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A Review of Creep Deformation and Rupture Mechanisms of Cr-Mo Alloy for the Development of Creep Damage Constitutive Equations under Lower Stress

Qihua Xu, Qiang Xu, Zhongyu Lu and Simon Barrans

School of Computing and Engineering, University of Huddersfield, Huddersfield HD1 3DH, UK

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Abstract: This paper presents a review of creep deformation and rupture mechanisms of low Cr-Mo alloy for the development of its creep damage constitutive equations under lower stress. The most popular KRH (Kachanov-Robatnov-Hayhurst) formulation was not necessarily developed and calibrated for low stress and can not depict the creep strain accurately under multi-axial state of stress due to the three-dimensional generalization method used. This paper summarizes a critical analysis on the cavity nucleation and growth, and the deformation mechanisms and creep damage evolution characteristics at the temperature ranging for 723 K to 923 K (450 °C to 650 °C), particularly under low stress level (0.2-0.4σ_Y), in order to form the physical base for the development of creep damage constitutive equation. Moreover, it covers the influence of the stress level, states of stress, and the failure criterion.

Key words: Cavitation, creep damage, low Cr-Mo alloy, stress level, stress state.

1. Introduction

Low Cr-Mo alloy steel is widely used for steam pipeworks in the power generation industry, particularly in fossil fuel plants and nuclear reactors at elevated temperatures of 723-823 K (450-550 °C) and varying stress levels of 40-200 MPa. This steel is selected since it offers the necessary creep strength at optimal cost. In attempt to expand its application, experimental work has been carried out to a wider range of stress (30-350 MPa) and even higher temperature (up to 650 °C) [1]. A stress level is conventionally deemed as low, intermediate, or high, depending on its ratio to the yield stress(0.2-0.4σ_Y, 0.4-0.5σ_Y, and > 0.5σ_Y) at a particular temperature. The long life of power generation installation signifies the importance of lifetime prediction under lower stress.

Clearly evidences from the industry and institutions show that a new set of creep damage constitutive equations is required to depict the creep deformation, damage, and rupture [2-4].

The most popular Kachanov-Robatnov-Hayhurst (KRH) formulation was not developed for low stress and cannot depict the creep strain accurately under multi-axial state of stress due to its three-dimensional generation method used [4-6]. In 2004, the ECCC (European Creep Collaborative Committee) [2] established a new project to develop a new set of constitutive equations for low alloy steel because the previous creep model can not present accurate results for the high temperature industry. Likewise, the same requirement raised by ECCC was raised by the Nuclear Research Index (UK) [3] to ensure the inspection of operated components. In 2012, Hosseini et al. [7] of the

Corresponding author: Qiang Xu, Ph.D., senior lecturer, research field: computational creep damage mechanics. E-mail: Q.Xu2@hud.ac.uk.

SFL (Swiss Federal Laboratories) demonstrated that the lifetime for lower stress is overestimated by five different sets of creep models; moreover, these creep models do not depict the tertiary stage which is closely related with lifetime fracture [7]. Therefore, it is important to conduct a critical review on the creep deformation process and rupture mechanisms to firmly establish the foundation for the development of a set of creep damage constitutive equations. At this current stage, the authors believe that for low alloy Cr-Mo steel there is a lack of clarity of the damage processes at different stress levels and stress states, as well as a lack of good understanding of the microstructure changes during creep services in terms of constitutive modeling.

This paper is an expanded work which includes the authors' previous published work on a critical analysis of creep deformation and rupture under creep stress levels and states at varying constant temperature on the low Cr-Mo alloy, such as 2.25Cr-1Mo (T/P22) steel [8-10]. This paper is organized as follows: Section 2 explains the influence of stress level on uni-axial creep specimens; Section 3 discusses the influence of multi-axial stress state for this work; Section 4 contains the existing creep rupture criterion used for low Cr-Mo alloy; Section 5 contains the multi-axial stress rupture criterion for low Cr-Mo alloy; Section 6 presents the summary of the preliminary results and discussions, as well as the key requirements for developing the new set of creep damage constitutive equations; and finally Section 7 draws the conclusion.

2. Effect of Stress Level under Uni-axial Creep

The data of the specimens to analyze the creep deformation and rupture processes were extracted from published literatures and research institutions' (universities, companies and high temperature industries) laboratories [1, 11-14].

2.1 Effect of the Stress Level on Creep Lifetime

Fig. 1 shows the relationship between lifetime and stress level. This figure reflects that at higher stress levels the damage mechanism differs from the low stress levels. This observation firmly indicates that (1) extrapolation from short-term (high stress level) data to long-term (lower stress) is highly questionable, no matter how attractive it is; (2) specific creep damage constitutive equation/modeling has to be developed according to the stress level in order to reflect the changing of damage mechanisms. Based on the experimental data of the stress versus time to the rupture, the mechanical relationship could be approximately assumed as:

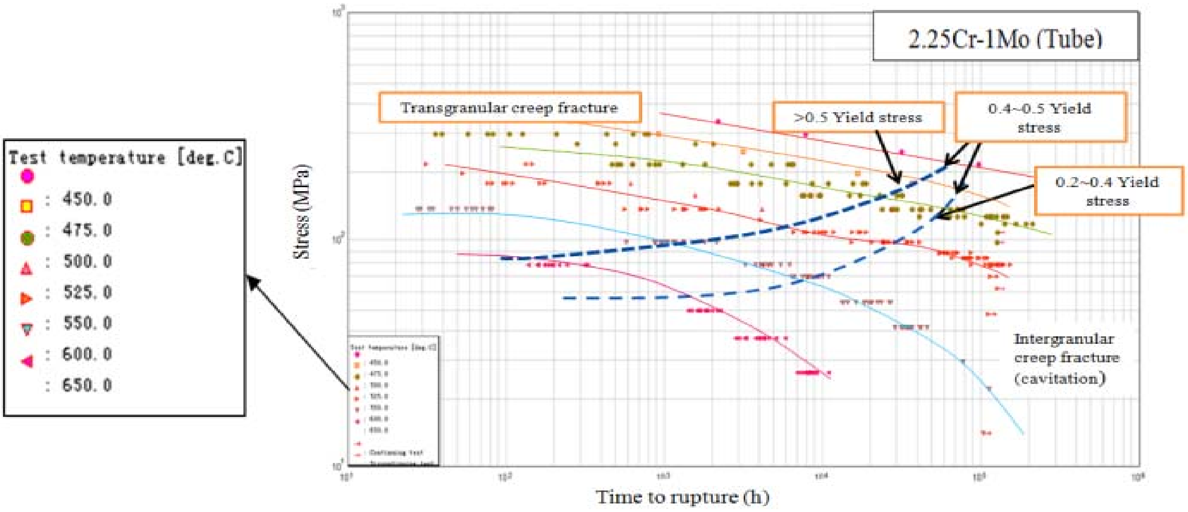

Fig. 1 Stress versus time to rupture at 450 °C, 475 °C, 500 °C, 525 °C, 550 °C, 600 °C, 650 °C for P22 steel tubes, adapted from Ref. [1].

$$T_f \propto \frac{1}{\sigma} \qquad (1)$$

where T_f is fracture time, and σ is stress.

2.2 Effect of the Stress Level on Strain at Failure

Fig. 2 shows that the strain at failure is increasing with the stress level.

Based on the experimental data of strain at failure versus stress, the mechanical relationship could be assumed as:

$$\varepsilon_f \propto A\sigma^n \qquad (2)$$

where ε_f is the strain at failure, and σ is stress.

2.3 Effect of the Stress Level on Creep Rate

Fig. 3 shows the creep behavior of the alloy 2.25Cr-1Mo at 450-650 °C (minimum creep rate against stress). The observation indicates that the stress level does influence the creep behavior of the alloy, having a larger effect on the minimum creep rate. A careful analysis was carried out with the creep data only to check the variation of the minimum creep rate with stress and verify the possibility of expressing the data according to this relation.

Based on the experimental data for stress versus minimum creep rate, a mechanistic relationship could be approximately assumed as:

$$\dot{\varepsilon}_{min} \propto e^{\frac{\sigma-n}{m}} \qquad (3)$$

where $\dot{\varepsilon}_m$ is minimum creep rate, σ is stress, and n and m are materials parameter.

2.4 Effect of the Stress Level on Ductility

In order to overcome the inaccuracy of elongation due to necking, some researchers have used ductility instead. An investigation from experimental aspects shows that at different regime of rupture ductility varies with externally applied stresses [12, 13]. The various ductility regimes are associated with distinct rupture mechanisms which affect the accuracy in investigating the constitutive equation [15-17].

Fig. 4 shows a ductile failure under higher stresses; and it decreases with the stresses level.

ECCC proposed a general trend of elongation versus the log rupture time to depict the effect on ductility [17].

The ductility equations for multi-axial stress states have been summarized in Table 1, which could be used to develop the new set of creep damage constitutive equations when the dominated fracture mechanism has been carried out form the analyze existed experiments.

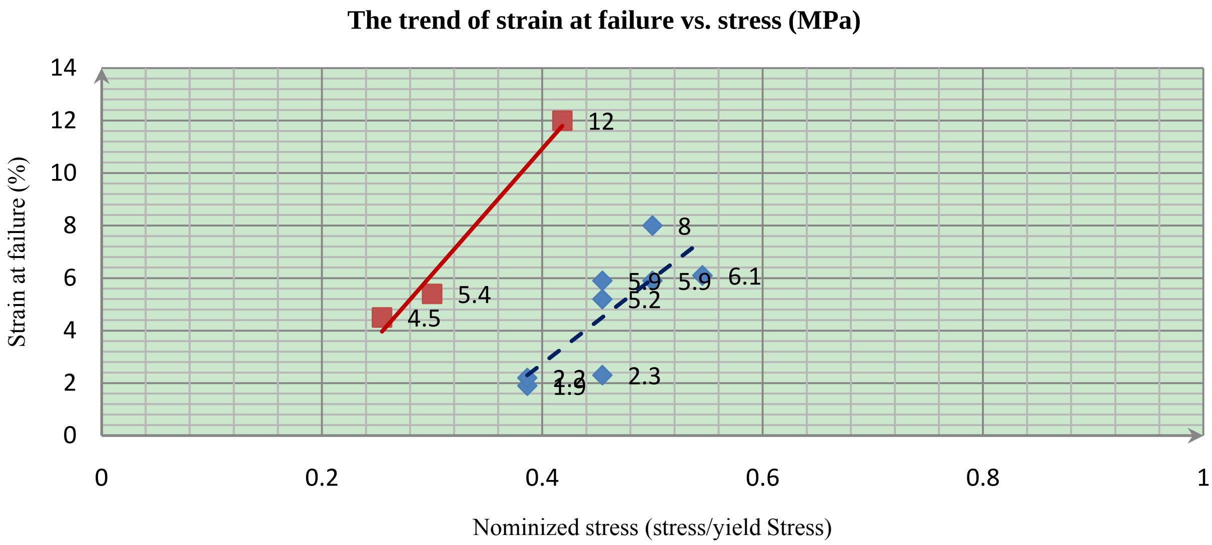

Fig. 2 Strain at failure and stress level experimental data summarized from Ref. [14] at the temperature of 640 °C (dash line) and 620 °C (solid line), data collected from ERA's report.

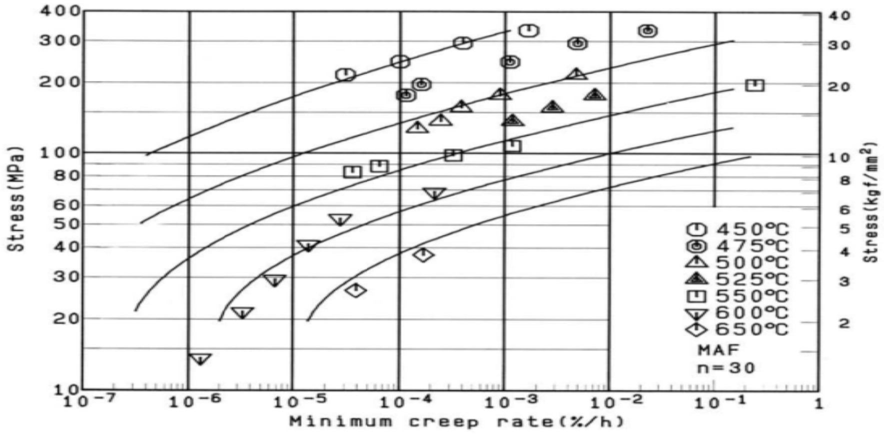

Fig. 3 The stress versus minimum creep rate relation for P22 steel tubes [13].

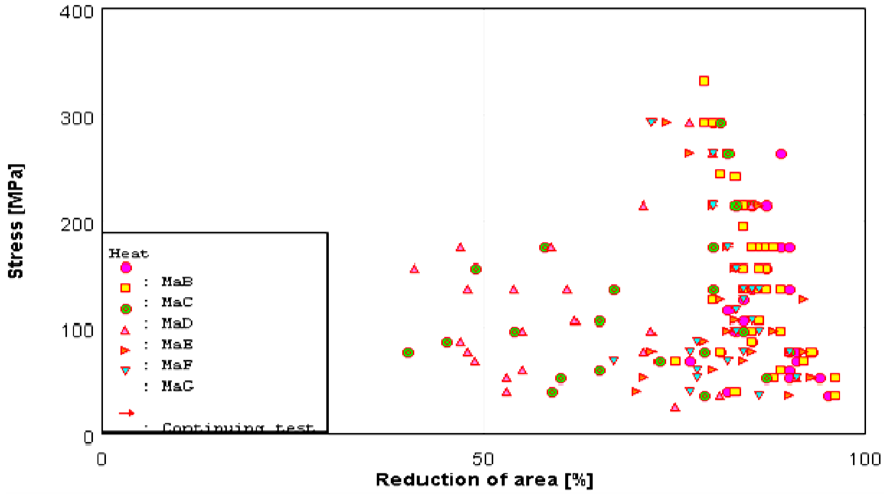

Fig. 4 The stress and ductility relationship for 2.25Cr-Mo steel (P22) [1].

Table 1 The ductility equations for dominate mechanism under low, intermediate and high stresses for multi-axial stress states, ECCC [2].

	Stress level	Dominate mechanism	Model developer	Ductility model	
Multi-axial rupture ductility model	Under High stress level $> 0.5\ \sigma_Y$	Grain boundary cavity growth	Marlof et al. [18]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{1}{3}\frac{\sigma_{vm}}{\sigma_m} = \frac{1}{2}\frac{(\sigma_1 - \sigma_m)}{\sigma_m}$	(4)
			Ewald [19]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{3}{2}\frac{\sigma_1 - \sigma_m}{\sigma_1}$	(5)
			Sheng [20]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{3}{2}\frac{(\sigma_1 - \sigma_m)}{\sigma_{vm}}\left(\frac{\sigma_{vm}}{\sigma_1}\right)^m$	(6)
	Between high and low stress $0.4 - 0.5\ \sigma_Y$	Diffusion controlled cavity growth	Hales [21]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{2}{3}\frac{\sigma_1}{S_1}\left(\frac{\sigma_{vm}}{\sigma_1}\right)^{m+1}$	(7)
	Under low stress $0.2 - 0.4\ \sigma_Y$	Constrained cavity growth	Spindler [22]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \exp\left[p\left(1 - \frac{\sigma_1}{\sigma_{vm}}\right) + q\left(\frac{1}{2} - \frac{3\sigma_m}{2\sigma_{vm}}\right)\right]$	(8)

2.5 Creep Damage Characteristics and Mechanism under High Stress Level

At high stress ($> 0.5\ \sigma_Y$) the plasticity-controlled cavity growth mechanism is predominant, and there is an increasing rupture strain with the increasing creep strain rate [23, 24]. Under this stress level, the creep rupture occurs based on the wedge-type micro-crack which forms at a triple grain junction and the growth cracks will lead to local grain-boundary separation [23, 24]. Furthermore, failure occurs relatively quicker and is accompanied by elongation deformation at this stress level [23, 24]. The speed of the plastic strain increases rapidly after the external loading is applied. In this condition, the fracture is based on the transgranular cavities [23-25]. Further study shows that the creep failure is associated with ductility because the reduction area of the specimens presented is around ¾ of the cross section under high strength condition [23-25].

The experimental data which have been plotted as the typical creep curve (creep strain versus lifetime) for low Cr-Mo alloy shows the primary creep stage often occupied approximately 10% of the total specimens' lifetime; however, the tertiary creep stage takes the largest portion of about 80% of the total lifetime [23-25].

2.6 Creep Damage Characteristics and Mechanism under Moderate Stress Level

Mohyla and Foldyna [26] report that at 873 K (600 °C) and at intermediate stress level 110 MPa (0.4-0.5 σ_Y), 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 under the stress level of (0.4-0.5 σ_Y).

2.7 Creep Damage Characteristics and Mechanism under Low Stress Level

At low stress (0.2-0.4 σ_Y), Parker and Parsons claimed that the nucleation controlled constrained cavity growth is the predominant mechanism [23, 24]; and the fracture is due to the intergranular cavities behavior.

In 2004 Dobrazanski [27, 28] classified the creep evolution of low-alloy Cr-Mo steel as the development of cavities, the formation of microcracks and macrocracks which lead to eventual rupture. His research reflects that under low stress level, the 1Cr-0.5Mo steel and T/P23 steel start to nuclei at 0.4-0.6 T_R; the report from EPRI shows similar result that T/P22 steel starts to nuclei at 0.25 T_R [4]; these results seem to contradict the earlier assumption about instant nucleation cited and then used by Dyson [29]. Consequently, this leads to the question of the need to examine the applicability of Dyson's creep damage constitutive equation under low stress.

3. Effect of Multi-axial Stress State

Comparing with the specimens' lifetime under the tensile stress and notched bar (which provide the tri-axial stress state) condition, the life under the tri-axial stress state has been extended due to the reduction of von Mises stress occurred when hydrostatic stress is imposed on uni-axial tension [30].

Needham [31], by comparing smooth and notched specimens (under higher stresses), examined the effect of the stress state on the nucleation rate in two Cr-Mo steels. Needham [31] found that it is the maximum principal stress, σ_1 which controls the nucleation; likewise, von-Mises equivalent rate is usually less important at high stresses. Currently, the experiment of the creep deformation performance on the notched bar of 2.25Cr-1Mo steel under higher stresses is been conducted [32], the results illustrate that the cavity size around the crack tip increases dramatically, but the cavity number only increases slightly [32]. Walker et al. [33] claimed that for 1/2CrMoV notched specimens (70 mm deep 30° angle), its cavity density depends on the stress level, lower relative cavity density observed as the applied stress is increased from 35 MPa to 80 MPa (low stress level) at 600-640 °C. He has also reported that the temperature influence on the mechanism behavior at lower stress is negligible [33]. Cavitation formed only on the five grains of the intercritical region, with an average grain diameter of 5 μm, average cavity size 1-2 μm [33]. Cavity nucleated on grain boundaries and its growth is relative with matrix and precipitates and inclusions [33].

Liu et al. [34] present that for 2.25Cr1Mo steel notched specimens firstly have been loaded at a nominal stress of 40 MPa for 4,520 h, and next increased the load up to 114 MPa and after 196 h. The specimens failed. This experiments shows a fairly abundant number of cavities near the hole, which were observed near the edge of the hole covering an area about 30 °C to either side of the axis of minimum cross-sectioned area; the cavitation is fairly extensive near the point of crack initiation and to one side of the fracture surface; however little or no cavity was found elsewhere; also, the results show an etched section taken in an area near the fracture surface, but away from the center hole; the bulk of the cavitation was in the neighborhood of the central hole, some isolated cavitation was observed at a distance midway between the hole and the edge of the specimens. Several cavities observed located at about one-third the way between the hole and the edge [34].

Myers and et al. [35] claim that for the 1Cr-0.5Mo steel smooth and notched specimens which were tested under 823K (550 °C) at 120-160MPa, the rupture life depends on maximum principal stress, σ_1. Its cavity size has been observed spacing. Cavity growth is dependent on σ_1 when the mechanism is unconstrained, and on $\bar{\sigma}$ (von Mises effective stress) for constrained growth mechanism [35]. Needleham [35], studied on the growth of grain boundary cavities under tri-axial stress found that the increase of tri-axiality enhances the flux of material flowing from the cavity surface to the boundary and thus increases the volumetric growth rate. Metallographic evidence supports the concept of a change in cavity growth mechanism from diffusive growth to a diffusive constrained diffusive mechanism [35].

As has been reported by Longsdale and Flewitt [36] and Chuman et al. [37], the hydrostatic stress has great influence on the multi-axial stress; Also, they [36, 37] have indicated that the domination multi-axial stress is hydrostatic stress which leads to final creep fracture under lower stresses [37], and the equivalent stress is dominant to evaluate the creep fracture under higher stresses [38]. Therefore, further work will focus on the experimental results which could show the dominate stress that could reflect the multi-axial state influence. If this has been carried out, a hypothesis will be made to derive uni-axial equations set to multi-axial equations set.

4. Creep Rupture Criterion

4.1 Summary of the Existing Creep Rupture Criterion

Table 2 summarizes the different creep rupture criteria which have been applied in creep damage constitutive equations for low alloy; nevertheless, the majority of these creep rupture criteria do not necessarily have good physical meanings reflecting the real creep rupture and rupture mechanism [38].

The statistic creep rupture criterion do not have physical meanings and are not able to predict the accurate creep curve and creep deformation behavior [3-5]; therefore, a new consideration of the rupture criterion should be conducted.

Table 2 Failure criterion for low alloy creep damage constitutive equations.

Types of constitutive equation used for low Cr-Mo alloy	Originated from year	Failure criterion
Kachanov [39]	1958	Critical damage $D = 1$
KR (Kachanov Robatnov) [40]	1969	Critical damage ω_c
Lemaitre [41]	1985	Critical damage D_c
Piques [42]	1989	$f =$ porosity
KRH (Kachanov–Robatnov-Hayhurst) [43]	1995	Critical damage ω_c
Dyson and McLean [44]	2000	Critical strain at failure $\varepsilon_f = 5\%$
Qiang Xu [4]	2000	Critical damage ω_c
Michel [45]	2004	limit load $\lVert\vec{P}_L(\sigma_0)\rVert$
Lmaitre and Desmorat [46]	2004	Critical damage D_c
Whittaker and Wilshire [47]	2012	Limited activity energy: Q_C^*

4.2 Cavity Nucleation and Growth Rates under Lower Stress Level

Longsdale and Flewitt [36] reported that under lower stresses (55.6 MPa, 60.6 MPa and 70.6 MPa) at 600 °C for 2.25Cr-1Mo steel, the cavity rate of accumulation increases monotonically with time. At a given time, it was greatest for the largest applied stress [36]; 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. From the experimental observations on the cavity nucleation and cavity growth, Needham [31] found that the functional relationship for cavity nucleation rate, cavity growth rate, and the rupture lifetime for 2.25Cr-1Mo steel and 1Cr-0.5Mo steel are inversely related to maximum principal stress, σ_0, by a power law, under lower stresses; the power law index number is presented in Table 3 for these two grades.

4.3 Cavity Nucleation Rate and Cavity Growth Rates under High Stress Level

Kawashima et al. [48] reported that for 2.25Cr-1Mo steel the creep ruptures lifetime depends on the cavity nucleation rate and cavity growth size.

Table 4 shows that the growth rate increases with the increase of the applied stresses under higher stresses [36]. These results indicate that the cavity growth behavior is associated with the creep rupture behavior and mechanism.

Under high stress level, Needham [31] claimed that the functional relationship for cavity nucleation rate, cavity growth rate, and the rupture lifetime for 2.25Cr-1Mo steel and 1Cr-0.5Mo steel are inversely related to maximum principal stress, σ_0, by a power law, under higher stresses; the power law index number is presented in Table 5 for these two grades.

As the cavity nucleation rate is strongly dependent upon the maximum principal stress (under low stress conditions), and dependent upon both of the maximum principal stress and the equivalent stress (under intermediate and high stresses), the rupture lifetime could be predicted from knowledge of the nucleation rate determined under a uniaxial tensile [31]. Therefore, further work will focus on the critical value of the void nucleation rate and the growth rate depending on the creep lives. If this has been carried out, a hypothesis of a new creep rupture criterion will be developed to

Table 3 Summary of stress index for power law behavior under the low stress [31].

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

Table 4 The Cavity growth rate versus stress in low Cr-Mo alloy, under the high stress [48].

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 5 Summary of stress index for power law behavior under the high stresses [31].

Under intermediate and high stresses (> 0.4 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

conduct the physical-based creep rupture behavior and mechanism.

5. Multi-axial Stress Rupture Criterion

The multi-axial stress rupture criterion of low Cr-Mo alloy has been determined from analyses of hollow cylindrical, notched bar and hollow cruciform specimens [30, 36, 48].

From the analyses of the previous experimental data, the results show the maximum principal stress σ_1, Mises stress σ_{Mises} and hydrostatic σ_H are associated with creep damage process which leads to the rupture [37]. Moreover, the results indicate that the dominated stress system leading to the intergranular fracture seems to be the hydrostatic stress, and the rupture behavior has a strong dependence on maximum principal stress σ_1; therefore, the equation of the multi-axial stress rupture criterion could be expressed such as [36]:

$$\sigma_{eq} = \alpha\sigma_1 + \beta\sigma_{Mises} + \gamma\sigma_H \qquad (9)$$

$$\gamma > \alpha > \beta$$

It is cautioned here by the authors that the validation and calibration of such equation needs to cover a wide range of stress states which has been emphasized before, such as Ref. [4].

Experimental observation detailing the influence of states of stress on the nucleation, growth, and final coalescence will be needed prior to modeling.

6. Result and Discussion

Based on the review of experimental data and the microstructure observation under varying stress ranges and stress states, the new set of creep damage constitutive equation to be developed should satisfy the following requirements which should be able to:

(1) represent the transition between lower-shelf intergranular rupture and upper-shelf ductile-transgruanlar rupture as a function of temperature, strain rate, stress and material pedigree;

(2) express the mechanistic relationship between applied stress versus time to rupture:

$$T_f \propto \frac{1}{\sigma}$$

(3) reflect the mechanistic relationship between the strain at failure versus stress:

$$\varepsilon_f \propto A\sigma^n$$

(4) show the mechanistic relationship between minimum stress rate and applied stress:

$$\dot{\varepsilon}_{min} \propto e^{\frac{\sigma-n}{m}}$$

(5) depict the dominated constrained cavity growth deformation mechanism under low stress level, 0.2– 0.4 σ_Y;

(6) depict the dominated plastic hole growth deformation mechanism under high stress, $> 0.5\ \sigma_Y$;

(7) depict the diffusion deformation mechanism stress between 0.4 σ_Y and 0.5 σ_Y;

(8) show the effect of the stress states on creep ductility, under multi-axial conditions;

(9) show, under lower stresses, the rupture criterion is amalgamated with the cavity density;

(10) show, under higher stresses, the rupture criterion is amalgamated with the cavity size;

(11) express the multi-axial stress rupture criterion.

7. Conclusion

This paper provides a critical analysis of the obtained experimental observation on the creep deformation and the creep damage evolution mechanisms. The requirements of the creep damage constitutive equation in terms of lifetime and strain at failure under a range of stress states and stress levels have been summarized. 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, or with the finite element continuum damage mechanics methods. The intergranular creep cavitation is the process of micro-cavities nucleating at the inclusions and particles along grain boundaries or near the triple points of the grain boundaries. Subsequently, the cavities growth depends on time until finally being coalesced which forms the micro-cracks and eventually leads to failure.

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