A minimum creep rate for 2-1/4Cr-1Mo steel consistent with the ASME Section III, Division 5 rules

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ABSTRACT

This technical note describes a minimum creep rate model for 2-1/4Cr-1Mo steel that is consistent with the current creep strain equation embedded in the ASME Boiler & Pressure Vessel Code Section III, Division 5, Subsection HB, Subpart B isochronous stress-strain curves. Minimum creep rate models for all the Section III, Division 5 Class A materials are required for the development of improved high temperature design methods. Of all the Class A materials only 2-1/4Cr-1Mo does not have a readily identifying minimum creep rate term in the current isochronous stress-strain curve model.

1 Background

As part of recent Code modernization efforts the ASME Boiler & Pressure Vessel Code Subgroup on High Temperature Reactors identified the need for minimum creep rate models for the Section III, Division 5, Subsection HB, Subpart B Class A materials in a new evaluation procedure for the primary load check that does not involve stress classification. The 2021 Code edition of the Subsection HB, Subpart B rules contains isochronous stress-strain relations for these materials. The equations underlying these curves are uniaxial, monotonic constitutive models of the form:

$$\varepsilon = \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{creep} \tag{1}$$

where $\varepsilon_{elastic}$ is the elastic strain, $\varepsilon_{plastic}$ is the time-independent plastic strain, and ε_{creep} is the creep strain. For all the Class A materials except 2-1/4Cr-1Mo the creep deformation model, ε_{creep}, contains a simple, definite minimum creep rate term that can be extracted from the full creep strain equation to form the required minimum creep rate model.

The new primary load design procedure explicitly calculates stress relaxation damage due to secondary stresses using an elastic-creep constitutive model and the material minimum stress to rupture. The design method then requires a conservative estimate of stress relaxation in the material – i.e. a creep model that produces higher stresses and more creep damage than the actual relaxation. Basing the relaxation analysis on the material minimum creep rate is therefore an appropriate, conservative approximation.

The creep model underlying the Subsection HB, Subpart B isochronous stress-strain curves (ISSC) for 2-1/4Cr-1Mo originates with [1,2]. The following equations describe the model:

$$\varepsilon_c = \begin{cases} 0 & T < 371 \\ \varepsilon_2/100 & \varepsilon_2 < \varepsilon_1 \\ \varepsilon_1/100 & t < t_1 \\ \varepsilon_3/100 & \text{otherwise} \end{cases}$$

with,

$$\varepsilon_1 = \frac{C_1 p_1 t}{1 + p_1 t} + \dot{\varepsilon}_1^{(ss)} t \tag{2}$$

$$\varepsilon_2 = \frac{C_2 p_2 t}{1 + p_2 t} + \dot{\varepsilon}_2^{(ss)} t \tag{3}$$

$$\varepsilon_3 = \frac{C_2 p_2 t'}{1 + p_2 t'} + \dot{\varepsilon}_2^{(ss)} t \tag{4}$$

where ε_c, t, and T represent creep strain, time in hours, and temperature in degree Celsius, respectively. The remaining symbols represent parameters, with the parameter definitions taken from Section III, Division 5 of the ASME Boiler & Pressure Vessel Code [3] and the original model references. Appendix A defines these parameter values, including the definition of the modified time t', which have complicated mathematical definitions.

The general model form is a fairly straightforward decreasing primary creep rate plus constant secondary creep rate model. The multiple regions of behavior capture the non-classical shape of the creep curves observed in [2] for 2.25Cr-1Mo steel. This region-splitting means we cannot extract a simple minimum creep rate model directly from the original equations.

2 Model

The model minimum creep rate is the minimum of $\dot{\varepsilon}_1^{(ss)}$ and $\dot{\varepsilon}_2^{(ss)}$, which are the time independent terms in the creep rate equations. In this work, we first find the region in temperature–stress space corresponding to the lower of the $\dot{\varepsilon}_1^{(ss)}$ or $\dot{\varepsilon}_2^{(ss)}$ such that we can use it to simplify the minimum creep-rate equation for 2-1/4Cr-1Mo. We consider temperatures between 371 to 649 °C, based on the Section III, Division 5 temperature limits expressed in Table HBB-T-1834-1 and stresses between 0 to 800 MPa to identify the bounding surface separating the minimum creep rate between $\dot{\varepsilon}_1^{(ss)}$ and $\dot{\varepsilon}_2^{(ss)}$. The upper limit of stress value (800 MPa) is twice the maximum stress value (414 MPa) reported for the current isochronous stress strain curves for 2-1/4Cr-1Mo and therefore bounds all operating stress conditions for 2-1/4Cr-1Mo.

This work numerically discretizes the space to 500 points in each of temperature and stress dimensions, and then identifies the minimum rate between $\dot{\varepsilon}_1^{(ss)}$ and $\dot{\varepsilon}_2^{(ss)}$. Figure 1 shows the boundary separating the minimum between the two creep rate expressions.

To generate a simple minimum creep rate we derive an algebraic expression for the boundary curve between the two regions. To do so, we divide the region into an approximate linear region (linear part in Fig. 2) and a polynomial region (polynomial part in Fig. 2) and fit the boundary using least square regression. Figure 2 (black curve) shows the result, which accurate capture the exact boundary. Applying the algebraic equation for the boundary, the reduced minimum creep rate formulation for 2-1/4Cr-1Mo is:

$$\dot{\varepsilon}_c = \begin{cases} \dot{\varepsilon}_2^{(ss)} & \text{if } \sigma < 60.0 \\ \dot{\varepsilon}_h & \text{if } \sigma \geq 60.0 \end{cases}$$

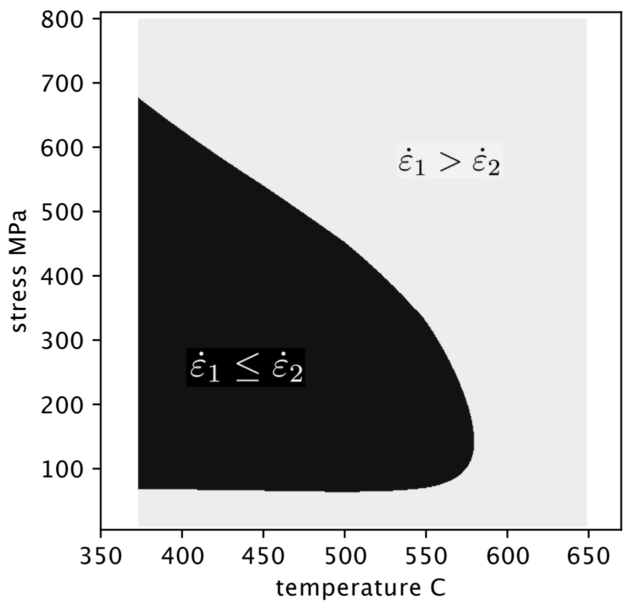

Fig. 1. Bounding region for minimum creep rates for 2-1/4Cr-1Mo between a temperature range of 370 to $650\,^{\circ}\mathrm{C}$ and a stress range of 0 to $800\,\mathrm{MPa}$. Darker region corresponds to the temperature and stresses for which $\dot{\varepsilon}_1^{(ss)} \leq \dot{\varepsilon}_2^{(ss)}$, while lighter gray area are regions where $\dot{\varepsilon}_1^{(ss)} > \dot{\varepsilon}_2^{(ss)}$.

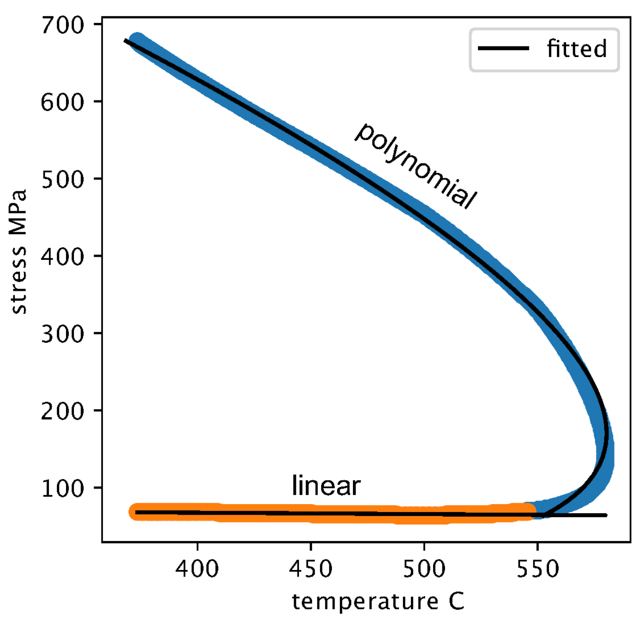

Fig. 2. Numerical determination of the boundary of minimum of $\dot{\varepsilon}_1^{(ss)}$ and $\dot{\varepsilon}_2^{(ss)}$, shown in Fig. 1, by fitting separately a linear region (highlighted in orange) and a second order polynomial region (highlighted in blue) with the black curve showing the fitted result.

with,

$$\dot{\varepsilon}_h = \begin{cases} \dot{\varepsilon}_1^{(ss)} & \text{if } T \leq 13.571\sigma^{0.68127} - 1.8\sigma + 437.63 \\ \dot{\varepsilon}_2^{(ss)} & \text{if } T > 13.571\sigma^{0.68127} - 1.8\sigma + 437.63 \end{cases}$$

where

$$\dot{\varepsilon}_1^{(ss)} = \frac{10^{\left(6.7475+0.011426\sigma+\frac{987.72}{U}log_{10}\sigma-\frac{13494}{T+273.15}\right)}}{100} \tag{5}$$

$$\dot{\varepsilon}_2^{(ss)} = \frac{10^{\left(11.498-\frac{8.2226U}{T+273.15}-\frac{20448}{T+273.15}+\frac{5862.4}{T+273.15}log_{10}\sigma\right)}}{100} \tag{6}$$

The definitions of $\dot{\varepsilon}_1^{(ss)}$and $\dot{\varepsilon}_2^{(ss)}$come from the original references, defined in full in Appendix A. Table 1 lists the values of U at different temperatures, [1,2]. We use linear interpolation to obtain U values for intermediate temperatures not listed in Table 1.

Table 1. Temperature dependent values for parameter U in creep rates.

T (°C)	U
371	471
400	468
450	452
500	418
550	364
600	284
621	300
649	270

Figure 3 shows a fringe full plot of the ratio between the creep rates obtained using the new, simplified minimum creep rate model and the exact creep rates from the full set of equations for creep times of 10, 100, 100000, and 300000 hours, along with the boundary separating the minimum creep rate regions (black curve). The red regions in the plot are temperature-stress combinations where the current formulation does not provide a lower bound to the full creep rate. These regions occur only along the boundary between the linear and polynomial regions and the differences between the full and simplified models are not significant compared to the uncertainty in actual experimental measurements of the minimum creep rate. Except in these very narrow regions the new minimum creep rate model conservatively bounds the full creep rate expression. The full creep rate and the new minimum creep rate models agree exactly for long times, which is to be expected as the primary creep contribution in the full model goes to zero.

Acknowledgements

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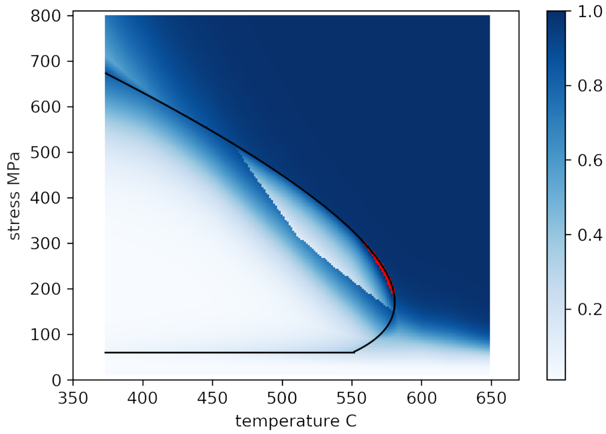
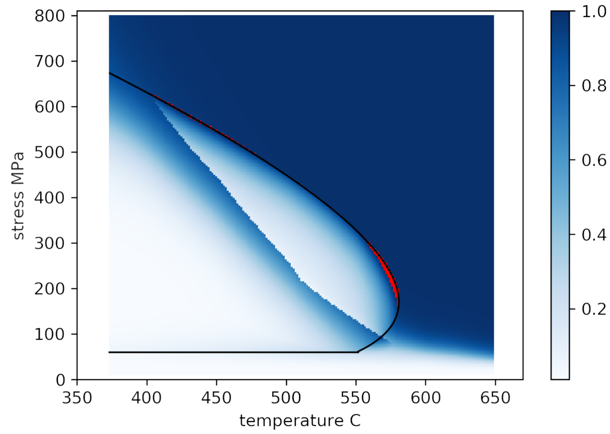
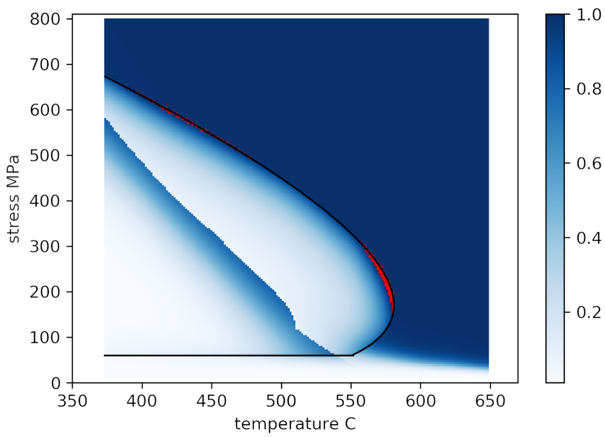


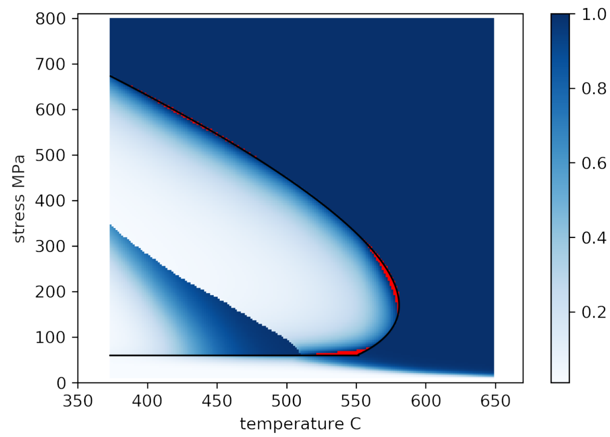
(a) t = 10 hours



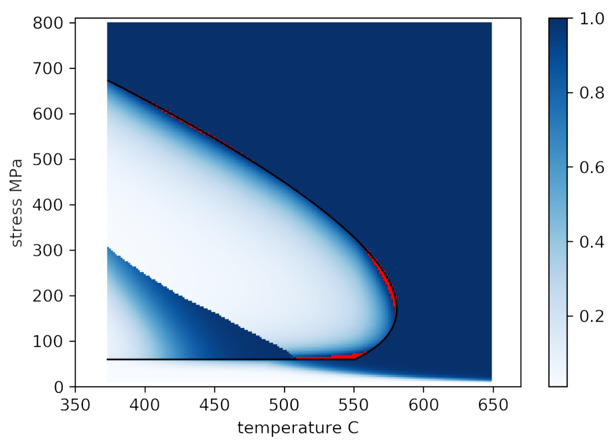
(b) t = 100 hours



(c) t = 1000 hours



(d) t = 100000 hours



(e) t = 300000 hours

Fig. 3. Ratio of the newly formulated creep rates to those obtained from ISSC shown as a field between 0 and 1 for creep times of 10, 100, 1000, 100000, 300000 hours. Regions in red highlight locations where the ratio is greater than one (the formulation failed), and lie very close to the transition of the linear and polynomial regimes as shown in Fig. 2.

References

[1] Klueh, R., and Hebble, T., 1976. "A mathematical description for the stress strain behavior of annealed 2-1/4 Cr-1 Mo steel". *Journal of Pressure Vessel Technology,* ***96***(2), pp. 118–125.
[2] Booker, M., 1977. "Analytical description of the effects of melting practice and heat treatment on the creep properties of 2 1/4 Cr-1 Mo steel". In *Effects of Melting and Processing Variables on the Mechanical Properties of Steel*, G. V. Smith, ed. The American Society of Mechanical Engineers, New York, NY, pp. 1–44.
[3] The American Society of Mechanical Engineers, 2021. "Section III, Division 5, Subsection HB, Subpart B". In *Boiler and Pressure Vessel Code*, 2021 ed.

Appendix A: Creep Model Parameters

The parameters given in this appendix are in units consistent with the unit scheme described in the main body: strain in mm/mm, time in hours, and temperature in degrees Celsius. The symbol log refers to the base 10 logarithm. Where the symbol U appears it refers to the temperature-dependent values given by interpolation in Table 1.

Parameters for ε_1

$$C_1 = 10^{d_1} \tag{A-1}$$

$$d_1 = 1.0328 + \frac{168680}{U\left(T+273.15\right)} - 0.023772U + 0.0079141U\log\sigma \tag{A-2}$$

$$p_1 = 10^{q_1} \tag{A-3}$$

$$q_1 = 7.6026 + 3.3396\log\sigma - \frac{12323}{T+273.15} \tag{A-4}$$

$$\dot{\varepsilon}_1^{(ss)} = 10^{e_1} \tag{A-5}$$

$$e_1 = 6.7475 + 0.011426\sigma + \frac{987.72}{U}\log\sigma - \frac{13494}{T+273.15} \tag{A-6}$$

Parameters for ε_2

$$C_2 = 10^{d_2} \tag{A-7}$$

$$d_2 = -0.051086 + \frac{140730}{U\left(T+273.15\right)} - 0.01U + 0.0037345U\log\sigma \tag{A-8}$$

$$p_2 = 10^{q_2} \tag{A-9}$$

$$q_2 = 8.1242 + 0.0179678\sigma + \frac{404.63}{U}\log\sigma - \frac{11659}{T+273.15} \tag{A-10}$$

$$\dot{\varepsilon}_2^{(ss)} = 10^{e_2} \tag{A-11}$$

$$e_2 = 11.498 - \frac{8.2226U}{T+273.15} - \frac{20448}{T+273.15} + \frac{5862.4}{T+273.15}\log\sigma \tag{A-12}$$

Parameters for t_1

$$t_1 = \begin{cases} t_1^{(a)} & T \leq 454 \\ t_1^{(a)} + \frac{t_1^{(b)} - t_1^{(a)}}{56}\left(T-454\right) & 454 < T \leq 510 \\ t_1^{(b)} & T > 510 \end{cases} \tag{A-13}$$

$$t_1^{(a)} = 10^a \tag{A-14}$$

$$a = -13.528 + \frac{6.5196U}{T+273.15} + \frac{23349}{T+273.15} - \frac{5693.8}{T+273.15}\log\sigma \tag{A-15}$$

$$t_1^{(b)} = 10^b \tag{A-16}$$

$$b = -11.098 - \frac{4.0951\sigma}{U} + \frac{11965}{T+273.15} \tag{A-17}$$

Parameters for t'

$$t' = t - (t_1 - t_c) \tag{A-18}$$

$$t_c = \frac{-\dot{\varepsilon}_2^{(ss)} - C_2 p_2 + \varepsilon_1' p_2 + \sqrt{4\varepsilon_1' \dot{\varepsilon}_2^{(ss)} p_2 + \left(\dot{\varepsilon}_2^{(ss)} + (C_2 - \varepsilon_1')\, p_2\right)^2}}{2\dot{\varepsilon}_2^{(ss)} p_2} \tag{A-19}$$

$$\varepsilon_1' = \frac{C_1 p_1 t_1}{1 + p_1 t_1} + \dot{\varepsilon}_1^{(ss)} t_1 \tag{A-20}$$