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

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Content

1 Introduction

- High Cr steel such as P91, P92 and E011 developed and used
- Long term performance and creep rupture strength is below originally expected from simple extrapolation of short term creep data
- For example, Ennis et al

  n = 16 if the stresses > 150 MPa at 600^{o} C

  and > 110 MPa at 650^{o}C,

  n = 6 if the stresses < these values
- Similarly, for the ASTM grade 92 steel, Lee et al

  n = 17 for short test

  n = 8 for long-term test (550–650°C for up to 63 151 h)

- There were several literature review and summary about the microstructural changes/evolutions and their effects on the creep strength.
- For example, Parker [3] summarized the following microstructure degradation effects appearing to be primarily responsible for the loss of long term creep strength:

➢ the formation of new phase which leads to dissolution of fine M_2X and MX carbinitrides;

➢ 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

➢ the development of creep voids resulting in a significant loss of creep ductility.

- General speaking, that the creep deformation under lower stress is of diffusional and the void nucleation is controlled by the maximum shear stress;
- Specifically, Lee et al summarized and reported for 9Cr–1.8W–0.5Mo–VNb steel as:
  - The steel shows ductile to brittle transition with increasing rupture life, and the breakdown accords with the onset of brittle intergranular fracture;
  - Creep cavities are nucleated at coarse precipitates of Laves phase along grain boundaries;

- It is further articulated that

  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.

- Furthermore, Type IV cracking in the FG-HAZ or IC-HAZ.
  - Weak creep region in HAZ due to thermal cycle
  - Mismatch of the mechanical properties in weldment
  - $M_{23}C_6$ 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
  - 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 [8].

- Interrupted creep tests of Mod.9Cr-1Mo Steel found that:
  - the creep voids begin to form at the early state (at about 0.2 of rupture lifetime)
  - the number of voids increases all the way up to about 0.7 of rupture lifetime.
  - 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 tri-axial 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 on welds [8] as:
  - 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;
  - 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;
  - 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;
  - the Type IV life is significantly below that of the parent under the same conditions.

- It was also reported by Parker [8] 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.
- The detailed knowledge of nucleation, growth, and coalescence under different levels and states of stress are needed.

2 Cavitation

- 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 [7] .
- This was also found by Dyson [11] 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 [12].
- The significance of the creep cavity for damage is also found in the long-term creep test of 12%Cr steel (up to 139,971 h): creep cavities lined up along the former austenite grain boundary perpendicular to the direction of applied stress [13].

- There are two types of cavity nucleation mechanisms, e.g. creep strain controlled or local stress controlled.
- Yin [14] proposed a creep strain controlled damage controlled (power law) recently.
- The influence of stress state on the formation and growth of cavity has been highlighted and investigated experimentally by Gaffard *et al* [15] 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
- (stress controlled nucleation law developed in Chu and Needleman [16] or Herding and Kuhn [17])
- On contrary, Magnusson [8] 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.
- For example, the application of microtomography to investigate the creep cavity damage where the size, shape and spatial distribution of voids can be obtained [18-19].
- The second is interrupted creep testing [9] 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.
- More and new ……

- The application of microtomography to E911 after long term creep 26,000 h at 575 °C under multi-axial stress state [18]

➢ 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 [19] has provided four dimensional characteristics of creep cavity growth in copper.

3 Physically based creep damage constitutive equations

- **3.1 Dyson framework**
- The physically based continuum creep damage mechanics (CDM) was summarized and detailed in one of Dyson's publication [11].
- According to that 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
  - ➢ 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:

equ. (1)

$$D_N = \frac{\pi d^2 N}{4}$$

$$\dot{D}_N = \frac{kN}{\epsilon_{f,u}}$$

$$\dot{\varepsilon} = \dot{\varepsilon}_o sinh\left[\frac{\sigma(1-H)}{\sigma_O(1-D_N)}\right]$$

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

equ. (2)

$$D_G = \left(\frac{r}{l}\right)^2$$

$$\dot{D}_G = \frac{d}{2lD_G}\dot{\varepsilon}$$

$$\dot{\varepsilon} = \dot{\varepsilon}_o sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_N)}\right]$$

;

- Strain-induced: multiplication of Mobile Dislocation: equ. (3)

$$D_d = 1 - \frac{\rho_i}{\rho}$$

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

- Thermally-induced: particle coarsening:
  equ. (4)

$$D_p = 1 - \frac{P_i}{P}$$

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

- Thermally-induced: depletion of solid solution element: equ. (5)

$$D_s = 1 - \frac{\bar{C}_t}{C_o}$$

$$\dot{D}_s = K_s(1 - D_s)D_s^{\,1/3};\ \dot{\varepsilon} = \frac{\dot{\varepsilon}_o}{1-D_s} sinh\left[\frac{\sigma(1-H)}{\sigma_O}\right]$$

- This framework seems 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.
- It is essentially a uniaxial version
- The multi-axial version needs to be generalized. How to do it?

- **3.2 Specific Application**
- **3.2.1 Yin's uniaxial version**

Yin *et al* [14] 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: equ. (6)

$$D_N = A\varepsilon^B$$

where A and B are temperature dependent material constants.
(Are they stress level dependent?)

- This version has also been used for P91 steel long term test
- The creep damage is still essentially creep strain controlled.
- There is no multi-axial version proposed yet

- **3.2.2 Chen's uniaxial version**

Chen *et al* [21] 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's uniaxial version**

Inserted them directly into the Orowan's equation. The temperature and stress level's influence is realized by the dependence of two material constants.

- **3.2.4 Semab's uniaxial version**

Semab *et al* [23] 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's uniaxial version**

Oruganti *et al* [24] 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 [25].

However, due to its popularity and been used by some researchers [26] 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.

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

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

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

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

where $N=1$, $\sigma_1 > 0$ and $N=0$, $\sigma_1 < 0$

A, B, h, H*, Kc, D and ν are material constants, where ν is related to tri-axial stress-state sensitivity of the material.

H ($0 < H < H^*$): 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.

Φ ($0<\Phi<1$) describes the evolution of spacing of the carbide precipitates.

ω2 ($0<\omega_2<1/3$), represents intergranular cavitation damage. The maximum value of ω2 (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**

A one state variable version of creep damage constitutive equations (Hayhurst, [28] 1972) was slightly modified by Petry et al. and it is given as:

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

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

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

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.

There was some compromise in determining α due to lack of experimental data for notched bar test.

- **3.5 Naumenko's approach**

Within the phenomenological approach framework, a version of stress-range-dependent creep damage constitutive model was proposed [29]. The key differences are:

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

Damage evolution is controlled by stress not creep strain

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

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

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 in a wide range of stress levels [15].

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

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.
- Later use of it for P92 did show some difficulty discrepancy in creep displacement

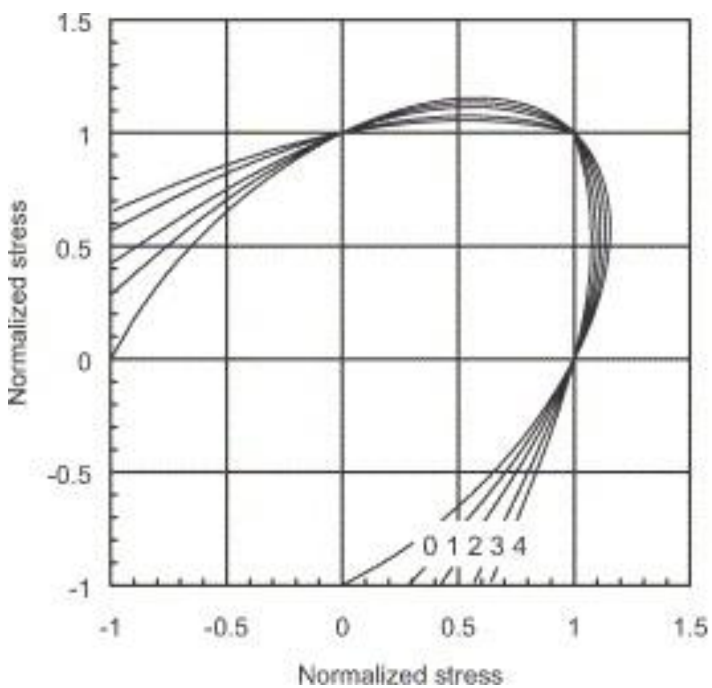
5. Multi-axial generalisation and validation

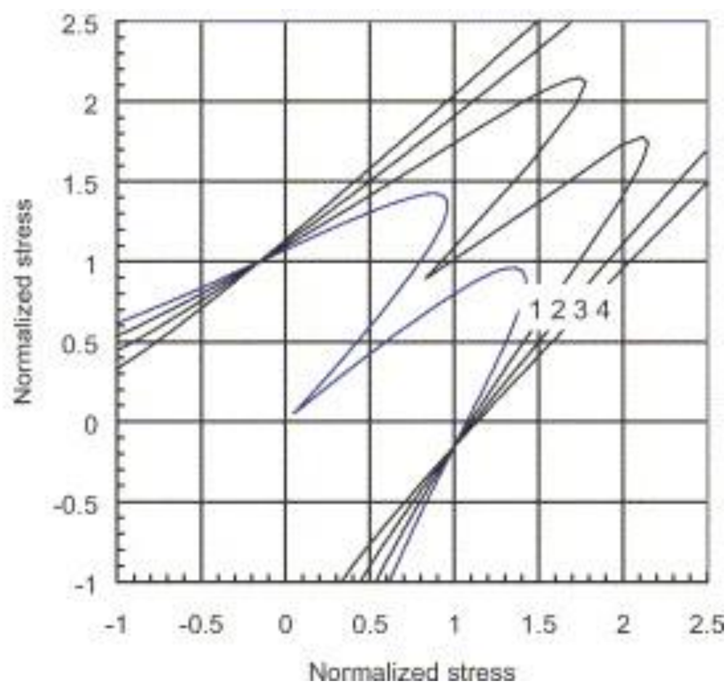
Multi-axial generation method: not well documented but essentially

- Creep damage evolution law is generalized: creep strain controlled but affect by the states of stress
- Coupling the creep damage with creep deformation

Validation of the Hayhurst' multi-axial formulation has revealed that [30]:

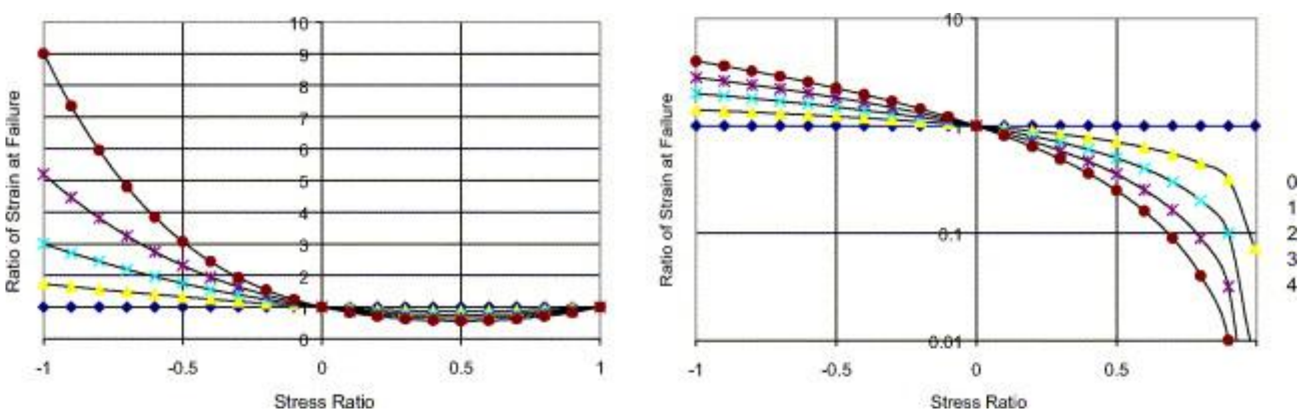
- A significant creep strength increase under plane strain condition when the tri-axiality is about the order of 1.5–2.8.





- The lifetime predicted under uni-axial tension and bi-axial equal tension is the same, which does not agree with the generally experimental observation.

- Furthermore, the ratios of strain at failure for the previous formulation shown are conjugated with the shape of isochronous rupture loci 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 [20].
- 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 also suggested 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.
- The material constants A and B is stress dependant?
- 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

- Stress breakdown:
  - 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.
  - The multiple deformation and damage mechanisms approach offers theoretically advantage.
  - Creep rate and stress relationship: the sum of linear and power-law creep rate; shine law, and the power law

- Different failure modes and the creep strain at failure

➢ The phenomenological curve fitting can not provide the solution suitable for a wide stress level

- The cavity nucleation, growth and coalesces
  - contributes to that final failure
  - lack of precise understanding under different stress levels and states
  - more experimental data is needed
  - How to interpret them is crucial for the developing and/or validating the nucleation and growth models

- Dyson’s framework seems is open and it is up to user to select to right elementary damage mechanisms to compose a suitable one.
  - However, conceptually, it has been limited to strain induced damage.
  - The stress controlled damage evolution kinetic rules and laws may be included in future?
  - The need is even more evident when considering the generalization for multi-axial version.

- Multi-axial generation: the creep damage law and its coupling with creep deformation

Thank you for
your time and listening