Investigation of modelling the minimum creep strain rate of P91 over a wide range of stress

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ABSTRACT

Four sets of experimental data of a minimum creep rate of P91 in different range of stress (from 1.1 to 350 MPa) were compiled for the calibration of the linear + power law and modified sine law. An investigation was conducted to examine the accuracy of both laws in different range of stress. It appears that modelling result of linear + power law fitted experimental data well in low and high stress level while modified sine law fits experimental data in all stress level. The predicted results from narrow ranges of stress indicates that linear power law requires data from both high and low stress levels to make a prediction, modified sine law could make prediction on a wider range of stress with data from a narrow range of stress. This conclusion could help research on predicting low stress level’s data with experimental data from high stress level.

Introduction

The knowledge on the creep damage and rupture at low stress level is needed and useful in various industrial applications. In the recent decades, it appears that materials for power plants' reactors need the ability to provide long-term services at high temperature which may exceed a 60-year period [1]. The operating environment of reactor pressure vessels could be in a temperature ranging from 300°C to 650°C (1). Such facility is typically working at a very low stress, for example, 20 MPa, according to 2. P91 is a type of high Chromium (Cr) steel widely used in high-temperature environment nowadays [3]. In such a long-term service, the material needs the ability to survive long enough to fulfil the duty. Thus, the research on creep rupture time of these materials has been carried out frequently in recent decades. An accurate description of the minimum creep strain is the pre-requisite for either the development of creep damage constitutive equations and/or creep lifetime prediction such as Monkman approach [4,5] or recently the modified sine formulation [Vito Cedro 6].

Due to the creep rupture time of high Cr steels is very long under low stress and a creep test measuring the whole lifetime of a material is expensive, accelerated creep tests are used for research in creep mechanics. However, the extrapolation of the results from these accelerated tests at higher stress to lower stress level is questionable as observed and reported as stress breakdown [7].

The modelling of the (minimum) creep strain rate with stress level has evolved from a simple power law to the modified hyperbolic sine law, primarily due to the need to cover a wider range of the stress. Recently, the modified hyperbolic sine law was originally proposed by the fourth author and used for low Cr steels (Xu, 2016) and further applied to high Cr steels [Xu, Yang and Lu, 2017, 8 and Zheng et al, 9]. It is anticipated that this improved modelling of the minimum creep strain rate over a wider range of stress will be used for the development of creep damage constitutive equations. Therefore, further researches about how to model the creep cavitation damage, the coupling of the creep deformation, creep damage and multi-axial generalisation et al., are needed and have being carried out [9–13, 14].

This work focuses on an even wider range of stresses for the as-received P91 ranging from 1.1 to 350 MPa at 600°C and aged (10,000 h) at 650°C under stress ranging from 0.95 to 240 MPa [15]. This is shown in Table 1.

Literature review on recent research on minimum creep strain rate

The conventional power law and sine law do not fit the minimum creep rate over a wide range of stress well [16, and 1718], a modified sine law was originally
The stress range in the chosen data sets 2 and 3 is wider than that have been used before: a range of 80–160 MPa published by 8, and 80–200 MPa reported by Yang et al., 2017. Aged materials were also included in the analysis.

The smaller ranges of stresses were used to compare with results from the wider ranges to help determine whether the equations could predict results in a wider stress range with only data from a narrow range of stress or not.

Methodology

The equations used to study the relationship between stress and minimum creep rate are Equations 3 and 4. Microsoft Excel was used to produce the numerical and graphical results. A trial-and-error method was used to assess the goodness of the predicted results with experimental data where a series of values for A, B, n and q were used.

Results

Linear + power law

Comparison between predicted data from linear + power law and experimental data are shown in Figures 1–4.

\[ A = 4 \times 10^{-4} \text{%/h*MPa}, B = 0.83, n = 8, 70 \sim 200 \text{MPa}, 2425]. \]

\[ A = 4 \times 10^{-8} \text{%/h*MPa}, B = 0.83, n = 8 \] with experimental data of MGC P91 steel in 600°C, 70 ~ 355 MPa, 23.

The graphs have two sections if the range of stresses were wide enough, it could be used to describe the relationship between minimum creep rate and stress in low and high-stress levels. Whether the material is aged or as received.

It was noticeable that in other data sets with the narrow range of stress, the graph only showed one section rather than two. It indicates that a full prediction requires data from both low and high stress level, otherwise it could only be used to predict high or low stress level.

From material science’s view, there should be a transition rather than blunt change, so it can only be used for estimation [26].

The predicted value did not agree with experimental data when the graph of experimental data was in middle-stress level and non-linear. So, the middle stress level’s data cannot be used with this equation.

The modified hyperbolic Sine Law

Comparison between predicted results from the modified hyperbolic sine law and experimental data are shown in Figures 5–9.

Figure 5 and Figure 6 showed that the modified sine law can produce a similar prediction with different parameters.
Figure 1. Comparison of modelling result with experimental data as received P91 at 600°C ($A = 9 \times 10^{-13} \%/h*MPa$, $B = 7.9 \times 10^{-3}$, $n = 15$).

Figure 2. Comparison of modelling result with experimental data for aged 10,000 h P91 at 650°C ($A = 4 \times 10^{-13} \%/h*MPa$, $B = 2.3 \times 10^{-4}$, $n = 2$).

Figure 3. Comparison of modelling result with experimental data for P91 MGC at 600°C.
Figure 4. Comparison of modelling result.

Figure 5. Comparison between modelling with experimental data for as received P91 at 600°C (A = 8*10^-10 %/h*MPa, B = 1.115*10^-4, q = 2). The experimental data is from literature [15].

Figure 6. Comparison between modelling with experimental data for as received P91 at 600°C (A = 5*10^-11 %/h*MPa, B = 1.1*10^-2, q = 1.25). The experimental data is from literature [15].
Judging from the trend of a minimum creep rate, the data of two lowest stress and third highest stress could be an error during data collection and should not be included in the prediction.

Figure 7 shows the result from a test when subjected to a narrow range of stress, where the A, B and q values were not very different to those from Figure 8. This indicates that the modified sine law could make some prediction of low stress level minimum creep rate using data from a higher stress level.

Discussion

From the results, it seems that both equations have a positively accurate prediction of a minimum creep damage in a high and low stress range but the fitting with experimental data varies at medium stress levels. The requirement for a reliable prediction is also different. Linear + power law needs data from low and high stress level to make the prediction otherwise there will be only one section of graph that is useable.

The graph describing the relationship between minimum creep rate and stress in certain temperature could be considered as a 3-phase structure:

1. Low-stress level, the minimum creep rate increases slowly comparing with the other two phases as the stress increases. The graph seems to be approximately linear.
2. Mid-stress level, the trend of minimum creep rate is going up very fast as the stress increases, causing the graph to appear as a curve when compared with the other two phases.
3. High-stress level, minimum creep rate is increasing very fast comparing with the other two phases of the graph. As the stress increases, the minimum creep rate increases significantly along with it, which means the graph looks linear again. Although the linear trend is different to that of the low-stress level.

Both equations have the following features:

For the linear + power law:

1. The graph made by this equation is very straight forward, it is a polyline with a vertex located on the point where B+σ = 1.
2. The graph is linear, which can be used to describe the relationship between minimum creep rate and stress in low and high-stress level. A reasonable agreement with experimental data observed in these stress levels.
3. The predicted value did not match the experimental data very well when the graph of experimental data is in the middle-stress level and is going like a curve rather than linear. That means data from this stress level is not useable when implementing this equation.
4. Even at high and low stress levels, the trending of minimum creep rate is not completely linear, so a perfect fit is not possible.

For the modified sine law:

1. This equation can produce a wider range of the curvature depending the value of q: The conventional law is a special case when q = 1.
2. From results of figure 5 to figure 7, it appears that the equation has the ability of producing a reliable prediction over a wide range of stress on as received or aged materials.
(3) In Figure 8. The parameter of making such prediction is not very different from Figure 5. Meaning this equation could still make reasonable prediction on low stress level’s minimum creep rate with data from a higher and narrower range of stress.

**Conclusion**

It appears that modified sine law could reach better accuracy in medium stress area where the graph of experiment data has a curve trend. It is possible to reach a positive agreement with experimental data in a wider stress area as well. The possibility of predicting low stress level’s data with experimental data from higher stress level is also positive.

On the other hand, the linear + power law can be used in low and high stress level when data from both stress level is available.

This research indicated a possibility to implement modified sine law with experimental data from high stress level to predict data from lower stress level. Due to the long-time testing, creep rupture time of low-stress level estimation is needed. This could help reducing time and financial cost for creep rupture lifetime prediction in the future.

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No potential conflict of interest was reported by the author(s).

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**References**

[1] Chant I, Murty KL. Structural materials issues for the next generation fission reactors. Jom. 2010;62(9):67–74.
[2] OECD (2014). Status Report on Structural Materials for Advanced Nuclear Systems, Nuclear Science, OECD Publishing, Paris, 10.1787/9789264208551-en.
[3] Pandey C, Mahapatra MM, Kumar P, et al. Comparative study of autogenous tungsten inert gas welding and tungsten arc welding with filler wire for dissimilar P91 and P92 steel weld joint. Mater Sci Eng A. 2018;712:720–737.
[4] Maruyama K, Sekido N, Yoshimi K. Changes in Monkman-Grant relation among four creep regions of modified 9Cr-1Mo steel. Mater Sci Eng A. 2019;749:223–234.
[5] Monkman FC, Grant NJ. American society of testing materials. Process, 56, 593–620. Murty, K. L., & Charit, I. (2008). Structural materials for gen-IV nuclear reactors: challenges and opportunities. J Nucl Mater. 1956;383(1):189–195
[6] Iii A VC, Pellicoteb J, Bakhia O, et al. Application of a modified hyperbolic sine creep rate equation to correlate uniaxial creep rupture data of Sanicro 25 and HR6W. Mater High Temp. 2020;37(No6):434–444.
[7] Lee JS, Armaki HG, Maruyama K, et al. Causes of breakdown of creep strength in 9Cr–1.8 W–0.5Mo–vNb steel. Mater Sci Eng A. 2006;428(1–2):270–275.
[8] Zheng X, Xu Q, Lu Z, et al. The development of creep damage constitutive equations for high Cr steel. Mater High Temp. 2020;37(2):129–138.
[9] Xu Q. Development of constitutive equations for creep damage behaviour under multi-axial states of stress. Structures and Materials. 2000;2000(6):435–445.
[10] Xu Q, (2001). Creep damage constitutive equations for multi-axial states of stress for 0.5Cr0.5Mo0.25V ferritic steel at 590°C. Theor Appl Fract Mech. 2001;36(2):99–107.
[11] Xu Q. (2004). The development of validation methodology of multi-axial creep damage constitutive equations and its application to 0.5Cr0.5Mo0.25V ferritic steel at 590 °C. Nucl Eng Des. 2004;228(1–3):97–106.
[12] Xu Q, Barrans S. (2003). The development of multi-axial creep damage constitutive equations for 0.5Cr0.5Mo0.25V ferritic steel at 590°C. JSME International Journal, Series A: Solid Mechanics and Material Engineering. 2003;46 (1):51–59.
[13] Xu Q, Hayhurst DR. (2003). The evaluation of high-stress creep ductility for 316 stainless steel at 550 °C by extrapolation of constitutive equations derived for lower stress levels. Int J Press Vessels Pip. 2003;80 (10):689–694.
[14] Wang X, Wang X, Xu Q, et al. (2020). Investigation on the validity of creep damage mechanics for the lifetime prediction of T92 welded joint. Int J Damage Mech. 2020;29(3):467–481.
[15] Skleniška V, Kuchařová K, Svoboda M, et al. Long-term creep behavior of 9–12% Cr power plant steels. Mater Charact. 2003;51(1):35–48.
[16] Xu Q. (2016). Development of Advanced Creep Damage Constitutive Equations for Low CR Alloy Under Long-Term Service. Doctoral thesis, University of Huddersfield. http://eprints.hud.ac.uk/id/eprint/34682 , accessed on October 2020
[17] Yang X. (2018) The development of creep damage constitutive equations for high chromium steel based on the mechanism of cavitation damage. Doctoral thesis, University of Huddersfield. http://eprints.hud.ac.uk/id/eprint/34682 , accessed on October 2020
[18] Xu Q, Lu Z, Wang X. Damage modelling: the current state and the latest progress on the development of creep damage constitutive equations for high Cr steels. Mater High Temp. 2017;34(3):229–237.
[19] Bailey RW. Creep of steel under simple and compound stress. Engineering. 1930;121:265.
[20] Dyson BF. Use of CDM in materials modeling and component creep life prediction. J. Pressure Vessel Technol. 2000;122(3):281–296.
[21] Altenbach H, Gorash Y, Naumenko K. Steady-state creep of a pressurized thick cylinder in both the linear and the power law ranges. Acta Mech. 2008;195 (1):263–274.
[22] Xu Q, Yang X, Lu Z. On the development of creep damage constitutive equations: modified hyperbolic sine law for minimum creep strain rate and stress and creep fracture criterion based on cavity area fraction along grain boundaries. Mater High Temp. 2017;34 (5–6):323–332.
[23] Kimura K, Kushima H, Sawada K. Long-term creep deformation property of modified 9Cr–1Mo steel. Mater Sci Eng A. 2009;510:58–63.
[24] National Institute for Materials Science. (2014). NIMS CREEP DATA SHEET NO.43. Testing Material (Creep). https://smds.nims.go.jp/MSDS/ja/sheet/Crep.html#3 , accessed on October 2020
[25] Dyson BF. Continuous cavity nucleation and creep fracture. Scr Metall. 1983;17(1):31–38.