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Preliminary analysing of experimental data for the development of high Cr Alloy Creep damage Constitutive Equations

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***Abstract*—This conference paper presents the current research of preliminary analysing of experimental data for the development of high Cr Alloy Creep damage Constitutive Equations (such as P91 alloy). Firstly, it briefly introduces the background of general creep deformation, rupture and continuum damage mechanics. Secondly, it illustrates the constitutive equations used for P91 alloy or its weldment, especially of the form and deficiencies of two kinds of most widely used typical creep damage constitutive equations Kachanov-Rabotnov-Hayhurst (KRH) and Xu's formations. And then, the methodology for development of new set constitutive equation proposed by Xu (2004) has been followed in this research. Fourthly, there is a critically analysis of the specific experiment data for P91 alloy and its weldment. Afterwards, the specific requirements for developing a new set constitutive equation have been reported.**

Finally it suggests the directions for future work. This paper contributes to the knowledge for the developing creep damage constitutive equations for the specific material.

***Keywords*: creep damage, constitutive equations, P91 alloy and weldments.**

I. Introduction

High Cr alloy (such as P91) developed in Japan originally have been widely used in industries. Creep damage has become a seriously issue in industries, especially in the weldment [1] and the assessment of P91 weldment has become a seriously problem which engineers are facing [2].

To analyse the complex of creep deformation and rupture, the creep damage constitutive equations should be able to depict the behaviour of material, especially for predicting the lifetime of materials, within the frame work of continuum damage mechanics (CDM). The types and special applications of a set of creep damage constitutive equations for P91 alloy and its weldment are summarised, especially for KRH (Kachanov-Robatnov-Hayhurst) type and Xu's formulation.

This paper presents following parts---the first part includes general background of creep deformation, rupture and continuum damage mechanics and typical constitutive equations within CDM. The second part addresses the current research of creep deformation and creep damage mechanisms of P91 alloy and its weldment, the specific experiment data of P91 alloy and its weldment under uni-axial and multi-axial situations. The third part presents the deficiencies of the most popular constitutive equations of KRH and Xu's formulations. The next two parts mainly focus on the specific requirements and methodology of developing constitutive equations. Finally, outline the further work of this research.

II. Background of Creep Deformation, Rupture and Continuum Damage Mechanics

A. Deformation and Failure under creep condition

Deformation and fracture of materials are time-dependent process under elevated-temperature creep conditions. The creep plastic deformation (creep) which eventually leads to creep fracture becomes the determination factor for the design of a structure. The uniaxial creep tests are conducted to study deformation and failure of materials process. There are two important curves which should be referred--- creep strain against time curve (standard creep curve) and creep strain rate against time curve. The standard creep curve contains primary, secondary and tertiary stages. The creep strain rate decreases in primary stage, increasing during the secondary creep stage and decreasing within tertiary stage. Generally speaking, creep deformation includes diffusion creep processes and dislocation creep processes. In addition, there are some micro-mechanisms underlying the creep curve. In briefly speaking, primary and secondary creep stages are determined by the combined action of strain hardening and thermally activated recovery of the dislocation structure. The diffusion creep process takes demonstration in tertiary stage which leads to the fracture [3, 4]. There are three basic mechanisms contribute to creep in metals, namely: dislocation slip and climb, grain boundary sliding and diffusion flow. Creep deformation could be divided into cavities nucleation, growth and coalescence on grain boundaries. As Riedel [3] reported that the cavities may be nucleated early in primary stage.

B. Creep Fracture

The formation and joining of micro-cavities on grain boundaries are the main reasons accelerate creep in the tertiary stage. Therefore, creep fracture is generally inter-granular.

C. Continuum damage mechanism (CDM)

Continuum damage mechanics (CDM) based design method for multi-axial creep was developed from initial work of Kachanov in 1958. CDM-based approach was used to predict the failure time and rupture strain when components situated at high temperature by introducing the appropriate variables and constitutive equations. By contrast with CGM-based design method, CDM-based method is developed on the phenomenological way and presented from the viewpoint of mechanics [5]. The CDM-based method could provide information of the local stress and strain field through simulating the process of damage evolution with the numerical methods. Within CDM method theory, there are qualities of multi-axial creep constitutive equations have been presented to analyze the creep damage and failure of materials.

III. TYPICAL CONSTITUTIVE EQUATIONS WITHIN CDM

A. Introduction

Creep damage constitutive equations are proposed to depict the behaviours of material during creep damage (deformation and rupture) process, especially for predicting the lifetime of materials, within the frame work of continuum damage mechanics (CDM). Kachanov-Rabatnov-Hayhurst (KRH) is one of the most widely used constitutive equations within CDM. Due to the deficiencies of KRH approach, Xu [6] has improved a new set constitutive equation which called Xu's formulation. Otherwise there still are some specific constitutive equations used for P91 alloy and its weldment, such as, Norton's law, Robinson model, Hill's anisotropic potential function and Kachanov type. The Kachanov-Rabatnov-Hayhurst (KRH) and Xu's formulation will be introduced as followed in details.

B. Kachanov-Rabatnov-Hayhurst (KRH)

– Uni-axial form

$$\begin{cases} \dot{\varepsilon} = A\sinh\left(\frac{B\sigma(1-H)}{(1-\varphi)(1-\omega)}\right) & (1.1) \\ \dot{H} = \frac{h}{\sigma}\left(1-\frac{H}{H^*}\right)\dot{\varepsilon} & (1.2) \\ \dot{\varphi} = \frac{K_C}{3}(1-\varphi)^4 & (1.3) \\ \dot{\omega} = C\dot{\varepsilon}^* & (1.4) \end{cases} \quad (1)$$

A, B C, h, H* and Kc are material parameters. H (0<H< H*) indicates strain hardening during primary creep, φ (0< φ < 1) describe the evolution of spacing of the carbide precipitates [7].

– Multi-axial form

$$\begin{cases} \dot{\varepsilon_{ij}} = \frac{3S_{ij}}{2\sigma_e}A\sinh\left(\frac{B\sigma_e(1-H)}{(1-\varphi)(1-\omega)}\right) & (2.1) \\ \dot{H} = \frac{h}{\sigma_e}\left(1-\frac{H}{H^*}\right)\dot{\varepsilon} & (2.2) \\ \dot{\varphi} = \frac{K_C}{3}(1-\varphi)^4 & (2.3) \\ \dot{\omega} = C\dot{\varepsilon_e}\left\langle\frac{\sigma_1}{\sigma_e}\right\rangle^{\nu} & (2.4) \end{cases} \quad (2)$$

Where < > is heavy step function and ν is stress state index defining the multi-axial stress rupture criterion. The state of stress function was originally proposed by Cane according to Perrin [8].

C. Xu's formulations

Xu [9] published paper mentioned that: "The fundamental deficiency in KRH approach is that the creep strain consistency requirement is not satisfied. The new formulation introduced two functions to depict the effect of states of stress on the damage evolution and creep strain, respectively." Therefore, the new multi-axial formulation could be defined as:

$$\begin{cases} \dot{\varepsilon_{ij}} = \frac{3S_{ij}}{2\sigma_e}A\sinh\left(\frac{B\sigma_e(1-H)}{(1-\varphi)(1-\omega_d)}\right) & (3.1) \\ \dot{H} = \frac{h}{\sigma_e}\left(1-\frac{H}{H^*}\right)\dot{\varepsilon_e} & (3.2) \\ \dot{\varphi} = \frac{K_C}{3}(1-\varphi)^4 & (3.3) \\ \dot{\omega} = CN\dot{\varepsilon_e}f_2 & (3.4) \\ \dot{\omega_d} = \dot{\omega}f_1 & (3.5) \end{cases} \quad (3)$$

$$\begin{cases} f_1 = \left[\frac{2\sigma_e}{3S_1}\right]^a exp\left\{b\left[\frac{3\sigma_m}{S_s}-1\right]\right\} & (3.6) \\ f_2 = \left(exp\left\{p\left[1-\frac{\sigma_1}{\sigma_e}\right]+q\left[\frac{1}{2}-\frac{3\sigma_m}{2\sigma_e}\right]\right\}\right)^{-1} & (3.7) \end{cases}$$

Where f1 and f2 are functions of stress states internal variables are needed. Function f1 was introduced to better phenomenological couple tertiary deformation, creep damage and creep rupture. From the physical viewpoint, it is mean that creep deformation and creep rupture are two separate processes which need two different and separate variables [9, 10].

The most popular and widely used approach for analyzing the creep damage problem of P91 and its weldment is KRH approach. Recently, Hyde et al [7] have adopted KRH approach to produce a set of creep damage constitutive equations for P91 weldment in order to analysis the creep damage problem.

IV. THE SPECIFIC EXPERIMENT DATA FOR P91 ALLY OR ITS WELDMENTS

A. Creep deformation and damage mechanisms on 9-12% Cr steels and its weldment

Analysis current experiment data obtained from Kimura, Suzuki, Toda, Kushima and Abe [11], creep mechanics of degradation and assessment of long-term creep strength of advanced 9-12% Cr steels could be summarised as:

1. Microstructure changes depend on the stress and operating time. A homogeneous recovery change has been observed under high stress and short-term

period and inhomogeneous change observed under low stress and long-term period. Inhomogeneous microstructure recovery change result in and increase the degradation in the long-term.

2. Disappearance of MX particles as the consequence of nucleation and rapid coarsening of Z-phase

3. Recovery at the vicinity of PAGB is easily extended with assist of high stress, and the stress at the inflection of the curve corresponds to ½ of 0.2% proof stress

4. To predict long-term creep strength accurately should considerate a ratio of stress to 0.2% proof stress

Most of papers have referred that creep deformation mainly focus on the micro-structure changes; while, cavities nucleation, growth and coalescence could lead to material fracture.

B. Properties of P91 alloy and its weldment

P91 (also called 9 Cr 1 Mo steel based on its composition) alloy materials have been widely used in industries which developed in Japan originally. As a martensitic heat resistant steel, its operate temperature range from 600°C -650°C in order to fill the gap between pearlite and austenitic steel operating temperature. Compare with its predecessor--- T22 or P22, P91 have higher creep resistance, creep rupture strength, thermal stability and oxidation resistance. Therefore, it was successful widely used in the boiler and pipelines of power plant.

Actually, P91 is made of some new elements (such as N, Nb, V) based on 9Cr-1Mo steels, and then formation a new steel. The chemical compositions of P91 parent material and weld metal are listed in Table 1 and Table 2, respectively [12]. Because of the differences between microstructure and mechanical property, the weld metal of P91 is stronger than the parent material.

C	Si	Mn	Cr	Mo	S
0.09	0.31	0.46	8.68	0.92	0.002
P	Al	Ni	V	N	Nb
0.01	0.008	0.12	0.21	0.049	0.09

Table 1: Chemical composition of the initial P91-ingot produced by Forgemasters Engineering in wt%

C	Si	Mn	Cr	Mo	S
0.10	0.36	1.07	8.8	1.04	0.009
P	Co	Ni	V	Cu	Nb
0.014	0.01	0.06	0.26	0.03	0.06

Table 2: Chemical composition of the Oerlikon Chromocord 9M weld metal

C. Uni-axial creep testing data

As it is known, temperature and stress are two main factors to affect creep mechanism [4, 13]. Uni-axial creep tests for P91 or its weldment under low and high stress levels, under constant load and constant stress or microstructure degradation process have been conducted by many researchers, such as, [7, 12, 14, 15, 16 and 17]. These all highlight facts addressed that:

a) strain rate increasing with increasing stress level, so that the lifetime will reduce with stress increasing.

b) strain rate of weld metal is much quick than parent metal and HAZ

c) a longer lifetime under the constant stress than the constant load, but a small difference in strain when the minimum creep rate is achieved

d) a significant difference between BM, IC-HAZ and WM microstructures was their sub-grain size; the smallest size of sub-grain is welding metal, and the largest size is heat-affect zone whatever before creep or after that

D. Multi-axial creep testing data

Multi-axial stress states are a controversial topic up to now. The choosing of different constitutive equations will have an effect on research study. There may no specific experiment data or creep curve during multi-axial conditions at present. Due to the complex of multi-axial condition, most researchers were mainly analysing experiment data to make contribute to the finite-element analysis.

V. Deficiencies of KRH and Xu's formulation

Kachanov-Rabotnov-Hayhurst (KRH) is the most popular constitutive equations used to solve creep damage problem within the continuum damage mechanics. However, it is clear that KRH approach was blindly adopted and even with some comprise in the determination of the stress sensitively index [18]. The deficiencies of the most popular approach have been identified in recent published research [6, 10 and 18] namely:

- The adopted KRH generalisation formulation is not able to depict the creep deformation accurately [6, 10, 18];
- Within the framework of KRH [6, 10, 18], the determination of the value of ν was not done properly revealing of the lack of understanding of the multi-axial stress state effect on creep deformation and creep damage and rupture.

Xu's formulation is a rapid progress compared with KRH approach. However, there is no papers mentioned the creep deformation and damage for P91 and its weldment. It is clear that there is a need for the development of a new set of creep damage constitutive equations requiring fundamental research and with industrial significance.

VI. SPECIFIC REQUIREMENTS FOR DEVELOPING A SET OF CONSTITUTIV EQUATIONS

According to Xu [6] reported that there are two fundamental requirements needed to develop a new set of constitutive equations. These fundamental requirements have been illustrated as creep strain rate consistency and damage evolution consistency. The new set constitutive equation combined with computational method, the predict creep strain rate and damage evolution should consistent with the experimental observation under a several of stress states and stress levels.

For the new set constitutive equation for P91 alloy and its weldmennt should take several aspects into account, such as:

a) creep deformation and damage mechanisms

b) different stress range and stress states

c) well coupling between creep deformation and creep damage

d) constitutive equations could well describe the whole creep process. Based on this priliminary analysing of experimental data. It is concluded that the following requirements should be met:

- creep deformation mechanism under the different stress level
- creep damage mechanism under different stress level
- multi-axial stress state effect
- coupling between creep deformation and damage

VII. METHODOLY FOR DEVELOPING A SET OF CONSTITUTIVE EQUATIONS

The development of constitutive equation method proposed by Xu [10] will be adopted. The key steps are:

1) To critical evaluate and understand the creep deformation process and damage theories which combined with constitutive equations in phenomenological approach

2) To analyse the deficiencies of current most popular constitutive equations of KRH-based methodology

3) To devise a formulation for high Cr alloy which is capable of depicting the influence of stress levels and stress states and the coupling between creep damage and creep deformation. In order to achieve that, the following steps should be followed:

   - Accurate and better understanding of the coupling of the deformation and creep damage mechanisms

   - Understanding the characteristics of various formulations in terms of ability of depicting the creep deformation and creep damage evolution

4) To validate a set of creep damage constitutive equations for P91 alloy

VIII. FURTHER WORK

The next step should be focus on finding coupling of creep deformation and damage/rupture mechanisms, the multi-axial experiment data analysis.

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