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The Development of the Cavitated Volume Fraction as a Creep Damage Indicator for Creep Remnant Life Prediction

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Abstract. This paper highlights the advantages of using the cavitated volume fraction (f_v) as a superior creep damage indicator compared to traditional two dimensional (2D) based parameters. With the emergence of three dimensional (3D) experimental techniques like X-ray tomography, in-situ volumetric observations have become feasible, enabling a more accurate assessment of creep damage. The cavitated volume fraction offers a comprehensive evaluation of cavity distribution, overcoming the limitations of missing information and the impact of cavity coalescence on 2D-based assessments. We present the procedure for deriving the cavitated volume fraction using the cavity size distribution function and the cavity growth pattern equation. Additionally, we discuss the potential application of the cavitated volume fraction for rupture time prediction using early-stage creep data. Overall, this paper emphasizes the importance of adopting 3D-based parameters, specifically the cavitated volume fraction, for improved creep damage assessment and lifetime prediction.

Keywords. Creep damage, cavitated volume fraction, creep lifetime prediction

1. Introduction

Creep damage is a major concern for high temperature industries. The lifetime of components used in various high temperature applications is significantly limited by creep deformation or damage. The understanding and accurate description of creep deformation and fracture are of great interest to industries operating at high temperatures. It is widely recognized that creep cavitation at grain boundaries is the primary cause of creep fracture in most metals and alloys [1,2].

Creep deformation and fracture time predictions have mainly been characterised using the continuum damage mechanics (CDM) [3-6]; empirical models that depend on parameterizing the creep curve [7-9] and direct cavitation damage models [10-13]. It is well known that an accurate description of the creep deformation and lifetime is still a contemporary problem in material science and in structural integrity research. The situation stems not only from the strong stress level dependence of the minimum creep strain-rate and the creep time to fracture, referred to as the stress breakdown

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phenomenon [14]; it is also compounded by the ideas behind theoretical models and the lack of accurately measured cavitation data [15,16].

2. Challenges of Current Creep Damage Models

To prevent excessive deformation and premature rupture of critical components used in high-temperature industries, it is essential to establish safe operating limits, including acceptable strain, temperature limits, and life expectancy. However, obtaining long-term creep data exceeding 100,000 hours is both time-consuming and costly, making such data scarce. As a result, the current approach for predicting creep rupture time involves conducting accelerated creep tests under high stress and then extrapolating the data to predict long-term creep behaviour at lower stress level. It is recognised that predictions for long term creep behaviour via the extrapolation method have not met expectations, as discrepancies exist between creep behaviour during accelerated creep and long-term creep [15,17,18].

The challenges of current creep damage modelling have been critically reviewed in literatures [12,15,18,] and can be summarised as follows:

a) The parametric and CDM methods demonstrate inaccuracies when extrapolated out of the creep regime within which they were calibrated [15, 18].
b) There is a lack of accurate quantification and incorporation of cavitation damage mechanisms in creep modelling. Therefore, the models have seen limited success in their application over a wider range of stress and temperature [15, 16].
c) Early views on damage modelling have been reported not necessarily with an efficient experimental technique to accurately measure cavity profiles [15, 16, 19].

It is the authors' view, that a scientifically sound approach to tackle the stress breakdown phenomena is to directly model the creep cavitation, as the cavitation process is said to be stress driven, [20]. This approach has the advantage of traceability as it is based on quantifiable physical changes in the material (cavity nucleation and growth). Furthermore, cavitation damage characterisation has mostly been done using destructive two-dimensional methods, surface replica or a scattering method. Several literatures have shown that these methods are not efficient in characterising cavities, especially complex shaped cavities and they are also less comprehensive. Recently, there has been a significant increase in the use of 3D damage characterisation techniques like the x-ray synchrotron tomography technique as an efficient tool for damage characterisation. Amongst other advantages, the x-ray synchrotron tomography technique can measure the true size and shape of complex cavities in an in-si tu manner.

Yadav et al. [21] conducted a study on the creep damage evolution in P91 steel, subjected to 9000 hours of creep at 650 °C. They employed both 2D (Scanning Electron Microscope) and 3D (FIB serial sectioning) observation techniques to assess the damage, and the results obtained from these methods were compared. Interestingly, the 2D method was found to overestimate the cavity distribution when compared to the actual data obtained from the reconstructed 3D data. The researchers attributed this discrepancy to the limitations of the 2D method, which assumed that all cavities were spherical. Consequently, the 2D method interpreted complex-shaped cavities as multiple individual cavities, leading to erroneous calculations of the number of cavities per unit area or per unit volume.

The idea to make use of a 3D measured cavitation data like the x-ray synchrotron tomography for the development of a cavitation model was also advocated by Xu [10,15]. This work sought after and utilised such 3D measured data to aid creep damage modelling.

3. Cavitated Volume Fraction as a Damage Indicative Parameter

The discovery of 3D experimental techniques means in-situ volumetric observation of cavities is now possible. The cavitated volume fraction (fv) is reported in this section as an improved alternative to the 2D-based creep damage indicative parameters.

A quantitative evaluation of damage is usually done across the grain boundary area; the number of cavities per unit area is commonly used as an indicative parameter [22, 23]. This approach is two dimensional in nature. However, cavities in materials are distributed on grain boundary planes, which are randomly positioned in three dimensions. This discrepancy makes it challenging to interpret the physical meaning behind damage parameters evaluated using 2D techniques [21]. In 3D, the spatial distribution of cavities is more complex and may not be accurately represented by evaluating cross sectional areas. Not only can some information be missing, but also the linkage of cavities at the latter stage of creep life is a concern. When cavities link to form a coalesced cavity, the total number of cavities eventually decreases leading to an inaccurate assessment of the number of cavities per unit area. Furthermore, in other cases, the coalesced cavities are totally neglected or not taken into consideration, [1].

On the other hand, evaluating damage based on the cavitated volume fraction offers advantages in addressing the concerns with the 2D methods. The cavitated volume fraction provides a more robust assessment of creep damage, as the thickness of the material and the true shape of the cavity are incorporated. This is important in materials with complex geometries and cavities shapes, as chances of missing information are significantly reduced. Moreover, it is less sensitive to the problems associated with counting individual cavities in the grain boundary area.

Despite the advantages the 3D based damage indicators have over the 2D ones, not much comprehensive research has been carried out on the implementation and applicability of 3D-based indicators, like the cavitated volume fraction. This research gap hinders the progress towards more accurate and reliable assessments of creep damage and limits the potential for a more accurate rupture time prediction. Addressing this gap would facilitate the development of improved methodologies for creep damage evaluation and enhance our understanding of material behaviour under creep conditions. This paper reports the procedure for deriving the cavitated volume fraction (fv) and lays down the theoretical foundation for a possible creep remnant life prediction using early-stage cavitation data.

4. Aims, Experimental Data and Method

4.1. Aims

The primary aims of the work are to highlight the advantages of the cavitated volume fraction as a superior damage indicative parameter and to develop a method of deriving the cavitated area fraction for a possible creep rupture time prediction.

4.2. Experimental data

During an interrupted creep test, a study was conducted to examine the process of creep cavitation that leads to creep fracture in Cu-40Zn-2Pb material [24]. The material was subjected to a stress of 25MPa and a temperature of 375°C. X-ray synchrotron tomography was used for in-situ examination, allowing for detailed imaging and analysis of the cavitation process during creep.

- Creep data one: Evolution of number of cavities (number of cavities vs creep time)
- Creep data two: Cavity size distribution histogram at different creep time
- Creep data three: Evolution of the total cavity volume (total cavity volume vs creep time)

4.3. Method

The connection between experimental data and theories of cavity nucleation and growth is established through the cavity size distribution function, introduced by Riedel [1]. This function, denoted as N(R,t), describes the distribution of cavity sizes and their evolution over time.

$$N(R,t) = \frac{A_2}{A_1} R^{\beta} t^{\alpha+\gamma} \left(1 - \frac{1-\alpha}{1+\beta} \frac{R^{\beta+1}}{A_1 t^{1-\alpha}}\right)^{(\alpha+\gamma)/(1-\alpha)} \tag{1}$$

A general solution to these cavity nucleation and growth theories can be summarised in a power law form:

$$\dot{R} = A_1 R^{-\beta} t^{-\alpha} \tag{2}$$

$$J^* = A_2 t^{\gamma} \tag{3}$$

Where: $\dot{R}$ is the non-stationary growth rate of cavity radius; J^* is the nucleation rate of cavity; A_1, A_2, γ, α and β are all unknown material constants that may be dependent on stress.

To determine the extent of material damage, the cavitated volume fraction can be used as a measure. This quantity is computed by summing up the volumes ($4\pi R^3/3$) occupied by individual cavities with radius (R) and multiplying that by their number density (NdR). The result is then divided by the volume of the region of interest (ROI). This procedure is repeated for each interrupted creep test. The total volume (V_T) for a particular interrupted creep test:

$$V_T = \sum_{R_{min}}^{R_{max}} \frac{4}{3} \pi R^2 \cdot N(R,t) dR \tag{4}$$

Where: R_{max} and R_{min} are maximum and minimum cavity radius, R is the cavity radius, and $N(R,t)$ is the cavity size distribution function.

Given that 1 voxel is equivalent to 4.096 μm^3, the volume of the ROI is approximately 92038800 voxels [26]. The primary task in the cavitation modelling is to find a solution for a set of the five unknown material parameters (A_1, $A_{2,}\gamma, \alpha$ and β) over a series of creep times. Functional relationships between the cavitated volume fraction and creep time can then be developed to aid creep lifetime prediction.

5. Results

The procedure for determining the Determination of the material constants (A_1, A_2, γ, α and β) for the Cu-40Zn-2Pb material has been reported in an earlier publication [25], see table 1.

Table 1. Values for material constants at different interrupted creep test. [25]

Time (mins)	γ	A_1 ($\mu m^3/\ln mins$)	A_2 ($\mu m^3/min^2$)	β	α
52	0.50	1.080	6.218	0.500	1.000
110	0.50	1.103	6.218	0.500	1.000
137	0.50	0.983	6.218	0.300	1.000
196	0.50	1.0987	6.218	0.300	1.000
307	0.50	1.007	6.218	0.000	1.000
440	0.50	1.083	6.218	-0.400	1.000

Using the known constants and cavity size distribution function, $N(R,t)$, the number density of cavities was modelled and compared with experimental data, see figures 1 and 2.

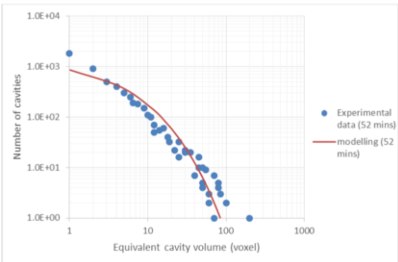

Figure 1. Cavity size distribution data at t=52 mins. Modelling result compared with experimental data. Retrieved from [25].

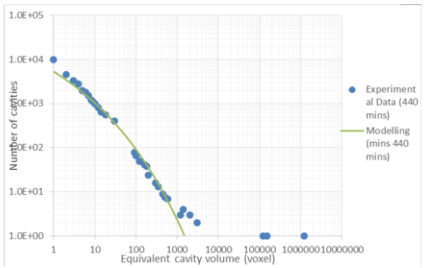

Figure 2. Cavity size distribution data at t=440 mins. Modelling result compared with experimental data. Retrieved from [25].

To calculate the total overall cavity volume (V_T) using equation 4, an equation that describes how the cavity radius (R) grows from R to (R+dR) as time t increases from t to (t+dt) needs to be defined. Having an accurate cavity growth equation and the correct values for material parameters is crucial for obtaining an accurate V_T.

Using the known material constants in table 1, an equation that defines the cavity growth pattern can be obtained by integrating equation 2.

When t = 52 mins:

$$\beta = 0.5,\ R^{\frac{3}{2}} = \frac{3}{2}(A_1\ ln\ ln\ t\ + C_1) \tag{5}$$

Where C_1, is an integration constant.

For a specific interrupted creep test, the maximum cavity radius (R_{max}) and minimum cavity radius (R_{min}) can be obtained from the cavity size distribution histogram. To calibrate the growth equations accurately, we need to determine the cavity incubation time (t_0), which is the time taken for the smallest cavity to appear. Additionally, the value of the integration constant (C_1) is required. Simultaneous equations are constructed to find these values. In this study, we demonstrate the process using a particular case, when (t_f) = 52 minutes. This procedure is repeated for other interrupted creep tests to obtain the necessary parameters for calibrating the cavity growth equations.

When (t_f) = 52 mins (where t_f is the end of an interrupted creep test) $\alpha = 1$, $A_1 = 1.080$, $\beta = 0.5$, R_{min}= 0.999 μm, R_{max}= 4.35 μm.

From equation 5:

When R is maximum,

$$(R_{max})^{\frac{3}{2}} = \frac{3}{2}(A_1 \, ln \, ln \, t_f \, + C_1) \tag{6}$$

When R is minimum,

$$(R_{min})^{\frac{3}{2}} = \frac{3}{2}(A_1 \, ln \, ln \, t_0 \, + C_1) \tag{7}$$

$$6.048429 = (A_1 \, ln \, ln \, 52 \, + C_1)$$

$$0.66566 = (A_1 \, ln \, ln \, t_0 \, + C_1)$$

$$4.98404 = (ln \, ln \, 52 \, - ln \, ln \, t_0 \,)$$

$$t_0 = 0.356 \text{ mins and } C_1 = 1.7811$$

The result trend for cavity growth for t_f= 52 mins is illustrated in figure 3.

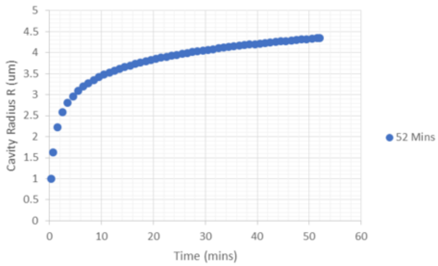

Figure 3. Predicted cavity growth pattern with time, for t_f= 52, [27].

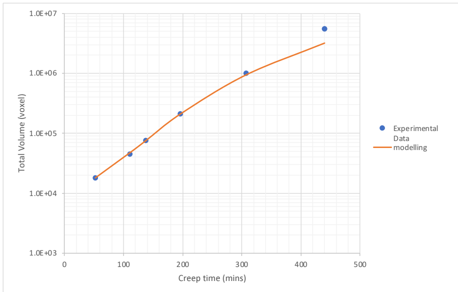

Figure 4. Modelling result [27], compared with experimental data from [24]. Evolution of total cavity volume with time.

Using the predicted growth patterns and total cavitated volume equation 2.0, the evolution of total cavity volume with time can be modelled. Table 2 shows the comparison between the modelling results and experimental data for the evolution of total overall cavity volume.

The comparison of the calculated cavity volume and experiemtnal measurement is shown in figure 4, and they agree well.

Table 2. Evolution of total cavity volume with time. Modelling result vs experimental data retrieved, from [24].

Time (mins)	C_1	Total cavity volume from experiment (voxel)	Total cavity volume from modelling (voxel)
52	1.781	18000	18101.46
110	1.822	45000	47006.92
137	1.527	75000	74393.10
196	1.795	210000	209094.65
307	1.330	1000000	936033.82
440	0.548	5500000	3162316.91

At around 80% of the creep time, the material experiences rapid degradation just before rupture, with cavity coalescence and crack propagation becoming prominent. Sklenička et al. [28] studied the long-term creep behaviour in 9-12%Cr steel and observed that during the final 20% of creep life, coalesced cavities become more pronounced, leading to grain boundary microcracks. These microcracks then grow and widen, forming macrocracks that eventually result in final failure due to rapid macrocrack propagation. The density of these cracks determines the location of the final fracture. Similar observations were reported by Hertzman, Sandstrom, and Wåle [29] in welded joints of 0.5CrMoV steel and by Trück et al. [30] in their study of creep damage behaviour in 12% Cr steel. They developed a damage map showing the formation of microcracks occurring after approximately 85-90% of creep life is consumed and the opening of microcracks occurring after approximately 95% of the creep life. These studies highlight the significance of crack propagation and linkage in the lead-up to final fracture.

Considering the issue of crack propagation and its potential impact on volumetric measurements, an ideal target point for creep rupture time prediction should be before the macrocracks begin to tear or widen. While crack tearing constitutes only a small percentage of the creep life, the widening of cracks can result in considerable false volumetric measurements in the short period preceding fracture and at the time of final fracture. Therefore, accurate rupture time prediction can still be achieved by focusing on the period before macrocracks start tearing or widening. Understanding the behaviour of microcracks and their progression into macrocracks is crucial for improving the accuracy of creep rupture time prediction models.

6. Conclusion and Future Work

The research presented is one of the initial explorations of the practical implementation and applicability of the cavitated volume fraction (f_v) as a creep damage indicative parameter. It further expands the application of the original idea [15] of using accurate and comprehensive cavitation data to develop the cavitation model and rupture model [10, 13] and contributes to the creep damage lifetime prediction methodology [12]. This approach is based on creep cavitation data with strong scientific bases.

While the paper discusses the advantages and derivation of the (f_v) parameter, it would be valuable to investigate its effectiveness in a broader range of materials and experimental conditions. Additionally, further research could focus on the correlation between the cavitated volume fraction and the remnant creep life or rupture time of the materials. This would provide a deeper understanding of the predictive capabilities of

(f_v) and its potential for real-world applications in assessing and predicting creep damage. Exploring these aspects would help bridge the gap between theoretical advancements and practical utility, enhancing the relevance and impact of the proposed cavitated volume fraction parameter.

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