The relative significance of internal damage mechanisms on the overall creep damage and ultimate failure of P91 steel

Xin Yang[a], Qiang Xu[b], Zhongyu Lu[c]

School of Computing and Engineering, The University of Huddersfield, Huddersfield, HD1 3DA

[a]U1371902@hud.ac.uk;[b]Q.Xu2@hud.ac.uk;[c]J.Lu@hud.ac.uk;

Corresponding Author: Dr Qiang Xu, Q.Xu2@hud.ac.uk

Abstract

This paper reports research on the study of the relative significance of various internal creep damage mechanisms on the overall creep damage and lifetime of P91 steel. The study is essentially parametric investigation based on the individual internal creep damage mechanisms and phenomenological modelling of creep cavity damage. The simulated results do show the importance of the cavity damage among all the creep damage mechanisms. However, more importantly, it also points out the deficiency in the latest approach of phenomenological approach of modelling cavity damage over a wider stress range, and addresses the necessity of considering and incorporating the micromechanics/mechanism of nucleation, growth, coalescence into the creep damage constitutive modelling work. This paper contributes to the knowledge and method for creep damage mechanics.

Keywords: Creep Damage Modelling, Creep Damage Mechanisms, P91

1. Introduction

With an overall improvement in standards of living for the people of the world, scientists estimate that the world electricity consumption will rapidly rise up another 50% in the next 20 years. Accordingly, the improvement and development of advance energy resources which must be cost effective, sustainable and environment friendly, such as supercritical thermal power group and nuclear power, is absolutely essential[1]. On account of the requirement of power generation industry, modified 9Cr-1Mo alloy, normally known as grade P91 steel, has been applied comprehensively for high pressure and high temperature piping and headers in conventional power plants mainly in the outlet section of the boiler such as final superheater and also main steam piping[2]. These components operate under continuous high temperature and with sustained stress and eventually lead to fail; therefore most researches have focuses on creep damage in the design and operation of these components to ensure life security.

Recently, many research studies have been achieved in elucidation and modelling of the creep behaviour of modified 9Cr-1Mo steel by continuum damage mechanisms modelling. The evolution of creep strain rate with time has been studied by typically based on the dislocation theory: Firstly, the Orowan Equation was employed to relate the density of mobile dislocations and their glide velocity. Blum et al. (2002) said that the evolution of dislocations was estimated based on a model proposed [3]. Secondly, Orowan's equation was modified by adding the contributions of influences of various creep damage mechanisms such as solid solution depletion, precipitate coarsening, and cavitation [1]. However, the ultimate of the failure of material and components are strongly related to the cavity nucleation, growth and coalesce, though the precise nature of this process is not well understood yet.

Phenomenological modelling of creep cavity damage based on continuum damage mechanics (CDM) has been developed and used. Recently, a specific cavity damage kinetic equation for high Cr steels was proposed by Yin et al [4] and incorporated within McLean and Dyson's CDM framework (McLean and Dyson, 2000). Since then, Yunxiang and Ke Yang (2011) have adopted that approach and developed a set of creep damage constitutive equations for P91 alloy under the medium and high stress level, where the strain hardening, solute depletion, and particle coarsening were included, while the multiplication of mobile

dislocations was ignored [5]. Yin's approach has been appreciated and adopted by other researchers such as [1]. It is of industrial and academic value to assess the suitability of such approach over a wide range of stress as the stress breakdown is well-known problem.

This paper presents research on the study of the relative significance of various internal creep damage mechanisms on the overall creep damage and ultimate failure of P91 steel based on the set of Yunxiang Chen and Ke Yang's creep damage constitutive equations [5]. The study is essentially parametric investigation based on the individual internal creep damage mechanisms and phenomenological modelling of creep cavity damage. The simulated results do show the importance of the cavity damage among all the creep damage mechanisms. However, more importantly, it also points out the deficiency in the latest approach of phenomenological approach of modelling cavity damage over a wider stress range, and addresses the necessity of considering and incorporating the micromechanics/mechanism of nucleation, growth, coalescence into the creep damage constitutive modelling work. This paper contributes to the knowledge and method for creep damage mechanics.

2. Internal creep damage mechanics description

The creep curve under uni-axial tension typically shows the primary, steady state and tertiary. Creep damage mechanics is one of the latest developments of solid mechanics where the additional internal variables are used to depict the creep strain and failure within the continuum framework, the typical approaches are summarised here: the theory of continuum mechanics has a great advantage on the mathematical modelling. Therefore, there are many existing with some microscopic defects inside of materials, such as dislocation, inclusions, cavitation at el. In order to describe the effects of the microscopic defects, Kachanov provided the concept of continuous damaged mechanics. The development and evolution of the continuum damage modelling is based on the concept later on. The main microstructural changes of P91 (high Cr) alloy is summarized below:

2.1. Dimensionless parameter of strain hardening (H)

The model of primary creep is a modification of that suggested by Ion et al. [6]. The dimensionless parameter H is defined as

$$H = \frac{\sigma_i}{\sigma} \tag{1}$$

where σ is the stress and σ_i is an internal back stress generated during stress redistribution within strain Harding as inelastic strain accumulates. The rate of H is as follows

$$\dot{H} = \frac{h'}{\sigma}\left(1 - \frac{H}{H^*}\right)\dot{\varepsilon} \tag{2}$$

The value of H is ranging from zero to a microstructure dependent maximum of H^* (H^*<1). The constant $h' = E\Phi$, where E is the Young's modulus and Φ is the volume fraction.

2.2. Solid solution depletion (Ds)

The alloying elements are added to enhance the resistance for dislocation motion, which increase the creep resistance of the material. The experimental data on 9Cr-1Mo have shown the creep resistance of precipitation is decreasing during Fe2Mo laves phase. During the conditions of long term high temperature and stress exposure, the Mo depletion in the subgrain matrix produced the decreasing of creep resistance. The element of Mo is added to the material in order to increase the mechanism of solid solution strengthening. There is no helping for the dislocations motion decreasing by the large size of the Laves phase of Fe2Mo and the low volume fraction [1]. The large size Laves phases at grain boundaries are the most likely source of cavity nucleation and the intergranular fracture. This mechanism is described the damage evolution of void nucleation and crack formation. According to Y.F. Yin (2006) [4], the damage owing of the solute depletion (D_s) is defined:

$$D_s = 1 - \frac{\overline{C_t}}{C_0} \tag{3}$$

where C_0 is the initial concentration of solid solution in the matrix, and $\overline{C_t}$ is their average concentration at time t. In addition, the rate of change of D_s by Dyson's approach follow by Wert-Zener equation [7] is

$$\dot{D}_s = K_s D_s^{\frac{1}{3}}(1 - D_s) \tag{4}$$

where the parameter of constant Ks is defined as:

$$K_s = [48\pi^2(c_0 - \frac{C_e}{C_\beta})^{1/3} n^{2/3} D \tag{5}$$

where D is the diffusion coefficient of Mo in matrix, the n is the number of precipitate particles and C_β is the concentration of solid solution in the precipitate of Laves. The values of C_0 and C_e using Thermo-Calc and found C_0 = 0.56 mol% and C_e= 0.33 mol% [1].

2.3. Particle coarsening (D_p)

In Dyson's approach, creep damage is owing to particle coarsening which is because of the interparticle spacing of the hardening particles [4]. The modifying of the precipitate coarsening of 9Cr-1Mo steel plays an important role in the creep resistance of this material that Nakajima et al. (2003) studied the coarsening of M23C6 and MX precipitates in T91 steel during creep processes. The stress, which required for dislocations to climb over precipitates, is decreased by the increased interparticle spacing. Following the damage because of the coarsening of M23C6 precipitate particles following Dyson's approach [4], Dp is defined as

$$D_p = 1 - \frac{P_0}{P_t} \tag{6}$$

where Po is the initial particle diameter and P_t is the particle size at any time t. It is a supposed that the coarsening of the particles obeys Livshitz-Wagner equation:

$$r^3 - {r_0}^3 = Kt \tag{7}$$

where the K is a constant determined by diffusivity, interfacial energy, equilibrium solute concentration. The above equation just only could apply to intragranular spherical particles such as MX, but could not for M23C6.

The rate of precipitate particle coarsening is described by

$$\dot{D}_p = \frac{K_p}{3}(1 - D_p)^4 \tag{8}$$

where K_p is the rate constant normalized by K and the third power of the initial particle size. As a result, 0< D_p <1.Using a constant K_p and an activation energy parameter Q_p, the below equation is shown the relationship of K_p and temperature T.

Where the R is the universal gas constant, the T is the temperature; Q_p is an activation energy parameter.

$$K_p = K_p' \exp(-\frac{Q_p}{RT}) \tag{9}$$

Where the R is the universal gas constant, the T is the temperature; the Q_p is an activation energy parameter.

2.4. Cavity nucleation, growth and coalescence (D_n)

Creep damage of 9Cr-1Mo steel is dependent on different mechanisms such as void nucleation and cavity formation [1]. The damage parameterD_n, which is for cavity nucleation and growth, is defined as the fraction of grain boundary facets cavitation [8]. The below equation shows the evolution of D_n:

$$\dot{D}_n = \frac{K_n}{\varepsilon_{fu}}\dot{\varepsilon} \tag{10}$$

where the ε_{fu} is the uniaxial strain at fracture and the k_n is a limit value blew 1/3. It means the damage of cavitation in proportion to strain rate.

Similar to the phenomenological modelling of damage in super plasticity, and based Yin and Faulkner [4] proposed the rate of evolution of D_n for P91 alloy as:

$$\dot{D}_n = A'\varepsilon^{B'}\dot{\varepsilon} \tag{11}$$

where the material constant of A and B are a function of temperature and stress. Where A' (A'=AB) and B' (B'=B-1) are large strains and high strain rates, D_n may be equal to or larger than one. This will cause a divergence in the computation at high stress and strain; so, the magnitude of D_n should not reach one, thus 0< D_n <1.

3. The evolution and the development of creep damage constitutive equations

3.1. Kachanov and Robotnov's equations

In order to descript the influence of the micro defect for mechanical properties of materials, Kachanov [9] originally put forward the fundamental theory of continuous damaged mechanics, and Rabotnov [10] lead damage fraction (D) to macroscopic constitutive equation in order to represent the damage state of materials characterized by distributed cavities in terms of appropriate mechanical variables (internal state variables), and then to establish mechanical behaviour of damaged materials.

$$\dot{\varepsilon} = \dot{\varepsilon}_0[\frac{\sigma}{\sigma_0(1-D)}]^n \tag{12}$$

$$\dot{D} = \dot{D}_0[\frac{\sigma}{\sigma_0(1-D)}]^n \tag{13}$$

where the $\dot{\varepsilon}$ is the creep rate during the process of creep; σ is the applied stress for materials during the process of creep. The symbol with the mark of zero is the initial state; n is the constant of materials and normally named stress exponent. Where $\dot{D}$and $\dot{D}_0$ are respectively meaning the change of creep rate in the materials during the creep processes and the creep rate at the beginning of the creep; the v is the material constant.

3.2. Ion's equation

During the secondary creep, it will occur strain hardening and recovery. Ion et.al [6] leads in the dimensionless parameter of H to the creep constitutive equations in order to present the influence of the working hardening. The creep constitutive equations of Robotnov [5] will be changed and shown in below:

$$\dot{\varepsilon} = \dot{\varepsilon}_0[\frac{\sigma(1-H)}{1-D}]^n \tag{14}$$

Where ε˙ is the creep rate during the process of creep; σ is the applied stress for materials during the process of creep. The symbol with the mark of zero is the initial state; n is the constant of materials and normally named stress exponent; H is the dimensionless parameter.

$$\dot{D} = \dot{D}_0[\frac{\sigma(1-H)}{\sigma_0(1-D)}]^v \tag{15}$$

Where $\dot{\boldsymbol{D}}$and $\dot{\boldsymbol{D}}_{\boldsymbol{0}}$ are respectively meaning the change of creep rate in the materials during the creep processes and the creep rate at the beginning of the creep; the v is the material constant; H is the dimensionless parameter.

3.3. Dyson's equations

The creep constitutive equation of Robotnov is based on the phenomenological theory. Using the D to indicate many microdefects such as solid solution depletion precipitate coarsening, void nucleation and crack formation et.al, it is too simple to show the influence of multiple microdefects for the process of creep. Dyson

modified the CDM model, and summarized the effects of creep rate including particle coarsening (D_p), solute depletion (D_s), cavity nucleation and growth (D_n) and dislocations (D_d) et.al creep damage mechanisms [8]. The physically based CMD model of Dyson shows below:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \frac{1}{(1-D_s)(1-D_d)} \times \sinh\left[\frac{\sigma(1-H)}{\sigma_0(1-D_p)(1-D_n)(1-Dcor)(1-Dox)}\right] \quad (16\text{-}1)$$

$$\dot{H} = \frac{h'}{\sigma}(1-\frac{H}{H^*})\dot{\varepsilon} \quad (16\text{-}2)$$

$$\dot{D}_s = k_s D_s^{\frac{1}{3}}(1-D_s) \quad (16\text{-}3)$$

$$\dot{D}_p = \frac{k_p}{3}\left(1-D_p\right)^4 \quad (16\text{-}4)$$

$$\dot{D}_n = A'\dot{\varepsilon}\varepsilon^{B'} \quad (16\text{-}5)$$

3.4. Yunxiang Chen's equations

The second-phase particles in P91 steel are mainly MX, $M_{23}C_6$, Laves phase and Z phase, especially, for Z phase present in a quite late of whole creep process. The research results of Sawada indicated that the time required for presenting Z phase is around 10000 hours, however, the creep time, continuum damage mechanics modeling of P91 under the condition of high stress and elevated temperature, is quite short. Meanwhile, the coarsening rate of MX and $M_{23}C_6$ is relatively less [5]. Therefore, in the creep damage constitutive equations of Yunxiang Chen just only considered the influence of the coarsening of Laves phase and get the new equations showing as below [5]:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \frac{1}{(1-D_s)}\left[\frac{\sigma(1-H)}{\sigma_0(1-D_p)(1-D_n)}\right]^n \quad (17\text{-}1)$$

$$\dot{H} = \frac{h'}{\sigma}(1-\frac{H}{H^*})\dot{\varepsilon} \quad (17\text{-}2)$$

$$\dot{D}_s = k_s D_s^{\frac{1}{3}}(1-D_s) \quad (17\text{-}3)$$

$$\dot{D}_p = \frac{k_p}{3}\left(1-D_p\right)^4 \quad (17\text{-}4)$$

$$\dot{D}_n = A'\dot{\varepsilon}\varepsilon^{B'} \quad (17\text{-}5)$$

4. Results and discussion

In order to represent the creep behaviour of P91 and the relative significance of internal damage mechanisms on the overall creep damage, the equations set by Yunxiang Chen which was modified from Dyson's equations was investigated. All the material and damage parameters are calculated out by experiment data and collection from different literatures [5][13][14]. The table1 below lists the values and units of these parameters.

Table1.
Parameters used in creep modelling

Parameter	Value	Unit
H^*	0.269	
h'	10000	
K_p	1.5×10^-7	S^-1
K_s	5×10^-8	S^-1
A	1.5	
B	2	
A'	2.9	
B'	0.95	

n	10.186	
σ_0	200	MPa
$\dot{\varepsilon}_0$	5.7×10^-6	S^-1

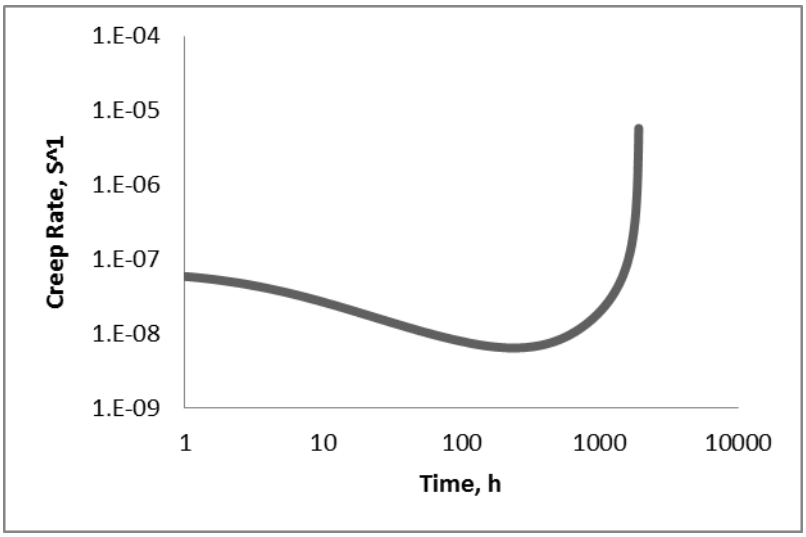

Fig.1. The creep rate of P91 under 130MPa at 600℃ [15]

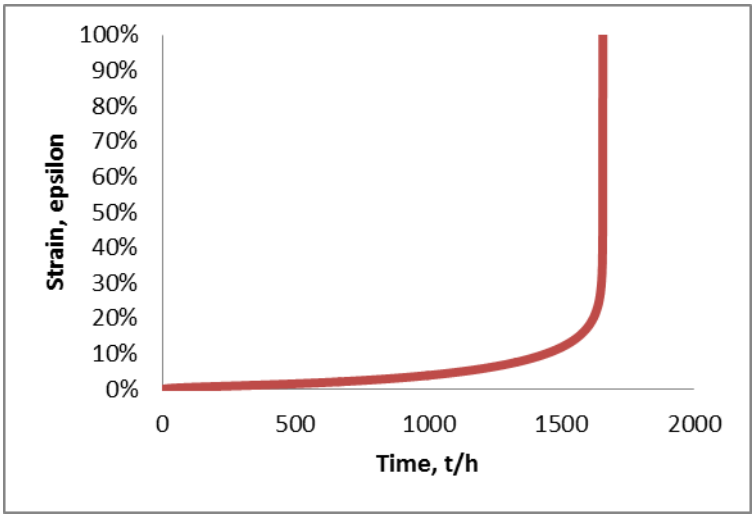

Fig.2. The strain line of P91 with all internal creep damage mechanisms under 130MPa at 600℃

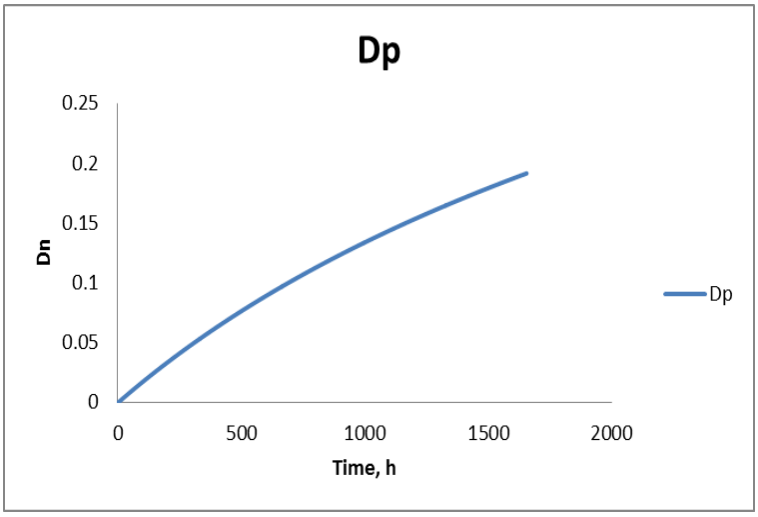

Fig.3. The curve line of particle coarsening vs. time for P91 with all damage under 130MPa at 600℃

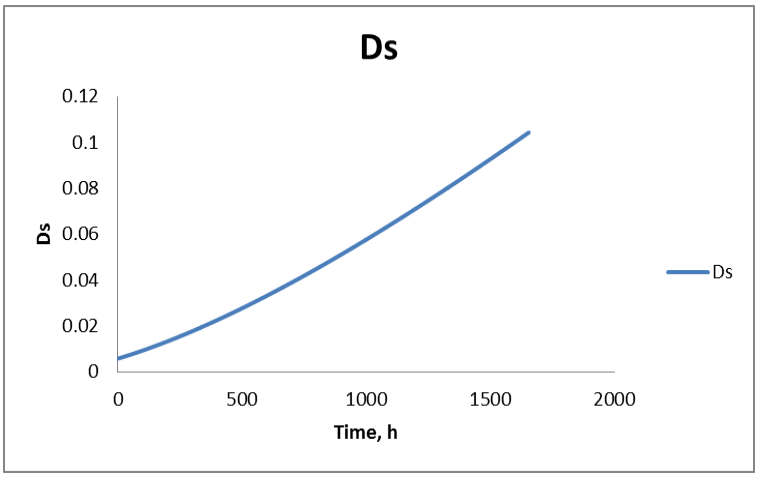

Fig.4. The curve line of solid solution depletion vs. time for P91 with all damage under 130MPa at 600℃

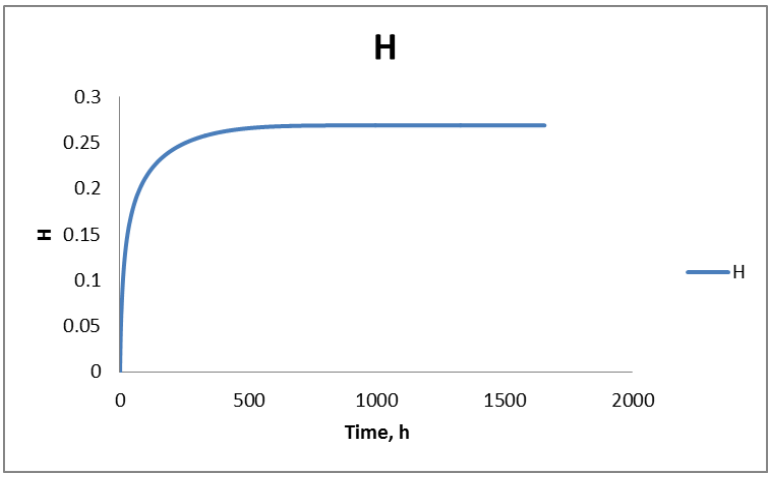

Fig.5. The curve line of solid solution depletion vs. time for P91 with all damage under 130MPa at 600℃

The creep curve of P91 under the same conditions without including any internal creep damage mechanisms are shown in Fig.6.

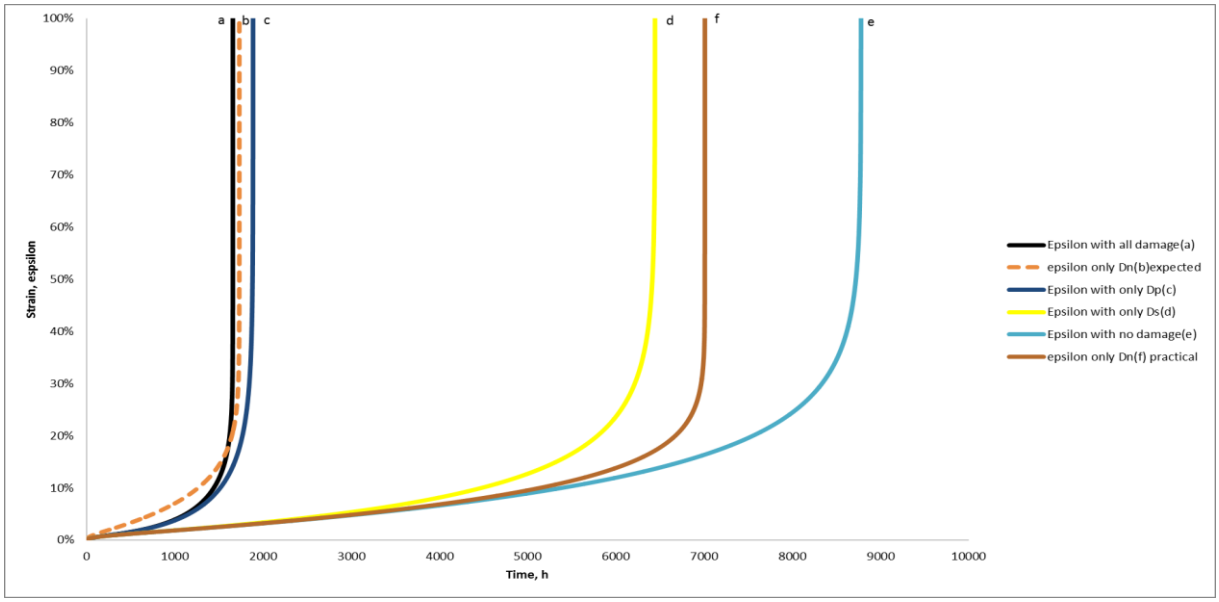

Fig.6. The comparison of creep rate by different internal creep damage mechanisms under 130MPa at 600℃

From diagram of above Fig.6, the curve a is the creep strain curve with all inter creep damage mechanisms considered and in deed has the shortest time. The right-most line (curve e) is the one without any internal creep damage mechanism considered and therefor has the longest life time. From the comparison between curve a and cure e, it indicates that the internal creep damage mechanisms have a great influence of shorting the lifetime for P91 and accelerated materials to ultimate rupture. The other curve lines with individual internal creep damage are expected and lied between the curve a and curve e. The curve b is the expected creep strain line with only cavitation; however, the practical modelling just gets the curve line f with only cavitation damage mechanism. Though the modelling result is not shown as expected, it could not deny that the cavitation is significant internal damage mechanism contributing to the ultimate failure of the material. Particle coarsening is the second most significant internal damage mechanism indicated by the curve c in the Fig.6. The influence of minimum internal damage mechanism is solid solution depletion and shown by curve d.

In order to further explore how the cavity damage is described by the specific equation, Fig. 7 and table 2 were produced.

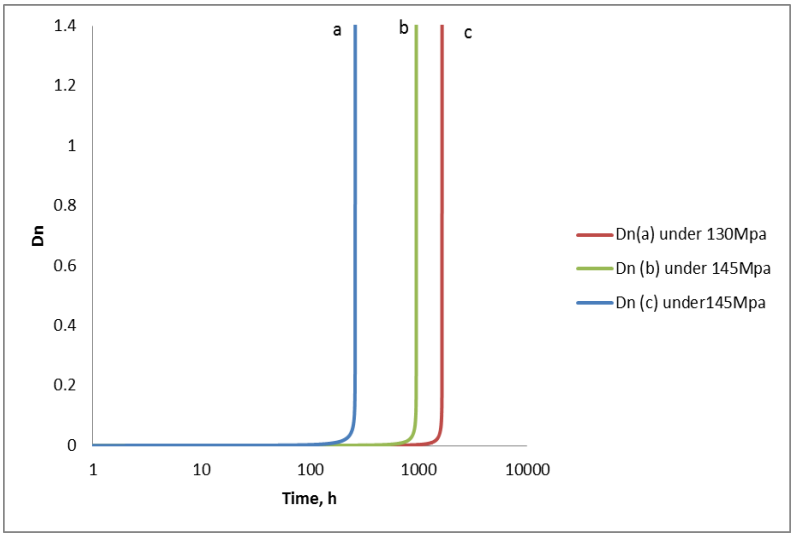

Fig.7. The curve line of Cavitation (D_n) vs. time for P91 with all damage under 130MPa, 145MPa and175MPa at 600℃

Table 2.
The cavitation rate ($\dot{D}_n$) date at the moment of ultimate failure for P91 at different stress at 600℃

	130MPa	145MPa	175MPa
$\dot{D}_n$ before ultimate failure	0.197789306	0.162333838	0.266203952
$\dot{D}_n$ at ultimate failure	2.1948015	1.160541335	6.974373972

From above Fig.7, it clearly indicates cavitation has a significant effect at the moment of ultimate failure for P91, prior to the failure; its influence is almost trivial. Table 2 reveals a jumping of the rate of cavity damage at the moment of failure.

The relative significance of internal creep damage on life time is shown by Fig. 6. On the whole, it shows that the cavity damage does have significant influence (curve f), however, it is not the most significant one as expected. The more like one should be something like curve b which was produced by a different vale of A.

In Yin's original idea, it was assumed that the material constant A is not changing with stress level. However, it has been reported by Basirat et al [1] that the constant A as a function of stress, as shown by Table 3, in his calibration. The effect of the material constant A on the creep curve and lifetime is shown by Fig. 8. The difference of the predicted life time is about 30%.

Table 3.
The values of exponent A under different stress at 600℃ [1]

Parameters	$\sigma = 80MPa$	$\sigma = 100MPa$	$\sigma = 150MPa$	Temperatures(℃)
A	57	83	1	600

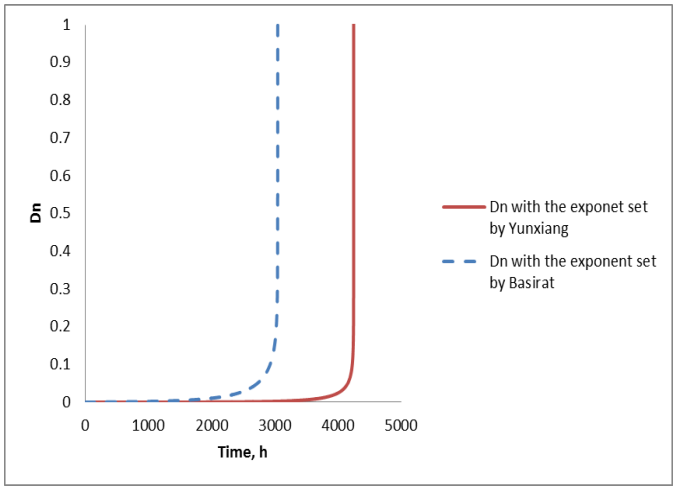

Fig.8. The cavitation (Dn) vs. time with the different exponent A under 100MPa at 600℃

This clearly reveals that the phenomenological approach in modeling of the cavity damage is not robust and there is a degree of uncertain in its application due to the varying value of A depending on the stress. This research indicates strongly the need for the micro-mechanism based cavity damage modeling.

5. Conclusion

The modelling of creep damage mechanisms equations is an effective simulation technique to predict P91 steel. However, in Yins approach, cavity damage, one of the most important internal creep damage, is of phenomenological. Thus, its robustness is questionable. Furthermore, extrapolation of such set of creep damage constitutive equation is not permissible. This research indicates strongly the need for the micro-mechanism based cavity damage modeling.

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