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Review of creep deformation and rupture mechanism of P91 alloy for the development of creep damage constitutive equations under low stress level

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Abstract —**This paper presents a review of creep deformation and rupture mechanism of P91 alloy for the development of its creep damage constitutive equations under lower stress level. 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 prediction the lifetime for this type of alloy, partially under low stress.**

The paper reports a critical review on the deformation and damage evolution characteristics of this alloy, particularly under low stress, to form the physical base for the development of creep damage constitutive equations. It covers the influence of the stress level, states of stress, and the failure criterion.

Keywords: creep deformation process, creep rupture mechanism, high Cr alloy, P91, low stress, brittle rupture

I. INTRODUCTION

Since high chromium alloy demonstrates considerable high temperature creep strength, high corrosion resistance, good weld ability and low oxidation speed, high chromium alloy such as 9Cr-1Mo-0.2V (P91 type) has been widely applied in advanced power plants as pipework components between 450^{o}C and 650^{o}C. Currently, most of the creep models are developed primarily based on the high stress tests at temperature range of 450^{o}C-650^{o}C. The models seem could also accurately predict the lifetime of materials [1-11]. An (2012) reviewed the current state of developing of advanced creep damage constitutive equations for high Chromium alloy (Grade 91). The new set of constitutive equations model should concern three aspects to improve the current models. These aspects are the influence of stress level, the influence of stress state and the failure criterion for high Cr alloy [12].

Nowadays, the life span under a low stress level has caught researchers' attention, because it is the lifetime the power generation installations which are designed and expected to last for. Therefore, the models developed for high stress level have been applied into the low stress conditions. However, many researchers realized that the creep strength and the creep life span have been over-estimated [13-21]. Therefore, Bendick, et al. [10] re-assessed the database due to the significant increase in test data, and a predicted duration of 10^5h for P91 steels, the updated value is 90MPa at 600^{o}C. Recently, Sawada et al. [18] also reported an investigation of the microstructural degradation under long-term creep condition.

To re-analyze the real creep deformation and rupture mechanisms of Gr.91 steel under different stress levels is one of the aspects in order to improve or develop a new set of constitutive equation model. Through observing the creep deformation and damage mechanisms, Petry and Lindet [1] found two kinds of rupture mechanisms dominate the creep damage of 9Cr-0.5Mo-1.8W-VNb (P92) steel according to the applied stress levels. He reported that the ductile rupture mechanism and creep cavitation damage mechanism dominate the creep damage process under high and low stress levels respectively.

In addition, Vivier and Panait et al. [3] also observed the ductile rupture mechanisms under high stress levels for P91 steel at 500^{o}C. Masse and Lejeail [21] utilized these two different rupture mechanisms with a new constitutive model to re-assess the lifetime of P91 steel in order to cope with the influence of stress level on the rupture. However, even though the model could describe the behavior of P91 steel under different stress levels effectively, he also pointed out there are still some limitations: strain localizations and geometry effects could be improved [19]. It is an interesting and significant progression and the authors of this paper believe that further investigation of the coupling between creep damage and creep deformation and its validation are needed.

A version of one of the most popular creep damage constitutive equations (KRH formulation) has been used to calculate the lifetime for P91 under a low stress level and it was found that it was overestimated [11]. All the above strongly show that further research work is needed to develop and validate the creep damage constitutive for a lower stress level.

This paper reports the review of the creep deformation and creep damage and rupture mechanisms in order to provide the physical base for the developing of the creep damage constitutive equation for P91 material under low stress.

This paper contributes to knowledge of the continuum creep damage mechanics.

II. THE CHARACTERICSTICS OF CREEP DEFORMATION AND RUPTURE OF GRADE 91 STEEL

From the literature, the high stress range varies depending on the temperature. For example, at 600ºC, the high stress range is around 130-200MPa; at 650ºC, it is around 70 -100MPa. Inversely, the stresses less than 130MPa belong to the low stress level at 600ºC; the stresses less than 70MPa belong to the low stress ranges at 650ºC [11, 22].

A. High stress creep deformation and rupture mechanism

1) Dislocation deformation

The dislocation deformation controls the creep deformation process under high stress level. An obvious dislocation structure could be clear observed before creep [16]. A research on the fractured specimens' surface also shows a high dislocation density [8].

2) Damage characteristics

The creep damage process with time of P91 steels is divided into 3 stages: 1) the cavity nucleation along the grain boundary, mainly in stress concentration area; 2) the cavity growth; 3) the cavity or precipitates coalescence and material necking until a ductile fracture with low (≈10%) volume fractions of cavities. The experiment data of P91 base metal steels under 90MPa, 100MPa, 110MPa and 120MPa at 650ºC come from Gaffard et al. [8, 9].

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 owing 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 fracture (only at the last 10% of the tertiary of stage).

3) Rupture mechanism

The trans-granular ductile failure with creep deformation, necking and the softening of material have been reported in the literature; for instance, the experiment data from Vivier et al. [2] under a high stress range of 270MPa-310MPa at 500ºC; Masse et al. [20] collected 388 creep tests between 450ºC-650ºC; Gaffard et al. and Bendick et al. [10] under 90MPa, 100MPa, 110MPa and 120MPa at 625ºC.

B. Low stress creep deformation and rupture mechanism

1) Diffusion deformation

The influence of the evolution of diffusion density, sub-grains size and precipitates ($M_{23}C_6$ carbides, Lave phase and MX-Type) in P91 steel presented here is based on many researchers observations [14-16, 21]. Although the dislocation creep happens during the whole creep process, the diffusion creep dominates the deformation mechanism under low stress levels. Nabarro-Herring creep is one of the diffusion ways. The strain rate of Nabarro-Herring creep is proportional to the stress levels; also the strain rate at the tertiary stage is proportional to the temperature due to its strong temperature dependence.

The detailed diffusion angles during creep has been reported by Gaffard et al. [8] and also reported by Masse and Lejeail [20-21]. The Electron Back Scattered Diffraction (EBSD) map shows most of the boundaries rotation angle is >15º and some of the boundaries rotation angle is 5º < angle <15º.

2) Damage characteristics

The damage characteristics of P91 steels under low stress level are significantly caused by coarsening of $M_{23}C_6$ carbides, precipitates and coarsening of Lave phase and a pre-recovery of matrix according to Panait et al. [15-16]. The study of microstructure of the P91 steels after more than 100,000h of creep exposure under 80MPa at 600ºC, and the results show an abundant of Laves Phases and a few mount of modified Z-phases (only 41 precipitates out of 640 identified precipitates) have been observed during a long-term creep. The size of $M_{23}C_6$ carbides grows from 150-180nm to about 300nm after creep and they mainly locates around the grain boundary. Some small MX type precipitates also observed in the martensite laths. The cavities nucleates next to Lave phase precipitates at grain boundary after creep 113,43h at 600ºC, and the coalescence of $M_{23}C_6$ carbides and Lave phase phenomenon were observed at the fracture surface [15-16]

3) Rupture mechanism

The diffusion-assisted brittle rupture looks like the rupture mechanism under low stress level. A premature failure of P91 steel has been observed during a long-term creep. The Laves phase emerges and cavities rapid coalescence during the tertiary creep stage causing a premature failure during the long-term test. The different preferential recovery mechanisms of martensite at the prior austenite grain boundary (PAGB) are homogenous and inhomogeneous recovery under high stress and low stress levels respectively. Due to the inhomogeneous recovery, a premature of tertiary creep stage happens in advance of rapid the failure [17]. Besides, NRIM creep data sheet [19] shows the elongation (EL) and reduction of area (RA) of P91 steel tubes at 600ºC under different stress levels. There are no EL and RA when the material ruptured under 100MPa at 600ºC. The values of elongation and reduction of cross area under 110MPa are 23% and 84%, respectively [6].

One typical experiment of P91 steels was conducted by Sawada et al. [18] during a long-term creep under 70MPa at 600ºC. The microstructure changes may take the main responsibility for the premature failure during a long-term creep, whereas, the failure may not depends on the martensite recovery and particles coarsening. The sub-grain size and the density of dislocation gradually increase with time; however, they sharp increase after 70,000h until rupture (80,7368 hours) under 70MPa at 600ºC. This agrees with the experiment results from K. Kimura et al. [17], that the Z-phase formation or the disappearing of MX particles just happens after a long time of creep.

C. Stress state effect

The most popular topic is about the stress state effect on the lifetime span of materials. Some small-punch tests were conducted by Nagode et al. [24] under 350N-550N at the temperature range $650^{O}C$-$690^{O}C$ at the high stress range, used minimum deflection rate to replace the minimum creep strain rate, it shows that the minimum deflection rate is almost inversely proportional to the time-to-rupture, i.e. the minimum strain rate is inversely proportional to the time-to-rupture. Moreover, the minimum strain rate is proportional to the stress levels.
For the weldment, the life span of P91 not only depends on the stress state and levels, but also depends on the notched size as well [22].

1) 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 [25-26]. 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 $q \approx 1.2$ and $q \approx 1.0$, the creep cavity densities are less than $30mm^{-2}$ and around $40mm^{-2}$ respectively for P91 steel at 600ºC [8]. 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.

2) 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 [7-8, 27-29]. 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 [7-8, 27-29].

The cavities preferentially nucleate at grain boundaries near the coarser carbides and Laves phase particles or at a triple conjunction [22]. A relatively high density of cavities in Type IV region was observed after a long-term creep exposure under 600ºC at 90Mpa (Tr=8853 hours). The interrupted experiment result shows: 1) there is no creep voids when t/tr=0.2; 2) a relatively high density of cavities observed when t/tr=0.7; 3) the cracks are only apparent until t/tr=0.9 [30]. Ogata [31] 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 650ºC 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 [31]. Moreover, the size of cavities only slightly increased during creep as mentioned by Gaffard [32].

The multi-axial state of stress is important; however, it is difficult to achieve systematically in the experiment. The information about the effect of states of stress on the creep deformation and creep damage evolution, including the cavity nucleation, growth, and coalescence should and can be extracted and distilled from the literature. This is still ongoing and will be reported in due course.

D. Strain at failure
The results of experiment conducted by Masse and Lejeail [18] show the creep strain at failure under different stress levels at 625ºC and 500ºC. Under high stress levels at 500ºC, the creep strain at failure is about 10%-12%, the creep strain at failure is around 1% under low stress levels. At 625ºC, the creep strain at failure is around 2% and 0.4% under high stress levels and low stress levels, respectively. The creep strain at failure at 600ºC under 70MPa is about 0.33% according to Sawada (2011) [18]. Therefore, the strain at failure varies depending on the different stress levels and temperature.

III. SUMMARY

This paper focuses on three fundamental aspects for developing a new set of constitutive equations of P91 steel. The following conclusions have been reached.

- Influence of stress levels
  The dislocation creep deformation with necking and the trans-granular ductile rupture mechanism are observed under high stress levels. The diffusion creep deformation and the cavity nucleation, growth and coalescence brittle rupture mechanism are observed under low stress level.
- Influence of stress state
  For the base material, the influence of stress state depends on whether the creep strain rate is proportional to the time-to-rupture or not. For the weldment, it not only depends on the stress rate and level, but also depends on the radius of notched bar.
- Strain at failure
  A varying range of values to describe the different strain at failure are reported under either high or low stress levels

The progress made in the current literature review, plus further analysis on the process of cavity nucleation, growth, and coalesces under the lower stress level, the coupling of creep damage and deformation, and the effect of states of stress will form a firm foundation for the development of physically-based creep damage constitutive equations which will be reported in due course.

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