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

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Abstract

In this paper, four sets of experimental data of a minimum creep rate of P91 in different range of stress (the widest range contains data from stress varies from 1.1 to 350 MPa) were compiled for the calibration of the linear + power law and modified sine law. By observing how well the modelling result fits with the experimental data, 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.

Keywords

minimum creep strain rate, modified sine law, creep strength, creep rupture, creep damage constitutive equations, chromium steels

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 (Chant et al., 2010). The operating environment of reactor pressure vessels could be in a temperature ranging from 300° C to 650° C (Murty et al., 2008). Such facility is typically working at a very low stress, for example, 20 MPa, according to OCED (2014). P91 is a type of high Chromium (Cr) steel widely used in high-temperature environment nowadays (Pandey et al., 2018). 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 (Monkman et al., 1956, Maruyama, 2019) or recently the modified sine formulation (Vito Cedro III a et al., 2020).

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 (Lee et al., 2006).

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, 2015) and further applied to high Cr steels (Xu et al, 2017, Zheng et al., 2020). 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 (Xu, 2000, 2001, 2004, Xu and Barrans, 2003, Xu and Hayhurst, 2003, Xu et al 2017, and Wang et al, 2020).

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 (10000 hours) at 650° C under stress ranging from 0.95 to 240 MPa (Sklenička et al., 2003).

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 (Xu, 2016 and Yang, 2018), a modified sine law was originally proposed by the third author and initially used for lower

Cr alloys (Xu 2016). Thereafter, it was applied to high Cr steels (Xu, et al, 2017, Zheng et al, 2020).

This Xu's modified hyperbolic sine law was also adopted directly and further expanded to include the temperature effect for the creep lifetime modelling (Vito Cedro III a et al., 2020) and results are very promising as it is one of the two best approaches.

Typical laws used for the modelling of minimum creep strain rate and stress are summarized below:

Power law (Bailey et al, 1930)

$$\dot{\varepsilon}_{min} = A\sigma^n \quad (1)$$

Hyperbolic sine law (Dyson et al, 2000):

$$\dot{\varepsilon}_{min} = A\sinh(B\sigma) \quad (2)$$

Linear + power law (Altenbach, 2008):

$$\dot{\varepsilon}_{min} = A\sigma[1 + (B\sigma)^n] \quad (3)$$

The Modified sine law (Xu et al., 2017):

$$\dot{\varepsilon}_{min} = A\sinh(B\sigma^q) \quad (4)$$

In these equations, A, B are material parameters, q, n are stress exponents, $\dot{\varepsilon}_{min}$ is the minimum creep rate and σ is stress.

In this research, the modified sine law and the linear + power law were investigated by means of P91 creep data analysis. The unit for A and B is %/h*MPa and MPa^{-q}, respectively.

Experimental data

Literature survey was conducted for the compilation of the experimental data. The below data sets were chosen:

1. National Institute for Materials Science (NIMS) in 2014, MGC P91 tube steel under stress ranging from 70 to 200 MPa in 600° C.
2. As-received state P91 steel subjected to stress ranging from 1.1 to 350 MPA in 600° C (Sklenička et al, 2003).
3. P91 steel with an ageing of 10000 hours in 650° C subjected to stress ranging from 0.95 to 240 MPA (Sklenička et al, 2003).

4. MGC P91 steel subjected to stress ranging from 70 to 355 MPa (Kimura et al., 2009).

Data set number	Material	Range of stress (MPa)	Temperature (° C)	Source
1	MGC P91	70-200	600	NIMS, 2014
2	As-received P91	1.1-350	600	Sklenička et al., 2003
3	10000 hours aging P91	0.95-240	650	Sklenička et al., 2003
4	MGC P91	70-355	600	Kimura et al, 2009

Table 1 Description of data sets. This table shows different data sets' corresponding material types, range of stresses, temperatures and sources.

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 Zheng et al., 2020 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.

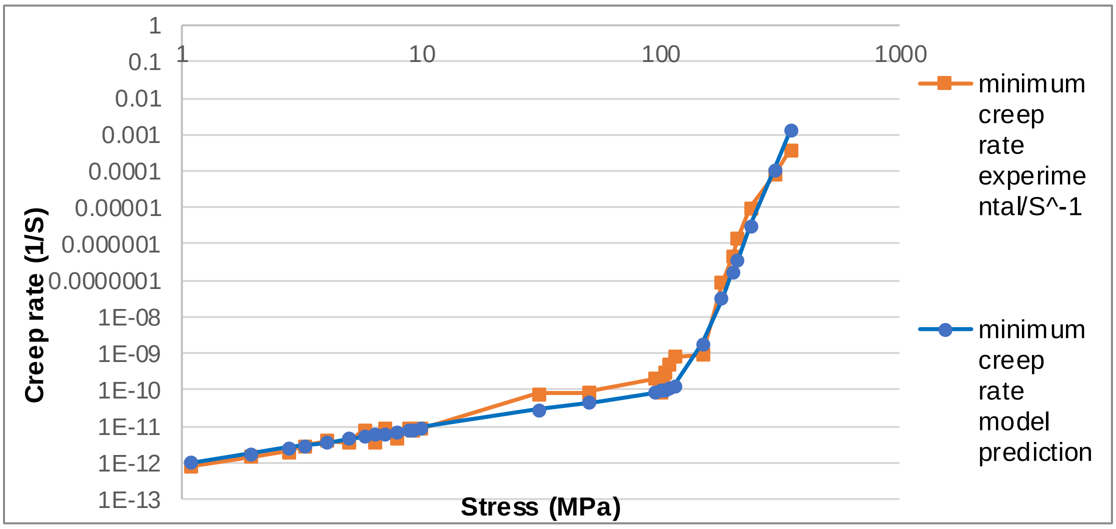

Figure 1. Comparison of modelling result with experimental data as received P91 at 600℃ (A= $9*10^{-13}$ %/h*MPa, B= $7.9*10^{-3}$, n=15)

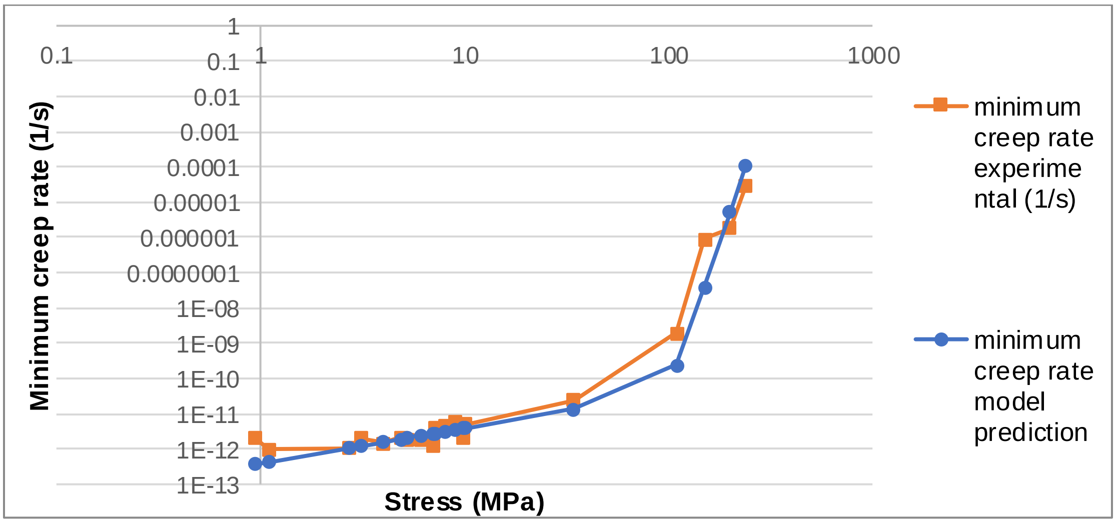

Figure 6.2. Comparison of modelling result with experimental data for aged 10000h P91 at 650℃ (A= $4*10^{-13}$ %/h*MPa, B= $2.3*10^{-4}$, n=2)

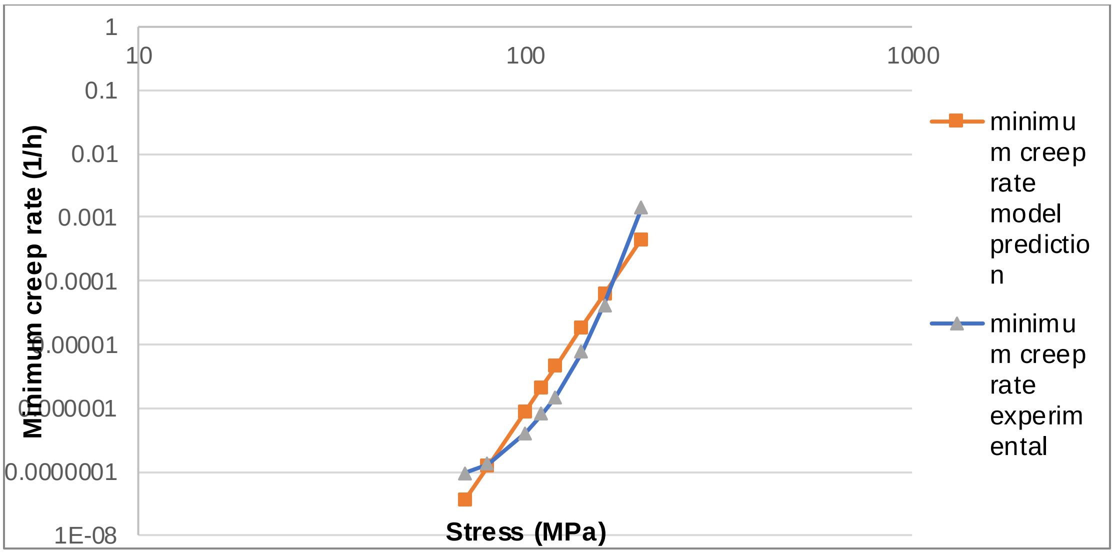

Figure 3. Comparison of modelling result with experimental data for P91 MGC at 600℃

(A=4*10^{-4} %/h*MPa, B=0.83, n=8, 70~200 MPa, NIMS, 2014).

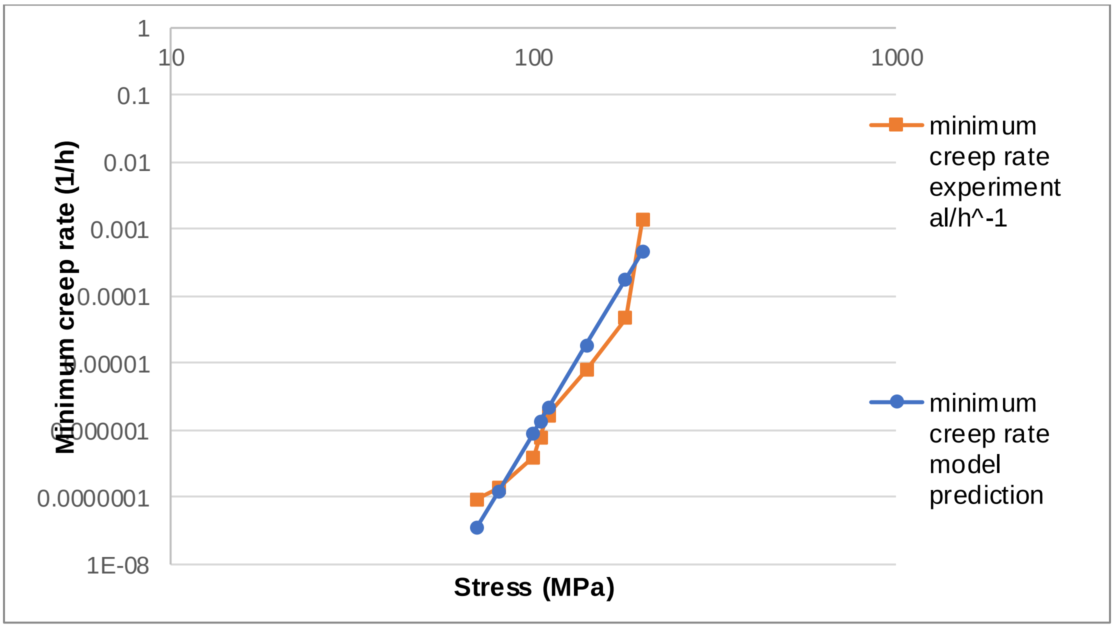

Figure 4. Comparison of modelling result

A(=4*10^-24 %/h*MPa, B=0.83, n=8 with experimental data of MGC P91 steel in 600° C, 70~355 MPa, Kimura et al., 2009).

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 (Dyson, 1983).

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.

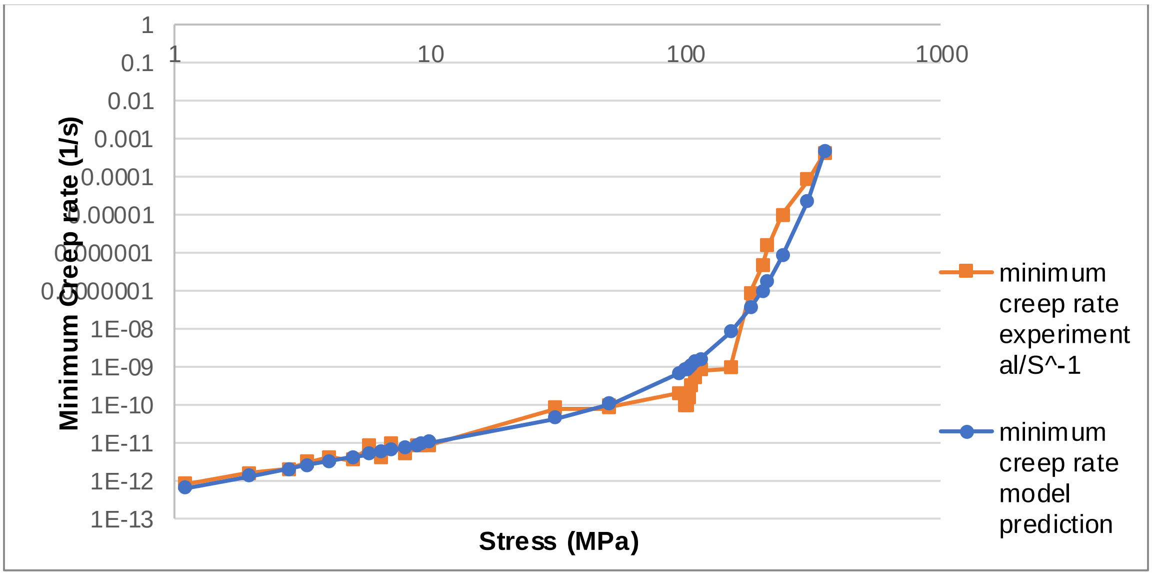

Figure 5. Comparison between modelling with experimental data for as received P91 at 600℃ (A= $8*10^{-10}$ %/h*MPa, B= 1.115*10^{-4}, q=2). The experimental data is from literature (Sklenička et al, 2003).

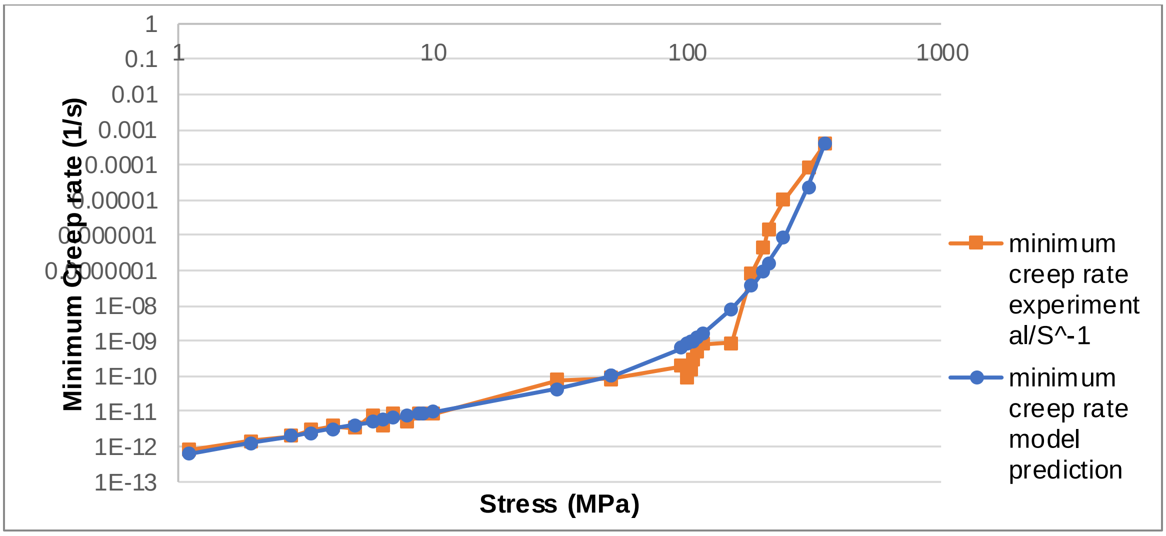

Figure 6. Comparison between modelling with experimental data for as received P91 at 600℃ (A= 5*10^-11 %/h*MPa, B= 1.1*10^{-2}, q=1.25). The experimental data is from literature (Sklenička et al, 2003).

Figure 5 and Figure 6 showed that the modified sine law can produce a similar prediction with different parameters.

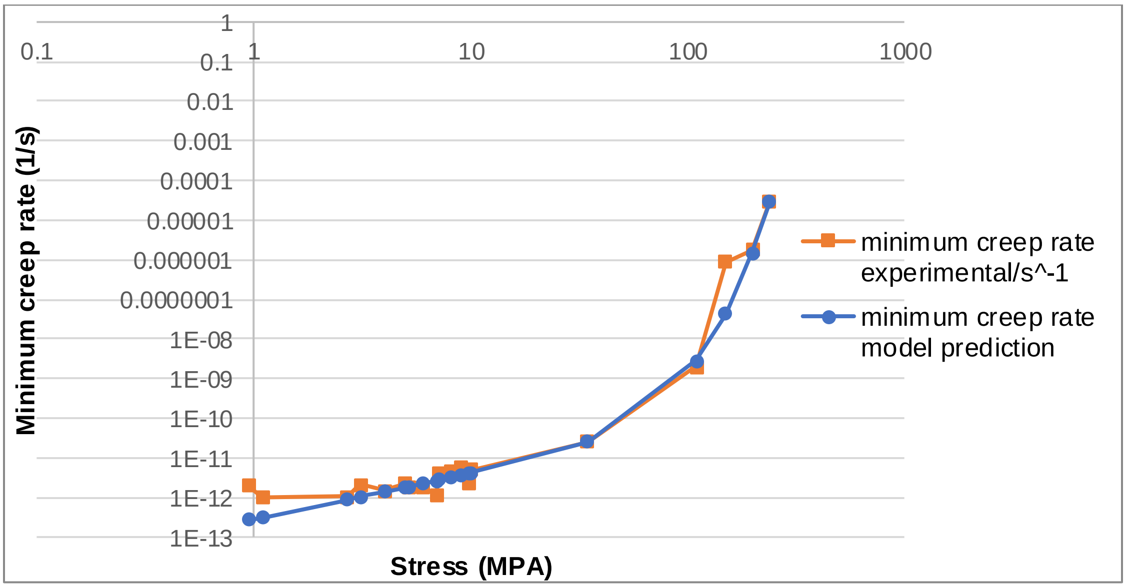

Figure 7. Comparison between modelling result with experimental data of 10000h aged P91 steel in 650° C (Sklenička et al, 2003). (A= 1*10^{-11} %/h*MPa, B= 0.0285, q= 1.2)

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.

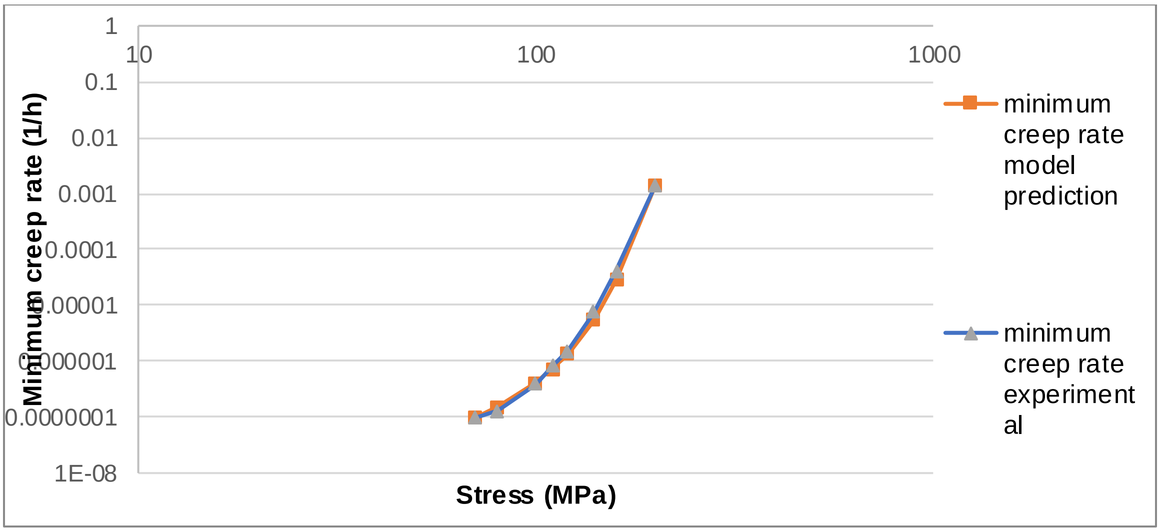

Figure 8. Comparison between modelling result with experimental data of P91 steel in 600° C (NIMS, 2014) (when A=6.09867*10^{-8} %/h*MPa, B=1.6*10^{-4}, q=2.1)

Figure 8 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 5. 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 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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