lead to the development and applications of high chromium ferritic creep-resistant steels. The steel P91 strengthened by Nb and V addition is being widely used for temperature up to 873 K. The 9-12% Cr steel strengthened by replacing Mo with W, namely P92 and P122 are being now performed for application to boiler component of ultra-supercritical (USC) power plants operating at around 898 K.

It is well known that the long term performance and creep rupture strength is below originally expected from simple extrapolation of short term creep data resulting in reductions in some of the values quoted as representing long term creep life, e.g. [1-4] among other publications. For example, Ennis et al [1] found that the stresses of above 150 MPa at 600^o C and above 110 MPa for 650^{o}C, the Norton stress exponent *n* was found to be 16; below these stresses an *n* value was 6. Similarly, for the ASTM grade 92 steel crept at 550–650 °C for up to 63 151 h, Lee et al found that [2] the stress exponent for rupture life to be decreased from 17 in short-term creep to 8 in long-term creep. It was also reported the change of fracture mechanisms with stress level [2]. More quantitative description of the dependence of the stress level on the minimum creep strain rate, creep lifetime, and strain at failure can be found in [4], for example shown in Figs. 1 to 3.

There were several literature review and summary about the microstructural changes/evolutions and their effects on the creep strength. For example, Parker [5] summarized the following microstructure degradation effects appearing to be primarily responsible for the loss of long term creep strength: a. the formation of new phase which leads to dissolution of fine M_2X and MX carbinitrides; b. recovery of the dislocation substructure (increase in subgrain size) and reduction in the overall dislocation density. This may be seen generally but is believed to initiate as the result of preferential recovery of microstructure in the vicinity of prior austenite grain boundaries, and c. the development of creep voids resulting in a significant loss of creep ductility. This will be discussed further in next section.

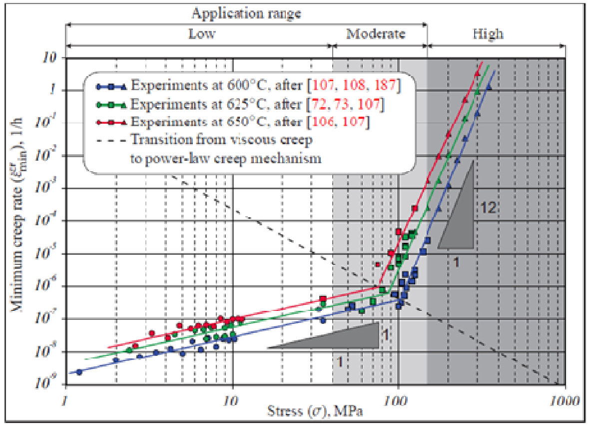

Fig. 1 Dependence of minimum creep strain rate on stress for 9Cr-1Mo-V-Nb [4]

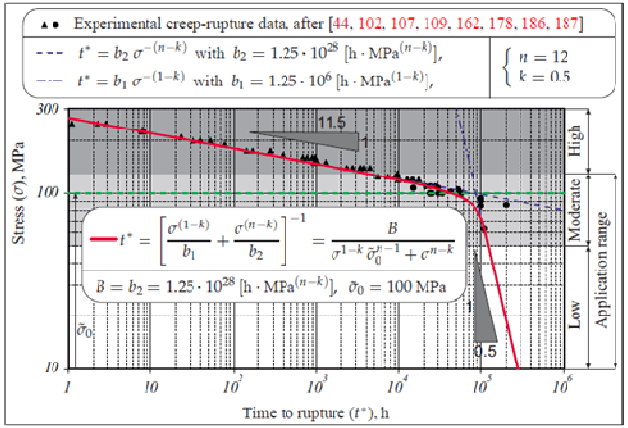

Fig. 2 Experimental creep-rupture data for the 9Cr-1Mo-VNb steel at 600◦C [4]

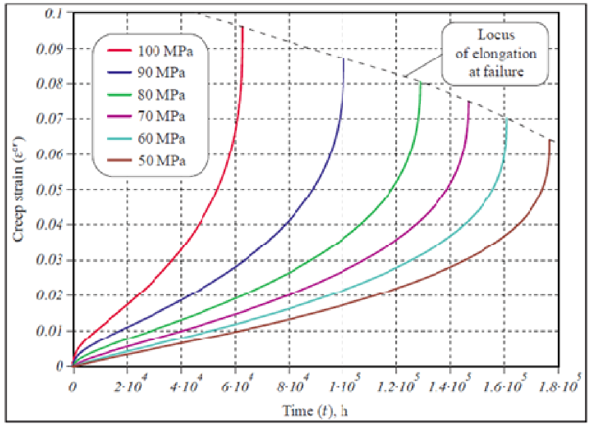

Fig. 3 stress-dependent multi-axial failure criterion based on long-term strength of the 9Cr-1Mo-V-Nb steel at 600◦C [4]

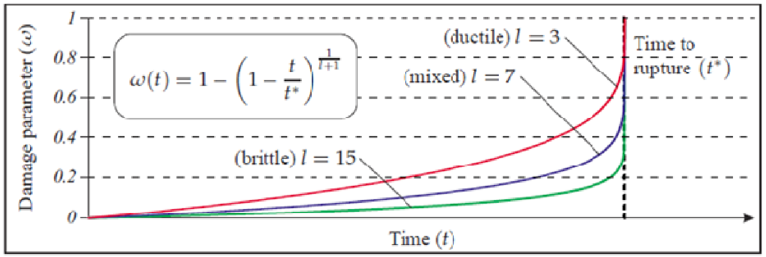

Fig. 4 Classification of accumulation character types for the scalar damage parameter *w* according to Kachanov-Rabotnov concept [4]

The change of the stress exponent value *n* in Norton power law indicates a change of creep deformation mechanism and possible the creep damage mechanism [4-8]. General speaking, that the creep deformation under lower stress is of diffusional and the void nucleation is controlled by the maximum shear stress; which is in line with the general understanding reported by Miannay [6]. Specifically, Lee et al [2] summarized and reported for P92 steel as: 1) the steel shows ductile to brittle transition with increasing rupture life, and the breakdown accords with the onset of brittle intergranular fracture; 2) creep cavities are nucleated at coarse precipitates of Laves phase along grain boundaries. It is further articulated that these findings suggest the following story of the breakdown of creep strength. Laves phase precipitates and grows during creep exposure. Coarsening of Laves phase particles over a critical size triggers the cavity formation and the consequent brittle intergranular fracture. The brittle fracture causes the breakdown. The coarsening of Laves phase can be detected non-destructively by means of hardness testing of the steel exposed to elevated temperature without stress.

Recently, more long term creep test data have been reported for high Cr steels. From the creep test of modified 9Cr-1Mo steel crept up to 70,000 h [9], it was reported that 1) no clear steady state was observed; 2) strain at failure is decreasing with the stress, 3) For evaluation of long-term creep strength properties, an experimental creep test data should be extrapolated in consideration of the stress dependence of creep deformation properties. Detailed investigation of microstructural change of G91 steel under long term creep up to 70,000 h was reported though no attention as paid to cavitation [10].

Furthermore, cavity was investigated in a long term creep test of P91 up to 100,000 h (stress 80 MPa and temperature 600^{o}C)[11]. Cavity was widely speeded over the specimen far away from the fracture surface, the site for cavity is clearly associated with Laves; the average equivalent diameter is 4 to 6 um, and the cavity density is about 10 to 20; the creep cavity is strongly associated with Lave phase.

Furthermore, the applications of these high Cr steels have been further hampered due the early cracking in weldment, namely Type IV cracking. It occurs in the FG-HAZ or IC-HAZ of weldment [12-15]. Firstly [12], the susceptibility of Type IV cracking is due to weak creep region in HAZ due to thermal cycle, as well as mismatch of the mechanical properties in weldment. Secondly [12], it has been that $M_{23}C_6$ precipitates and Laves phases form faster in the fine grain HAZ region in 9Cr martensitic type of steels compared with the other regions of the weldment. This metallurgical effect further increases the vulnerability of the type IV region. Since not only are matrix-strengthen elements such as Cr, Mo and W depleted but the Laves phase offers potential sites for the nucleation of creep voids. High density of creep voids are developed over the HAZ, with crack formation and final propagation occurring only very late in creep life, according to [12]. With interrupted creep tests it was found that: the creep voids begin to form at the early state (at about 0.2 of rupture lifetime) and the number of voids increases all the way up to about 0.7 of rupture lifetime [13]. After that it can be considered that the rate of void coalescence is higher than that of void formation. With the coalescence of creep voids, they grow into the crack, which is known as Type IV cracking. The area fraction of creep voids can be a good variable to predict the creep life since it always tends to increase during creep. They also suggested that the high level stress triaxial factor combined with the large equivalent creep strain in the fine grained HAZ accelerate the void formation in P91 steel weld joint during creep at elevated. Recently, Parker summarized [8] as: a. it is now widely accepted that in creep tests at relatively high stress and temperature the results of cross weld creep testing are not typical of long term damage in component welds; b. clearly then it is important to select test conditions and specimen geometries for laboratory test programs so as to produce failures where the damage mechanisms are relevant to long terms service, c. using these conditions it is apparent that failure occurs as a consequence of nucleation, growth and link up of creep voids. It appears that the damage is significantly greater within the volume of the specimen where relatively high constraint conditions are developed; and d) the Type IV life is significantly below that of the parent under the same conditions. It was also reported by Parker [13] that further work is in progress to examine Grade 91 welded samples which have been tested to different creep life fractions with advanced characterization techniques to establish further details of creep cavity nucleation and growth within the weld HAZ. Recently an investigation of Type Iv failure was reported [14].

For the safe design and operation, as well as for better design and develop new creep resistant steel itself, it is important to understand the creep damage evolution, particularly in terms of the detailed knowledge of nucleation, growth, and coalescence under different stress levels and stress states are needed. That is one of new research directions and it is understood that EPRI has undertaken [13] among others.

On the other hand, creep damage models have been developed. It is the intention to develop a set of creep damage constitutive equations which are suitable for this type of steels and its welds for a wide range of stress levels. Preliminary literature review of the creep deformation mechanisms and creep damage mechanism has been conducted and reported [7-8]. This paper expands the literature review on the creep damage constitutive equations developed and/or used for high Cr steels [16] paying more attention to the cavity nucleation and growth. This paper contributes to knowledge and the method for the development of creep damage constitutive equations.

2. Microstructural evolution and creep cavity

Creep cavities are observed mostly at grain boundaries perpendicular to the applied stress. The first to observe that nucleation is often strain controlled was probably Needham et al, according to Magnusson [12]. This was also found by Dyson [17] for ferritic 2.25% Cr steel, austenitic 347 steel, and Ni-based Nimonic 80A. The continuous nucleation has also been confirmed for 12% Cr steels by Wu et al [18].

The significance of the creep cavity for damage is also supported by the long-term creep test of G91 (100,000 h) [11], 12%Cr steel (up to 139,971 h) [19]. It was reported and stated that brittle fracture is of intergranular [2, 20]. Furthermore, it was qualitatively illustrated that the nucleation and cavity growth took about 80% of life time while ultimate damage and final fracture took up about last 20% of life time.

There are two types of view on the cavity nucleation mechanisms, e.g. creep strain controlled or local stress controlled. Yin [20] proposed a creep controlled damage controlled by power law of creep strain recently. The influence of stress state on the formation and growth of cavity has been highlighted and investigated experimentally by Gaffard *et al* [21] via notched bar creep tests of P91 material. Furthermore, Gaffard *et al* proposed the nucleation rate is strain controlled also depends on the stress state and a frame work of multi-deformation and damage mechanisms, which differs from other stress controlled nucleation law developed in Chu and Needleman [22] or Herding and Kuhn [23], without giving further explanation and justification. On contrary, Magnusson [12] adopted a linear creep strain control nucleation and growth of cavity for analyzing the creep strain and damage under uniaxial creep condition.

It seems that there is not adequate and/or definite experimental data for validation. However, it is noted that, advanced/sophisticated techniques do come into use and some useful results have been produced. The first one is the application of microtomography to investigate the creep cavity damage where the size, shape and spatial distribution of voids can be obtained [25]; the second is interrupted creep testing [13] where, combined with FE analysis, the void density and size and their distribution can be investigated and the influence of stress states can be identified.

The application of microtomography to E911 after long term creep 26,000 h at 575 °C under multi-axial stress state [24] the stress tri-axiality has the highest correlation coefficient (≈0.98) with the volumetric void density, the Von Mises stress and maximum principal stress have similar correlation, but, smaller, coefficients, still large enough to indicate their influence on damage. Its application to copper [23] has provided four dimensional characteristics of creep cavity growth in copper. Its finding has been compared with creep damage models.

3. Physically based Creep damage Mechanics

3.1 Dyson Framework

The physically based continuum creep damage mechanics (CDM) was summarized and detailed in one of Dyson's publication [17] and the creep damages were grouped into broad categories of creep damage based on solely on the kinetics of damage evolution, and they are: strain-induced damage; thermal induced damage; and environmentally induced damage. For brevity, only the relevant damage mechanism, damage rate, and strain rate are included here:

Strain-induced damage: creep-constrained cavity nucleation controlled:

$$D_N = \frac{\pi d^2 N}{4};\ \dot{D}_N = \frac{k_N}{\epsilon_{f,u}};\ \dot{\varepsilon} = \dot{\varepsilon}_o sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_N)}\right] \quad (1)$$

Strain-induced damage: creep-constrained Cavity Growth Controlled:

$$D_G = \left(\frac{r}{l}\right)^2;\ \dot{D}_G = \frac{d}{2lD_G}\dot{\varepsilon};\ \dot{\varepsilon} = \dot{\varepsilon}_o sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_N)}\right] \quad (2)$$

Strain-induced: multiplication of Mobile Dislocation:

$$D_d = 1 - \frac{\rho_i}{\rho};\ \dot{D}_d = C(1-D_d)^2;\ \dot{\varepsilon} = \frac{\dot{\varepsilon}_0}{1-D_d} sinh\left[\frac{\sigma(1-H)}{\sigma_0}\right] \quad (3)$$

Thermally-induced: particle coarsening;

$$D_p = 1 - \frac{P_i}{P};\ \dot{D}_p = \frac{K_p}{3}\left(1-D_p\right)^4;\ \dot{\varepsilon} = \frac{\dot{\varepsilon}_0}{1-D_d} sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_p)}\right] \quad (4)$$

Thermally-induced: depletion of solid solution element:

$$D_s = 1 - \frac{\bar{C}_t}{C_0};\ \dot{D}_s = K_s(1-D_s)D_s^{1/3};\ \dot{\varepsilon} = \frac{\dot{\varepsilon}_0}{1-D_s} sinh\left[\frac{\sigma(1-H)}{\sigma_0}\right] \quad (5)$$

This framework looks almost universal, and any need for the development of creep damage constitutive equations can be met combining the relevant elementary creep damage from the list.

However, it is essentially a uniaxial version and the multi-axial version needs to be generalized. This is not straightforward and will be discussed later.

3.2 Specific Applications

3.2.1. Yin *et al* [20] proposed an approach for creep damage modeling of P92 steel by including multiplication of mobile dislocation, depletion of solid solution element, and particle coarsening, equations 3, 4, 5 respectively, and replacing the strain induced damage by a new cavity damage kinetic equation:

$$D_N = A\varepsilon^B \quad (6)$$

where A and B are temperature dependent material constants. The justification was not given fully in the original paper. This uniaxial version was used to the intermediate and high stress level. This version has also been used for P91 steel. The creep cavitation damage is essentially creep strain controlled. There is no multi-axial version proposed yet, except an attempt by Yang *et al* [26].

3.2.2 Chen *et al* [27] had essentially adopted Yin's approach and developed a creep model for T/P91 material under high stress level (130 to 200 MPa) at 600^{o}C, existing literature have been used in the determining the values of material constants. Including the same elementary damage similarly to Yin's approach

3.2.3 Basirat *et al* [28] inserted them directly into the Orowan's equation. The temperature and stress level's influence is realized by the dependence of two material constants. It is worthy comparing the similarity between this and Yin's approach.

3.2.3 Semba *et al* [29] adopted the above Dyson's framework and proposed a version of creep damage constitutive equation where a novel way to incorporated the strain-dependent coarsening of subgrains and network dislocations.
3.2.4 Oruganti *et al* [30] aimed to build a comprehensive creep model using Dyson's framework. The significant efforts were placed on identify the critical microstructural features that controlled creep and quantification of their effect and evolution with time and strain. In this approach, coarsening of carbonitrides and subgrain structure resulting from martensitic transformation were incorporated in the damage constitutive equations.

3.3 Multi-axial Version

This specific version of multi-axial creep damage constitutive equations was originally developed for low Cr alloy Perry and Hayhurst [31]. However, due to its popularity and been used by some researchers [32] to analyze the creep damage problem of this type of steel and weldment, it is included in this review. The multi-axial generalization is based on the isochronous surface concept via stress state coupling on damage evolution.

$$\frac{d\varepsilon_{ij}^{c}}{dt} = \frac{3}{2}\frac{S_{ij}}{\sigma_{eq}} A \sinh\left[\frac{B\sigma_{eq}(1-H)}{(1-\Phi)(1-\omega_2)}\right], \qquad (7)$$

$$\frac{dH}{dt} = \frac{h\dot{\varepsilon}_{e}^{c}}{\sigma_{eq}}\left(1-\frac{H}{H^*}\right), \qquad (8)$$

$$\frac{d\Phi}{dt} = \frac{K_c}{3}(1-\Phi)^4, \qquad (9)$$

$$\frac{d\omega_2}{dt} = DN\dot{\varepsilon}_{e}^{c}\left(\frac{\sigma_1}{\sigma_{eq}}\right)^{\nu}, \qquad (10)$$

where N=1, $\sigma 1>0$ (tensile) and N=0, $\sigma 1<0$ (compressive). A, B, h, H*, Kc, D and ν are material constants, where ν is related to tri-axial stress-state sensitivity of the material. The state variable H ($0 < H < H^*$) represents the strain hardening occurring during primary creep. The H variable increases during the evolution of creep strain and reaches a maximum value of H* at the end of primary stage and remains unchanged during the tertiary creep. The state variable Φ ($0<\Phi<1$) describes the evolution of spacing of the carbide precipitates. The last-state variable, ω_2 ($0<\omega_2<1/3$), represents intergranular cavitation damage. The maximum value of ω_2 (at failure) is related to the area fraction of cavitation damage at failures, which in a uniaxial case is approximately 1/3.

3.4 Petry's Modification to Hayhurst Approach [33]

A one state variable version of creep damage constitutive equations (Hayhurst, [34] 1972) was slightly modified by Petry et al. and it is given as:

$$\begin{cases} H = H_1 + H_2 \\ \dot{H}_1 = \dfrac{h_1}{\sigma_{eq}}(H_1^* - H_1)\,\dot{p} \\ \dot{H}_2 = \dfrac{h_2}{\sigma_{eq}}\dot{p} \end{cases} \qquad (11)$$

$$\underline{\dot{\varepsilon}}^{vp} = \frac{3}{2}\dot{\varepsilon}_0 \sinh\left(\frac{\sigma_{eq}(1-H)}{K(1-D)}\right)\frac{\underline{\sigma}^D}{\sigma_{eq}} \qquad (12)$$

$$\dot{D} = A_0 \sinh\left(\frac{\alpha\sigma_1 + (1-\alpha)\sigma_{eq}}{\sigma_0}\right) \quad (13)$$

Comparing to the initial formulation, the hardening variable *H* has been attached to a more complex kinetics, with a subdivision between H_1 and H_2 parts, these two intermediary variables are respectively associated to the increasing and decreasing parts of the global hardening variable *H*.
This set of creep damage constitutive equations has been used for the prediction of uniaxial creep bar of P91 and P92 with success. Of course, there was some compromise in determining the value of α due to lack of experimental data for notched bar test. The critical damage value $D_c = 0.132$ was determined by comparing simulation against experimental data. The stress state index α is adopted from previous research.

3.5 Naumenko's Formulation [35-36]

Within the phenomenological approach framework, specific stress-range-dependent creep damage constitutive model was proposed in [35-36] and [4]. For the high stress level, it is the necking criterion to play and under low stress level, it is boundary cavity damage to play. The key features for the latter are:

1. The hyperbolic sine law has been replaced by the sum of a linear and power-law stress functions:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \frac{\sigma}{\sigma_0} + \dot{\varepsilon}_0 \left(\frac{\sigma}{\sigma_0}\right)^n = \dot{\varepsilon}_0 \frac{\sigma}{\sigma_0}\left[1 + \left(\frac{\sigma}{\sigma_0}\right)^{n-1}\right],$$

2. Damage evolution is controlled by stress not creep strain

$$\dot{\omega} = \frac{b}{l+1}\left(\frac{\sigma_T}{\sigma_0}\right)^k \frac{1}{(1-\omega)^l}, \quad \sigma_T = \frac{\sigma_I + |\sigma_I|}{2},$$

The multi-axial version is still of creep strain controlled and affected by the states of stress.

3.6 Multi Mechanisms Creep Failure Model

This creep failure model was developed based on the concept of that both deformation and damage evolution under multiple viscoplastic mechanisms is used to present high temperature creep deformation and damage of a martensitic stainless steel in a wide range of load levels [21].

$$\dot{\underline{\varepsilon}} = \dot{\underline{\varepsilon}}_e + \dot{\underline{\varepsilon}}_{vp} + \dot{\underline{\varepsilon}}_{dif}$$

Where the strain component is elastic strain, power-law creep strain, and diffusional creep strain tensor, respectively. The creep damage of each mechanism is explicitly defined using porous viscous material model:

$$\frac{\sigma_{eq}^2}{\sigma_m^{*2}} + q_1 f^* \left[h_M(X) + \frac{1-M}{1+M}\frac{1}{h_M(X)}\right] - 1 - q_1^2 \frac{1-M}{1+M} f^{*2} \equiv 0$$

This model has been used for predicting Type Iv failure of P91 weldment and the result is in agreement with experimental observation.

4. Void Growth Damage Model [37]

A void growth model considering combined mechanism of diffusion and power law creep deformation under constrained condition for the void growth, and derived the void growth rate equations for spherical and crack-like voids was proposed in [37]. The void growth simulation program incorporating the void growth rate equations was also developed [7]. The void growth equations for the spherical and the crack-like voids are expressed by the following equations for spherical and crack-like void, respectively;

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{a\dot{\epsilon}_c}{2h(\psi)}\left(\frac{\Lambda}{a}\right)^3 [L+M]^{-1}$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\alpha a\dot{\epsilon}_c}{4\pi h(\psi)}\left(\frac{\Lambda}{a}\right)^{5/2} [L+M]^{-3/2}$$

Void initiation period, ti is expressed by the next equation.

$$t_i = A\sigma_n^q$$

where A and q are material constants.

5. The Generalization Method based on Isochronous Loci
(Validation on Hayhurst Formulation) [38]

Although the set of creep damage constitutive equation described in 3.3 was popular, a critical review revealed its deficiency inherent from its generalisation method, namely: this method used lifetime (under plane stress condition) only and ignored creep deformation consistency [38-39].

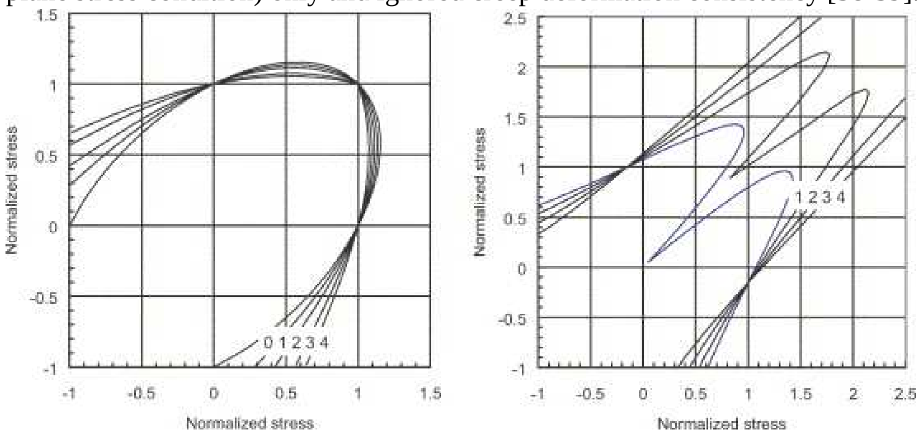

Fig. 5 Isochronous rupture loci for Hayhurst formulation [37]

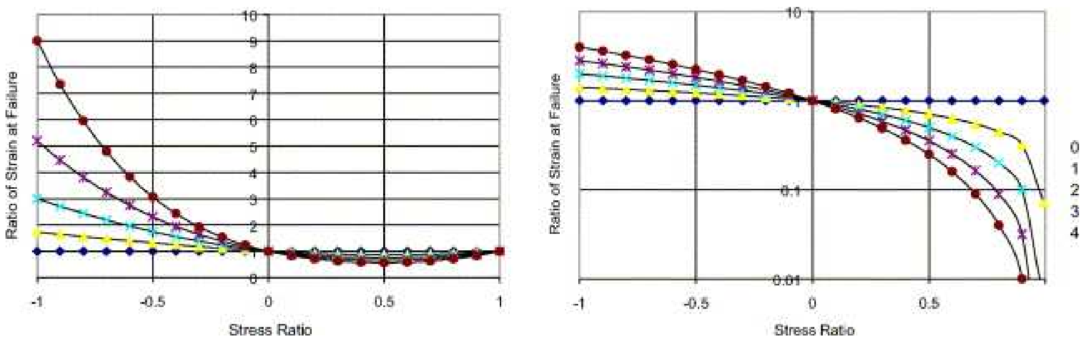

Fig. 6 Ratios of strain at failure of Hayhurst formulation [38]

The critical validation on the Hayhurst formulation has revealed that [38]:

1) A significant creep strength increase under plane strain condition when the tri-axiality is about the order of 1.5–2.8 as shown in Fig. 5. This increase is not realistic according to well-known creep

strength theory. Thus, the previous formulation is unable to find a value for stress sensitivity that can satisfy the isochronous rupture loci under plane stress and plane strain conditions simultaneously. This deficiency was not revealed in previous constitutive equation development and/or validation.

2) The lifetime predicted under uni-axial tension and bi-axial equal tension is the same, which does not agree with the generally experimental observation.
3) Furthermore, the ratios of strain at failure for the previous formulation shown in Fig. 6 are conjugated with the shape of isochronous rupture loci shown in Fig. 1 through the common stress sensitivity parameter v. Thus, there is no freedom provided to produce strain at failure consistent with experimental observation. This further demonstrates its incapability to predict consistently with experiment.

Furthermore, the Yin's uniaxial version has been generalized into multi-axial version where the creep strain and stress in uniaxial damage rate equation are simply replaced by effective creep strain and Von-Mises stress [26]. Firstly, it was found that the life time under plane stress situation is far longer than it is observed and/or expected, suffering the similar problem occurred in Hayhurst's multi-axial formulation mentioned above. This indicated the need to fundamentally research on the multi-axial generalization method. Secondly, the calibrated equation (6) based on middle and high stress is not applicable to lower stress as the predicted creep curve is still showing high strain at failure. This reveals further supported that the result of the evolution of cavity damage is different between lower and high stress level, probably resulted from different nucleation and growth laws in the first place.

6. Discussion and Conclusion

The following considered in the development of creep damage constitutive equations under lower stress:

1) Under lower stress range, the minimum creep strain rate is more or less linear to the stress applied; therefore a summation of linear and exponential function is a good choice;
2) The strain at failure is much small and the ultimate fracture is of brittle;
3) It has been reported in [4] schematically that the exponential l to present brittle damage is in the order of 8 schematically, the graph of creep cavity damage and time shows a abruptly increase towards the failure.

   On the other hand, a critical damage of 0.132 has been practically chosen which is very small; Combining the above together, it effectively indicates the creep curve for that version is almost a straight line and rupture, and there is no real increase of creep strain due to creep cavity.
4) Consequently, it raises a question of the coupling of the creep deformation and the creep cavitation. It is hence argued here that we could decouple them.
5) It is worth cross checking between the softening and the mechanism based approach to see if they agree or not.

More fundamental research is still needed in:

1) understand the characteristics of nucleation, growth, and coalesces; the application of X-atomograph seems provide some hope;
2) advance the classical cavitation theories to the lower stress range
3) coupling between creep cavitation and creep deformation and brittle fracture

4) develop and validate creep cavitation model
5) generalize into 3 dimensional version

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