Review of creep cavitation and rupture of low Cr alloy and its weldment

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Abstract. This paper presents a review of creep cavitation and rupture of low Cr alloy and its weldment, particular in the heat-affected zone (HAZ). Creep damage is one of the serious problems for the high temperature industry. One of the computational approaches is continuum damage mechanics which has been developed and applied complementary to the experimental approach and assists in the safe operation. However, the existing creep damage constitutive equations are not developed specifically for low stress. Therefore, in order to form the physical bases for the development of creep damage constitutive equation, it is necessary to critically review the creep cavitation and rupture characteristics of low Cr alloy and its weldment.

Introduction

The 2.25%Cr1%Mo (10CrMo9-10) steel has been widely used for high temperature structural components, such as steam pipeworks, fossil fuel plants and nuclear reactors in the power generation industry serviced at temperatures of 673K-873K (400 to 600℃) and at varying stress levels, from 40 MPa to 200MPa (MN m^{-2}) [1]; this steel is selected since it offers the necessary creep strength at optimal cost.

The microstructure changes in this steel are due to the long-term service at the elevated temperature under different stress states and stress levels causing the deterioration of the mechanical property of materials [2]. Furthermore, the mechanical property of 2.25%Cr1%Mo is strongly influenced by the microstructure and consequent microstructural changes during thermal aging and high temperatures and stress levels and states [3, 4]. Data on microstructural evolution during long-term exposure at the elevated temperatures and varying stress states and stress levels have been analyzed in this paper; the mechanical property and microstructure of the long-term serviced materials have also been investigated.

Xu *et al.* [5-7] have found that the reports from industry and institutions show that a new set of creep damage constitutive equations is required to be developed to depict the mechanical damage behavior and rupture lifetime. Also, Xu *et al.* [7, 8] indicated that the tertiary stage takes the largest part of the rupture life, and is closely related to the rupture behavior. Therefore, understanding the tertiary creep rupture behavior is important. As has been discussed in [8], there are typically two kinds of behaviors which lead to the tertiary stage rupture. Firstly, tertiary creep might be attributed to the reduction of a load carrying cross-section as deformation process; this is associated with the effect of the true stress. On the other hand, it might be due to the loss of the effective area on the grain scale; the build-up of cavities on grain boundaries will lead to the reduction of the load-carrying area, and increase of a local true stress at constant load. Subsequently, the increased strain rate may cause the cavity growth rate to increase. However, this is not the only possible mechanism for tertiary creep; from the observations of the metallurgical examination of some other materials shows that a few cavities were exhibited in the tertiary stage of material [2]. Therefore, thermal ageing is an alternative process leading to the matrix material rupture in the tertiary state [2].

Creep rupture and fracture properties, such as the creep rupture lives and the initiation and growth behaviors of creep voids are influenced strongly by material characteristics, temperature, applied stress states (the cavity nucleation and cavity growth rate are strongly dependent on the maximum principal stress, σ_1, the von Mises equivalent effective stress, $\bar{\sigma}$, and hydrostatic stress, σ_H, under varying multi-axial stress states), and stress levels [3]. Many investigations have been made upon the creep rupture and fracture properties of tension, torsion, combined tension and internal pressure and notched specimens at varying stress ranges [2, 3, 9]. However, the effects of these multi-axial stress components and material characteristics on the multi-axial creep rupture properties have not been clearly stated to date [10]. To sum up, this paper suggests the cavity nucleation and cavity growth considered as the reason which leads to the rupture under creep stress levels and states at varying constant temperature on the low Cr-Mo alloy, such as 2.25%Cr1%Mo (T/P22) steel.

The cavity nucleation and growth behavior under lower stress level

At low stress, (0.2~0.4σ_Y), Parker and Parsons [11] claimed that the nucleation controlled constrained cavity growth is the predominant mechanism; also, the fracture has been observed based on the intergranular cavities [11].

Longsdale and Flewitt [4] reported that under the stress level of 55.6, 60.6 and 70.6 MPa, at 873K (600℃) for 2.25%Cr1%Mo steel, the cavity rate of accumulation which increases monotonically with time and at a given time was greatest for the largest applied stress; the density of the cavity observed on the grain surfaces increased continuously throughout the creep life; its cavity growth rate is slightly increased with the accumulation of time [12]. From the laboratory research observation on the cavity nucleation and cavity growth, Needham [12] found that the functional relationship for cavity nucleation rate, cavity growth rate, and the rupture lifetime for 2.25%Cr1%Mo steel and 1%Cr0.5%Mo steel are inversely related to the maximum principal stress,σ_0, by a power law, under lower stresses [12]; the power law index number is presented in Table I for these two Grades.

TABLE. I. Summary of stress index for power law behavior under the low stress [12]

Under low stresses (0.2~0.4 yield stress) MPa			
depends on maximum principal stress	Cavity nucleation rate	cavity growth rate	rupture lifetime
power law stress index	5~7	3.5~4.5	4.8

Dobrazanski [13, 14] reported the creep damage process of low-alloy Cr-Mo steel is the development of cavities, followed by the formation of micro-cracks and eventually the macro-cracks which lead to the final rupture. His research demonstrated that under low stress level, the 1Cr%0.5%Mo steel and T/P23 (7CrWVNb 9-6) steel start to nuclei at 0.4~0.6T_R; the report from EPRI shows similar results that T/P22 steel starts to nuclei at 0.25T_R[15]. However, the above contradicts the assumption that the entire cavity is instantly nucleated, which was adopted by Dyson in developing creep damage constitutive equations [16].

The cavity nucleation and growth behavior under moderate stress level

Mohyla and Foldyna [17] stated that at 873K (600℃) and at 110MPa, the microstructure of the experimental specimens has seen the elliptical creep cavities, wedge type creep cavities and grain boundary cavities. These results indicate that the creep deformation and rupture behavior is a mixture mechanism under the stress level of 0.4-0.5σ_Y.

The cavity nucleation and growth behavior under high stress level

At high stress (>0.5σ_Y), the plasticity-controlled cavity growth mechanism is predominant. Moreover, there is an increasing rupture strain with the increasing creep strain rate [11, 18]. Under this stress level, the creep rupture occurs based on the wedge-type micro-crack which formed at a triple grain junction and the growth of those cracks will lead to local grain-boundary separation [11, 18]. Furthermore, failure occurs more quickly and is accompanied by elongation deformation [11, 18]. The speed of plastic strain increases rapidly after the external loading is applied. In this condition, the fracture is based on the transgranular cavities [11, 18-19]. A further study shows the creep failure is associated with ductility because the specimens presented the reduction area to be around ¾ of the cross-section under a high strength condition [11, 18-19].

Creep deformation and rupture have been studied in 2.25%Cr1%Mo steel over the range 60-210MPa (MN m^{-2}) at 565℃. Furthermore, Kawashima et al. [20] reported that for 2.25%Cr1%Mo steel the creep ruptures lifetime depends on the cavity nucleation rate and cavity growth size. Creep damage accumulates due to the initiation and growth of extensive cavitation at the prior austenite grain boundaries [20]. Cavity formation predominates during the initial transient and individual cavities appear to nucleate on grain boundary carbides [20]. Quantitative analysis of the cavitation kinetics in relation to the creep deformation processes suggested that cavity growth is directly related to deformation occurring at the grain boundaries [21].

TABLE II. The cavity growth rate versus stress in low Cr-Mo alloy, under the high stress [4]

cavity growth rate(m/s)	stress (MPa)
3.16228E-14	117.5
5.62341E-14	127.5
7.49894E-14	145
1.77828E-13	160
3.16228E-13	170
1.77828E-12	190
3.16228E-12	225

Table II shows the growth rate increases with the increase of the applied stresses under higher stresses [4]. These results indicate that the cavity growth behavior is associated with the creep rupture behavior and mechanism [2- 4].

Table III. Summary of stress index for power law behavior under the high stress [3]

Under intermediate and high stresses (>0.5 yield stress) MPa			
depends on maximum principal stress and equivalent stress	Cavity nucleation rate	cavity growth rate	rupture lifetime
power law stress index	3.5~5	3.5~5	3.5~5

As the cavity nucleation rate is strongly dependent upon the maximum principal stress under low stress condition, and dependent upon both the maximum principal stress, σ_1, and the equivalent stress, $\bar{\sigma}$, under intermediate and high stresses respectively, the rupture lifetime could be predicted from the nucleation rate determined under uniaxial tensile [3]. Therefore, further work will focus on the critical value of the void nucleation rate and the growth rate depending on the creep lives. Once this has been conducted, a hypothesis of a new creep rupture criterion will be developed to conduct the physical–based creep rupture behavior and the mechanism [22]. With a high stress ($\geq$90MPa) the specimens are fractured by the local necking following substantial elongations and reduction of cross-section area. It has been observed that some voids occurred in the necked region, characteristic of localized plastic flow; Moreover, this voiding was generally sited on boundaries oriented at a small angle, and was elongated in the direction of the tensile axis [1-3].

The cavity nucleation and growth at Type IV weldment zone

The research portfolio from the Electric Power Research Institute (EPRI) in 2012 stated that the failure of the components due to Type IV cracking in the HAZ of welds may depend on the applied post-weld heat treatment condition which may affect the grain size from the recrystallization process which may cause a typical grain size which could form a type of carbides [23]. Some evidences supported this statement; when the 2.25Cr-1Mo steel have been applied post-weld heat treatment, the optical metallography showed that the creep specimens have the carbides, were characterized from the electron diffraction pattern as being of the $M_{23}C_6$ type which could cause cavity nuclei and this carbide was found to be stable throughout the duration of the tests, which means the cavitation may be a cause which leads to final rupture [1].

As has been reported, the T/P 23 weld failure occurred in coal fired supercritical power plant were possibly because the voids formed at grain boundary and the residual stress form welding process may effected the crack growth; it has been proofed that the stress on the pipe was not the cause that lead to crack in HAZ [1-2, 24]. A majority of cavitation was observed to initiate at the carbides and inclusions along the grain boundary and cavities were observed on the fracture surfaces of both creep deformation and creep crack growth tested specimens [2, 24-25]; a variety of chromium-rich carbides ($M_{23}C_6, MC_6, M_7C_3$) were detected in the weld metal, primarily along ferrite boundaries; in addition, the coarse intergranular carbides, some intergranular Mo_2C carbides were only observed in the larger (approximately $10\mu m$ diameter) ferrite grains [2]. The voids along the grain boundaries are likely to grow and link together to develop an easy path for creep fracture [2, 24-26]. The weld material was found to demonstrate greater creep deformation rates and faster creep cracks propagation rates than the corresponding base material [25, 26].

Summary

This paper has reported the critical analysis on the obtained experimental observations on the creep cavity nucleation and cavity growth behavior which has been considered as the key feature which eventually leads to rupture in low Cr-Mo alloy and its weldment. The cavity nucleation rate and cavity growth rate in terms of lifetime and strain at failure under a range of stress states and stress level has been investigated. Further work will focus on the development of the creep damage constitutive equations for low Cr-Mo alloy which could be used in engineering design, either with approximate reference stress methods or with the finite element continuum damage mechanics methods.

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