An, Lili, Xu, Qiang, Xu, Donglai and Lu, Zhongyu

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Review on the current state of developing of advanced Creep Damage Constitutive Equations for high Chromium Alloy

Lili An[1, a], Qiang Xu[1, b], Donglai Xu[1, c], Zhongyu Lu[2, d]

[1] School of Science and Engineering, Teesside University, TS1 3BA, UK

[2]School of Computing and Engineering, University of Huddersfield, Huddersfield, HD1 3DA, UK

[a] L.An@tees.ac.uk, [b] Q.Xu@tees.ac.uk, [c] D.Xu@tees.ac.uk , [d] Z.Lu@hud.ac.uk

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Abstract. This paper presents a review of developing of creep damage constitutive equations for high chromium alloy (such as P91 alloy). Firstly, it briefly introduces the background of creep damage for P91 materials. Then, it summarizes the typical creep damage constitutive equations developed and applied for P91 alloy, and the main deficiencies of KRH (Kachanov-Robatnov-Hayhurst) type and Xu's type constitutive equations. 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.

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 [8] and the assessment of P91 weldments has become a seriously problem which engineers are facing [1].

To analyze 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 weldments are listed and the main deficiencies in the KRH (Kachanov-Robatnov-Hayhurst) type are reported [11-14]. Finally, the direction of future research has been outlined in conclusion.

Creep damage in P91 alloy and its weldment

Computational approach has been used in the research to understand the deformation and failure of P91 weldment. Some of the publications are listed here as examples:

1. G. Eggeler, A. Ramteke et al, (1994), Analysis of creep in welded P91 pressure vessel comparing the base metal (BM), the weld metal (WM) and the heat affected zone (HAZ) used Norton's law and Robinson model constitutive equations [5]
2. T.H. Hyde, W. Sun, A.A. Becker, J.A. Williams, (2006), Finite-element analysis of P91 pipes creep damage for Bar 257 steel and A-369 steel, tested at 650°C and 625°C, respectively [16]
3. B. Ule and A. Nagode, (2007), Power law constitutive equations for 9Cr-1Mo-0.2V (P91 type) steel [3]
4. J. Besson, V. Gaffard, et al, (2009), Analysis of creep lifetime of P91 welded pipe and the integrating multiple deformation and damage mechanics [10]
5. T. Ogata, T. Sakai and M. Yaguchi, (2009, 2010), 3-Dimensional Finite-element analysis of creep damage of P91 steel weldement under uniaxial and multiaxial creep [18] [20]
6. T.H. Hyde, W. Sun, M. Saber, (2010), 3-D Finite-element analysis creep crack growth data and prediction for P91 weld at 650°C [21] [22]
7. G.G. Shu, Y.F. Zhao,F. Xue, L. Zhang and G.D. Zhang, (2010), Experiment research and numerical simulation of creep damage for P91 steel at 546°C used Kachanov-Robatnov constitutive model [6]
8. A. Nagode, L. Kosec and B. Ule, (2011), Analysis creep behaviour of P91 type steel for uni-axial and multi-axial under constant load use different type constitutive equation [2]

The welding process results in the formation of typically four material zones for P91 type of weldment which is illustrated by Figure 1 [5]. A critical summary of experimental observation is listed below:

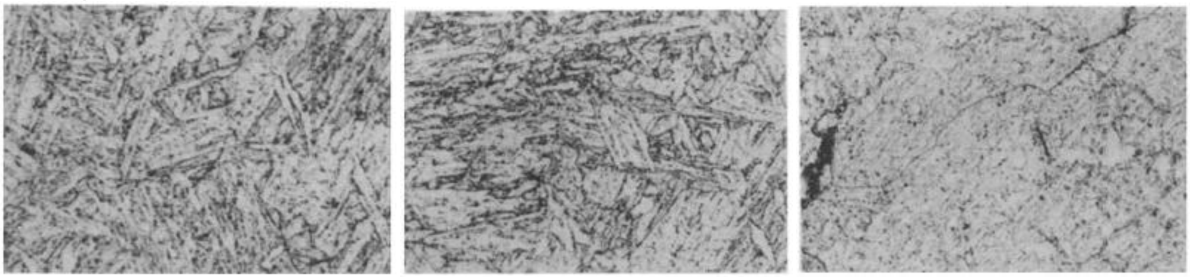
The different zones: The four zones have shown that the significant difference between these three micro-structures is their sub-grain size. It was found to be smallest for the weld metal and largest for heat affected zone material. An optical micrograph of base metal, IC-HAZ and weld metal micro-structure is shown in Fig.1. [5]

The uniaxial creep behaviour shows that the creep strength increased with decreasing sub-grain size, that the HAZ material creeps faster than the base metal and much faster than the weld metal. And the HAZ material is weaker than the base metal and meld metal. Example creep curves are illustrated by Fig.2. [5]

According to Hyde, et al [16, 21], the uni-axial and notched bar creep tests have shown that the creep rupture strengths are close to each other between parent material and weld metal; the weld metal is slightly stronger that the parent material. It was also shown that failure occurs at the Type IV position and controlled by the HAZ.

I.A. Shibli and N. Le Mat Hamata [9] revealed that crack growth rate of P91 weld metal is higher or close to the base metal, while, the crack growth rate in HAZ is faster than the base metal. Therefore, creep rupture time of the weld region within HAZ is reduced significantly from that of the base metal.

It was found that creep rupture time of the weld joints was reduced significantly from that of the base metal due to Type IV failure under low stress and higher temperature conditions, which is approximately 1/5 of base metal. It was suggested that multi-axial stress states caused acceleration of creep damage evolution in the HAZ [18].



BM IC-HAZ WM

Fig.1. Optical micrographs of BM, IC-HAZ and WM [5]

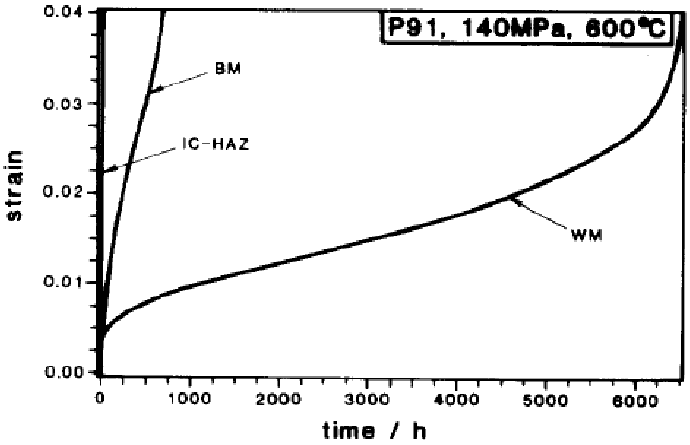


Fig.2. A strain-time creep curves for the three material states at 60°C and 140 MPa [5]

Types of constitutive equations used for P91

The types of creep damage constitutive equations developed and used for P91 available in literature are listed in Table 1.

Table 1: The type of creep damage constitutive equations

Type of constitutive equation	Applications
Norton's Law	Hyde, et al, 2010, *Testing and modelling of creep crack growth in compact tension specimens from P91 weld at 650°C* [21] G. Eggeler, A. Ramteke et al, 1994, *Analysis of creep in a welded P91 pressure vessel* [5] T. Watanabe, M. Tabuchi and M. Yamazaki, 2006, *Creep damage evaluation of 9Cr-1Mo-V-Nb steel welded joints showing Type IV fracture* [19] Hyde, et al, 2003, *The Influence of Heat Affected Zone Characteristics on the Creep Failure of P91 Welds – An Initial Sensitivity Study Using Steady State Creep* [17] T. Ogata, T. Sakai and M. Yaguchi, 2010, *Damage assessment method of P91 steel welded tube under internal pressure creep based on void growth simulation* [20] T. Ogata, T. Sakai and M. Yaguchi, 2009, *Damage characterization of P91 steel weldment under uni-axial and multi-axial creep* [18]
Robinson Model	G. Eggeler, A. Ramteke et al, 1994, *Analysis of creep in a welded P91 pressure vessel* [5]
Liu and Murakami	Hyde, et al, 2010, *Creep crack growth data and prediction for P91 weld at 650°C* [22] Hyde, et al, 2010, *Testing and modelling of creep crack growth in compact tension specimens from P91 weld at 650°C* [21] T. Hyde and W. Sun, 2009, *Creep damage modelling of welds with heterogeneous structures* [23]
Hill's anisotropic potential function	T. Hyde and W. Sun, 2009, *Creep damage modelling of welds with heterogeneous structures* [23]
Kachanov	Hyde, et al, 2010, *Creep crack growth data and prediction for P91 weld at 650°C* [22] T. Hyde and W. Sun, 2009, *Creep damage modelling of welds with heterogeneous structures* [23] Hyde, et al, 2010, *Testing and modelling of creep crack growth in compact tension specimens from P91 weld at 650°C* [21] Hyde, et al, 2006, *Finite-element creep damage analyses of P91 pipes* [16] Hyde, conference on Mechanics and Material in Design, *Determination of creep properties for P91 weldment material at 625°C* [24]
Kachanov-Robatnov	G.G. Shu, Y.F. Zhao, F. Xue, L. Zhang and G.D. Zhang, 2010, *Experiment Research and Numerical Simulation of Creep Damage for P91* Steel [6]
Xu's formulation	Q. Xu, & M. Wright, 2011, *The development and validation of multi-axial creep damage constitutive equations for P91* [14]

Critical review of current constitutive equations

Whilst several types of creep damage constitutive equations have been developed and used, there is not definitive and/or clear understanding about their suitability and applicability. Recently, Xu [11, 13-14] has attempted to improve the methodology for the developing and validating of a set of creep damage constitutive equation and critical review revealed the deficiencies in the KRH type of constitutive equations which are primarily: 1) unable to depict the creep deformation accurately, 2) the value of ν was not able to depict the multi-axial stress state effect on creep deformation and creep damage and rupture. At this stage, it seems that Xu's type is better than that of Hayhurst type.

Even for the Xu's type of constitutive equation, further improvement may be needed in the following three directions: 1) rupture criterion, 2) influence of stress level, and 3) though validation under non-proportional multi-axial loading condition.

Proposed method or work for the development of Constitutive Equations for P91 type alloy

To develop a new set of creep constitutive equations for P91 and its weldments, several steps should be considerate to complete it. The development of constitutive equation method proposed by Xu [12] will be adopted. The key steps are:

To critical evaluate and understand the creep deformation process and damage mechanisms of P91 and its weldments under uni-axial and multi-axial conditions;

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:

Investigating the influence of stress level on the creep deformation and damage evolution mechanisms;

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

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

To validate the feasibility of the new set constitutive equations, the experiment data for P91 and its weldments which obtained from literature review are used to determine the material constants parameters via optimization techniques.

Further work will be focused on: 1) rupture criterion, 2) influence of stress level, and 3) though validation under non-proportional multi-axial loading condition.

Conclusion

This paper resents a critical review of different types of constitutive equations for the high Cr alloy. It concluded that Xu's formulation is better than KRH type and there is a degree of lack of the knowledge and understanding of the applicability of a set of constitutive equation. The directions of future research were outlined.

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