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Analyzing the characteristics of the cavity nucleation, growth and coalescence mechanism of 9Cr-1Mo-VNb steel (P91) steel

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Keywords: high Cr alloy, cavity nucleation, cavity growth rate, cavity coalescence, Type IV failure, high stress level, low stress level, stress state

Abstract. Creep damage is one of the serious problems for the high temperature industries and computational approach (such as continuum damage mechanics) has been developed and used, complementary to the experimental approach, to assist safe operation. However, there are no ready creep damage constitutive equations to be used for predicting the lifetime for this type of alloy, particularly for low stress. This paper presents an analysis of the cavity nucleation, growth and coalescence mechanism of 9Cr-1Mo-VNb steel (P91 type) under high and low stress levels and multi-axial stress state.

Introduction

A received ASME Grade 91 steel consists of a tempered martensite matrix with high dislocation density and precipices ($M_{23}C_6$ carbides and MX type carbonitrides within laths). The microstructure evaluation of P91 steels during a long-term exposure includes the precipitation of new phases (Lave phase and Z-phase), coarsening of precipitates and the recovery of a tempered martensitic lath structure. The long-term behaviour of materials under high temperature is an essential factor for an effective and reliable design. The long-term microstructure of the materials has been widely studied; however, the change of creep mechanism during the long-term has normally been neglected.

Due to the difficulties of obtaining the long-term creep data because of the high cost and the long creep test time, the extrapolation procedures are used to obtain the long-term creep data by using the short-term creep data. The current most popular creep and/or constitutive equations models are developed based on the short-term creep experiment, such as under the high stresses or high temperatures. The applications show the short-term creep behaviors and the life span of materials could be predicted accurately, at least for uni-axial case. However, the extrapolation of short-term creep data to long-term situation results in overestimation in general, and these models are more sensitive to high Cr alloy than the low Cr alloy [1-3]. Therefore, Bendick, et al. [4] re-assessed the database due to the significant increase in test data, and a predicted duration of 105h for P91 steels, the updated value is 90 MPa at 600oC. To develop a new set of constitutive equations model is necessary to understand the cavitation better in order to describe the creep damage and rupture under low stress level.

A better understanding of the cavities nucleation, growth and coalescence mechanism during creep process at high temperature provides more opportunities to develop new structural materials for various applications, such as the reactors and pressure vessels. Normally speaking, the cavities are preferential nucleation around grain boundaries or at the triple junctions [5]. The final stage of creep rupture due to elastic-plastic damage rather than creep damage has caught more researchers' attention [6]. Recently, Parker [7] reported that the tertiary stage and the increase of creep strain under constant stress are due to the number of microstructural evolutions. It is believed that the cavitation is the key factor which affects the creep damage and rupture [7]. Therefore, the purpose of this paper is to establish the critical and current knowledge on cavity nucleation, growth and coalescence mechanism to build up the base for developing the new set of creep damage constitutive equations model.

Nucleation and Growth of Creep Cavities for P91 Steel

Stress level region

The stress exponent n is general defined as:

$$n=\frac{\Delta(\ln(\dot{\varepsilon}_s))}{\Delta(\ln(\sigma))}$$

The variable $\dot{\varepsilon}_s$ is the steady state creep strain rate (minimum creep strain rate), σ is the normal stress. The regime between low stress level and high stress level is distinguished by the values of n. Moreover; the change of n value indicates a change of creep deformation mechanism. Kloc and Sklenicka [8] found n = 4.5 to be the stress changing regime indictor for P91 type steel; this value is much lower than n =12 for P91 steel above 100MPa under 873K at high stress level (power-law creep regime). The steady-state creep strain rate depends on the applied stress. The higher the applied stress, the higher the creep strain rate is.

Czyrska-Filemonowicz et al. [9] reported that the value of n changes from 6-16 from low stress level to high stress level. Chen et al. [10] mentioned that the previous stress regions were defined as n = 1 for the low stress level (primary creep stage), n = 4 for the transition region (secondary creep stage) and n = 10 for high stress region (tertiary creep stage). Recently, with the stress exponent n (n ≈ 4 or 5 for high stress region) increasing, the power law relationship between the minimum creep strain rate and stress will be suitable [11]. For ASME Grade 91 weldments, the transition stress between high stress and low stress level is about 70MPa at 625OC [12].

High stress level

It is generally known that the dislocation creep deformation assisted a ductile rupture process at the high stress level. The high stress dependence of creep rupture life span and the minimum creep strain rate is considerably caused by the plastic deformation under high stress levels for high Cr steels, such as P92 and 15% Cr alloy [13]. The cavities nucleation, growth and coalescence damage mechanism has been widely applied in order to analyze the microstructure behaviors of materials. The current research shows that just a few cavities have been observed under the high stress level, even in the fractured specimens. The fraction of cavity area is less than 1% in some of the fracture specimens according to Vivier et al. [14] when tested at 500^{o}C. The cavities nucleation mainly occurs around the grain boundaries, especially around the stress concentration area. The cavity growth is controlled by grain deformation and the coalescence of cavities. According to the doctoral thesis of Magnusson [15] the nucleation of the cavities is due to the grain boundary sliding. The rate of creep cavities nucleation and growth of 9-12% Cr steels are proportional to the minimum creep strain rate based on the classic cavity growth with continuous nucleation theory. When the10% grain boundaries are occupied by cavities, the assumed ruptures occur [15].

However, the ductile rupture is mainly owing to the necking phenomenon and the visco-plastic deformation [16-22]. Lim [23] who studied the tertiary behavior of P91 steel found that the necking with the creep softening behavior has a significant effect on the prediction of the material's lifetime. Material's necking is due to the initial lath martensite recovery during the creep process. Without taking the necking effect into account, the model Haff constitutive equations overestimated the lifetime of the P91 steel. The microstructure softening will increase the strain rate during the tertiary creep stage, and necking damage will lead to a quick drop before the ductile fractures (only at the last 10% of the tertiary of stage) [23]. Abe [24] found that the tertiary creep stage starts when the creep life time is less than 30% by analyzing creep strain data in the NIMS creep data sheet, 450^{o}C-725^{o}C and t_r=11.4-68,755 hours.

Low stress level

By contrast, the creep deformation process is controlled by the diffusion phenomena at the low stress level. Moreover, the degradation of material P91 is because of the microstructure changes, such as the MX particles, Lave phases, M23C6 carbides [2-3,13,17]. A premature failure is observed during a long term creep exposure. The reason for this premature failure was identified by Kimura et al. [25] and Sawada et al. [26]. The microstructure degradation of P91 steels during creep under low stress level shows that: 1) the rupture is caused by the large number of cavities nucleation, growth and coalescence (cavities and participates coalescence) at the low stress level; 2) the cavities start nucleating around grain boundaries, and grow due to the diffusion deformation and coalescence, finally leading to a micro or macro crack [16, 27].

According to the experiment reported by Rauch et al. [17], a significant number of cavities were observed at low stress level. The density of the creep cavities increases with a decreasing creep deformation or creep rupture elongation and the decreasing creep strain [18, 28]. The nucleation of creep cavities depends on the stress level. The size of creep cavities not only depends on the preparation technique (polishing and etching), but also depends on the creep fracture deformation values at the certain stress level and the failure creep strain [18].

Multi-axialilty of stress state

P91 steels

The relative higher creep strain rate is not only because of the high stress level, but also effected by the stress state. The lifetime of P91 steel is also reduced by the high creep strain rate. The larger the creep strain rate, the shorter the life span will be [28, 29]. The number and size of cavities in 9-12% Cr steels (E911 and P91) under the multi-axial stress state increases compared with the smooth specimens. The multi-axiality of stress state will increase the creep strain rate, and the creep cavity densities; such as the quotient of multiaxiality $q\approx1.2$ and $q\approx1.0$, the creep cavity densities are less than $30mm^{-2}$ and around $40mm^{-2}$ respectively for P91 steel at 600^oC [18]. The cavities nucleation has been detected if the creep deformation is greater than 1%, and the cavity densities are less than $50mm^{-2}$ up to 2%. The higher cavity densities were observed with a lower deformation and with a relatively low quotient of multi-axiality.

P91 steel weldment

Creep failure by Type IV cracking in P91 steel weldments is likely to be the main failure mechanism in high temperature for advanced power plant applications. Heat-affected zone (HAZ) is the weakest area compared with the parent material. The creep rupture time in HAZ is approximately 1/5 of the parent material. The number of creep cavities per area increases with the creep damage process and the highest density of creep cavities is located in the mid-thickness (or the center of the fine-grained heat-affected zone) region which is about 60% creep damage rather than the surface region of the fine-grained heat-affected zone [18, 30-33]. The tri-axial stress state will accelerate the creep damage evaluation in the HAZ. However, it may not affect the growth and coarsening of precipitates rates during the creep phenomena [18, 30-33].

The cavities preferentially nucleate at grain boundaries near the coarser carbides and Laves phase particles or at a triple conjunction [12]. A relatively high density of cavities in Type IV region was observed after a long-term creep exposure under 600^oC at 90Mpa (T_r=8853 hours). The interrupted experiment result shows: 1) there is no creep voids when $t/t_r=0.2$; 2) a relatively high density of cavities observed when $t/t_r=0.7$; 3) the cracks are only apparent until $t/t_r=0.9$ [34]. Ogata [35] reported that the diffusion mechanism of creep deformation controls the void growth for a 9% Cr welded specimens (HAZ region). Two interrupted specimens were 32% and 56% respectively under 650^oC with an internal pressure at 21.7Mpa. The results show that a very small amount of cavities was observed during 32% creep damage, and still a small amount of cavities was observed at 56% creep damage. The creep cavities have already nucleated on grain boundaries at less than 25% creep damage [35]. Moreover, the size of cavities only slightly increased during creep as mentioned by Gaffard [36].

Conclusion

The key characteristics of the cavity nucleation, growth and coalescence phenomena has been summarized and reviewed in this paper. Under high stress level, a few cavities were observed in the current experiment data. However, under the low stress level, there is a significant difference compared with the high stress level. A large amount of cavity nucleation, growth and coalescence leads to a micro or macro cracking during the creep. In other words, the creep cavity nucleation, growth and coalescence rate decide the life span of materials. Therefore, the variables to describe this rate should be introduced by the new set of constitutive equations model. These characteristics will be considered as the mechanisms' base for the future development of creep damage constitutive equations.

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