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Critical review the development of creep damage constitutive equations for high Cr steel

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Abstract – The creep deformation and failure of high Cr steel component or its weldment is a a challenging problem for power generation industries. There is a lack of good understanding of the precise nature and role of cavitation in terms of creep deformation and rupture. Creep damage constitutive equation developed either specifically developed for this type of steel or borrowed from existing one have been used in research. This review demonstrate the current state and outline the direction of future work.

Introduction and Creep Cavitation

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 (Parker, 2013a). For example, for P92 steel (Ennis et al, 1997) found that the stresses of above 150 MPa at 600^o C and above 110 MPa for 650^oC, the Norton stress exponent *n* was found to be 16; below these stresses an *n* value was 6. Recently a review of the microstructural change was conducted by Yan et al (2013). The following microstructure degradation effects appear to be primarily responsible for the loss of long term creep strength is summarized by Parker (2013a) as: 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.

The significance of the creep cavity for damage is also supported by the long-term creep test of 12%Cr steel (up to 139,971 h) it revealed that creep cavities lined up along the former austenite grain boundary perpendicular to the direction of applied stress (Eggeler, 2009). The influence of stress state on the formation and growth of cavity has been investigated experimentally by Gaffard *et al* (2005) via notched bar creep tests of P91 material. Multi-deformation and damage mechanisms: the nucleation rate is strain controlled and its rate also depends on the stress triaxility; which differs from other stress controlled nucleation law developed in Chu and Needleman (1980) or Herding and Kuhn (1996), without giving further explanation and justification. On contrary, Magnusson (2010) adopted a linear nucleation and growth of cavity for analyzing the creep strain and damage under uniaxial creep condition.

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 (Miannay, 2001, An *et al*, 2013a, 2013b, and Magnusson 2010). 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.

However, the applications of these steels have been hampered due the early cracking in weldment, namely Type IV cracking. It occurs in the FG-HAZ or IC-HAZ of weldment. The susceptibility of Type IV cracking is due to weak creep region in HAZ due to thermal cycle, as well as mistach of the mechanical properties in weldment. Furthermore, 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 Parker, 2013b). 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 Parker, 2013b). 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 (Li, *et al*, 2009). 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.
Parker summarized 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 lik 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 (2013b) 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.

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 (Parker, 2013b).
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 (An, 2013a, 2013b). This paper intends to review the existing creep damage models developed and/or used in the analysis of creep deformation and creep damage problem of high Cr steel and its weldment to establish the state of art knowledge on the creep model/creep damage constitutive equation. This paper contributes to knowledge and the method for the development of creep damage constitutive equations.

3. Physically based Creep damage Mechanics

3.1 Dyson framework

The physically based continuum creep damage mechanics (CDM) has be summarized and detailed in one of Dyson's publication (Dyson, 2000). According to Dyson (2000) he grouped the damage 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 elements of damage mechanism, damage rate, and strain rate is included here for brevity and relevance:
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 as long as the elementary creep damage can be identified from the list.
It is essentially a uniaxial version and the multi-axial version can be generalized though it is not straightforward as it looks. These two points will be discussed later.

3.2 Specific Applications

3.2.1. Yin et al (2008) proposed an approach for creep damage modeling of P92 steel by including multiplication of mobile dislocation, depletion of solid solution element, and particle coarsening, equation 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. Only this uniaxial version has been used to the middle and high stress level. This version has been used for P91 steel. The creep damage is still essentially creep strain controlled. There is no multi-axial version proposed yet.

3.2.2 Chen *et al* (2011) 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°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* (2012) 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 Semab *et al* (2008) 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* (2011) 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 (1996). However, due to its popularity and been used by some researchers (Hyde, 2006) 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, σ1>0 (tensile) and N=0, σ1<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<Φ<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

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

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

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

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

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 due to lack of experimental data for notched bar test.

3.5 Naumenko's Formulation

Within the phenomenological approach framework, a version of stress-range-dependent creep damage constitutive model was proposed (Naumenko, 2009). The key features 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

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

It claims that the definition of σ_T offers the possibility of transition from the pure ductile to pure shear brittle damage mode. This kinetic equation for creep damage rate is consistent with experimental fact that voids and microcracks nucleate on grain boundaries which are perpendicular to the first principal direction of the stress tensor and the void formation may progress even under pure hydrostatic pressure.

4. 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.

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

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:

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

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

5. The Validation on Hayhurst Formulation (Xu, 2004)

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 (Xu, 2000a and 2000b).

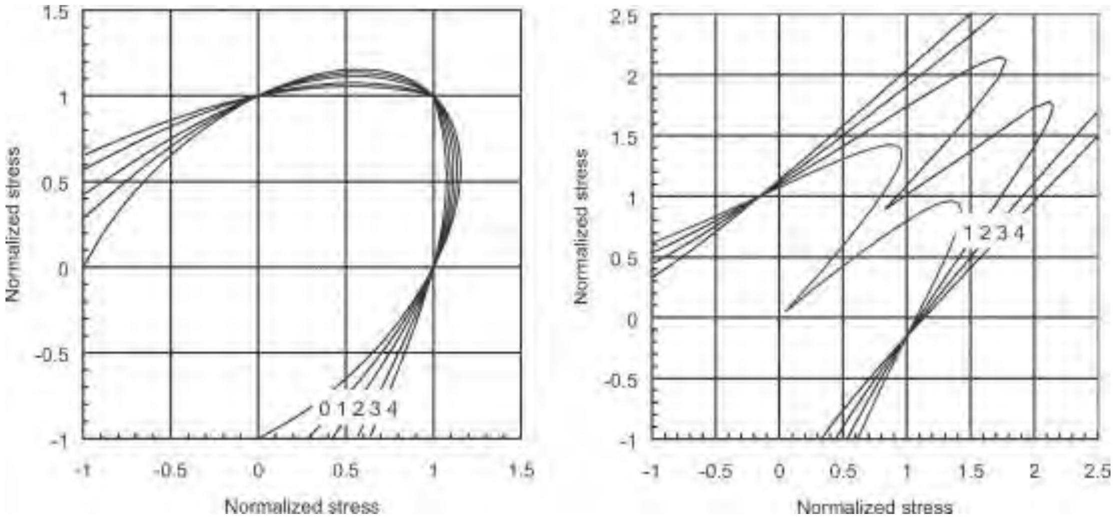

Fig. 1 Isochronous rupture loci for Hayhurst formulation (Xu, 2004)

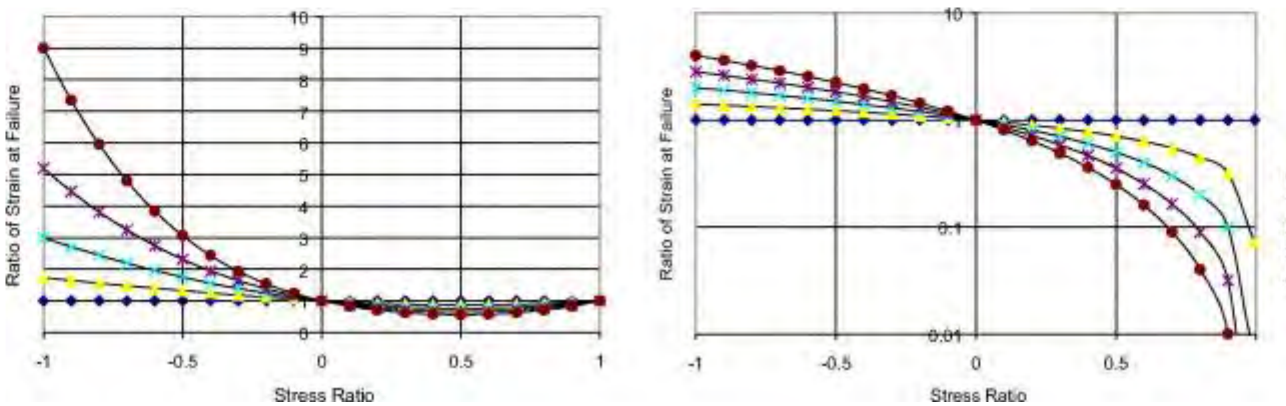

Fig. 2 Ratios of strain at failure of Hayhurst formulation (Xu, 2004)

The critical validation on the Hayhurst formulation has revealed that (Xu, 2004):

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. 1. 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. 2 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.

5. Discussion

1. The high Cr steel components will work under lower stress regime where the creep deformation and the creep damage evolution rules may differ from that under the middle and high stress level. It was noted

that the sum of linear and power-law creep rate equation and the multiple mechanisms approach offer apparent potential for achieving this task;

2. Dyson's framework is open and it is up to user to select to right elementary damage mechanisms to compose a suitable one. However, as it is primarily a uniaxial version, how to generalize it into multi-axial version is not straight forward and prone to suffering the pitfall identified in Hayhurst's approach.

3. However, conceptually, it has been limited to strain induced damage. The stress controlled damage evolution kinetic rules and laws may be included in future;

4. In fact, it is reported that the cavity is continually nucleated and grow and the nucleation and growth may be described differently depending on the level of stress and influenced by the stress sate. At this moment, only multiple creep failure model has clearly offered that capability;

5. There is a need to understand more about the nucleation, growth and coalesces.

Future work is outlined as:

1) better understanding the precisely the nucleation, growth and rupture in the parent as well as in welds under different stress levels and states;

2) develop the appropriate damage evolution rules;

3) develop the generalization method and conduct vigorous validation.

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