Assessment of Creep Damage Evaluation Methods for Grade 91 Steel in the ASME and JSME Nuclear Codes

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Abstract. Grade 91 steel is a Code-approved construction material in the American Society of Mechanical Engineers (ASME) and the Japan Society of Mechanical Engineers (JSME) nuclear codes. Applications of Grade 91 steel include intermediate heat exchanger, piping, steam generator tubing and shell, etc., for sodium fast reactor systems. Current creep-fatigue damage evaluation method in the ASME and JSME nuclear code differs in the method to calculate creep damage. In the simplified inelastic approach of the ASME Code, the stress relaxation history, required in the creep damage evaluation, is calculated using the isochronous stress-strain curves (ISSCs). In the JSME Code, the stress relaxation history is evaluated using a creep strain equation combined with the strain hardening formulation. In this paper, these two approaches will be reviewed and a strain hardening formulation based on the ASME creep strain equation is introduced in an effort to relieve the conservatism associated with the ASME ISSC approach. Stress relaxation predictions from these methods are presented.

Key Words: Grade 91, creep-fatigue, creep damage, design code rules.

1. Introduction

The creep-fatigue damage evaluation procedure is specified in American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section III, Division 5, [1], Subsection HB, Subpart B, HBB-T-1400. Generally, for a design to be acceptable, the creep-fatigue damage shall satisfy the following equation

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \le D \qquad (1)$$

where D is the total creep-fatigue damage given in Figure HBB-T-1420-2 of Division 5 for Grade 91; $(N_d)_j$ is number of design allowable cycles for cycle type, j, determined from the design fatigue curve of Figure HBB-T-1420-1E; and $(T_d)_k$ is the allowable time duration determined from the stress-to-rupture curves of Figures HBB-I-14.6F at that stress value determined by dividing the maximum stress (at the point of interest during the time interval, k) by the factor, K' (Table HBB-T-1411-1). The other quantities given in Eq. (1) are: $(n)_j$ the number of applied repetitions of cycle type j; q the number of time intervals; p the number of stress/temperature time histories; and $(\Delta t)_k$ the duration of the time interval, k.

Procedures for using either elastic or inelastic analysis results to satisfy the requirement of Eq. (1) are provided in HBB-T-1400. The development and verification of the creep-fatigue assessment methods using elastic analysis results and adjustments were described by Severud [2]. This paper concentrates on the elastic analysis approach.

The elastic analysis results may be applied for creep-fatigue evaluation only when (i) the elastic ratcheting rules with the effective creep stress parameter Z less than or equal to one are satisfied; (ii) the primary plus secondary stress intensity range limit of Division 1, NB-3222.2, but based on $3\bar{S}_m$ defined in HBB-T-1324, is met; and pressure-induced membrane and bending stresses and thermal induced membrane stresses are classified as primary (load-controlled) stresses.

The fatigue damage term in Eq. (1) can be evaluated using the linearly elastic analysis methods by accounting for the increase in the total strain range due to plasticity and creep as described in HBB-T-1432. The evaluation of the creep damage term of Eq. (1) using the elastic analysis results, per HBB-T-1433, is the main focus of this paper.

A key step in the creep damage evaluation procedure is the determination of the stress relaxation history during the hold period of a cycle being analyzed. In the HBB-T-1433 creep damage evaluation procedure the initial stress at the start of stress relaxation is obtained by entering the monotonic stress strain curve at a strain level equal to the total strain range.

The HBB-T-1433 creep damage evaluation procedure permits two general ways to determine the stress relaxation history. One corresponds to the application of uniaxial isochronous stress-strain curves (ISSCs), and the other involves the use of a uniaxial relaxation model, to determine the stress relaxation history at constant strain. Adjustment for multi-axial stress state effect, or the introduction of stress cut-off, is made to the stress relaxation histories determined from these uniaxial models. These different approaches for evaluating the creep damage are assessed in this paper.

2. Determination of Stress Relaxation History

2.1. Use of Isochronous Stress-Strain Curves

The ISSCs for Grade 91 are given in Figures HBB-T-1800-E-1 through 11 from 350 to 650°C of ASME Section III, Division 5, Subsection HB, Subpart B. The technical basis for these curves was given by Swindeman [3]. Uniaxial tensile and creep data were used to develop the equations for the hot tensile curve and the creep curves. A correlation for the total strain ε as a function of time t, temperature T, and stress σ under the creep condition was developed

$$\varepsilon(t,T,\sigma) = \frac{\sigma}{M(T)} + \varepsilon_p(T,\sigma) + \varepsilon_c(t,T,\sigma) \tag{2}$$

where M is the modulus in MPa, and ε_p and ε_c are the plastic strain and creep strain, respectively. The plastic strain is assumed to be of the form

$$\varepsilon_p = \begin{cases} \dfrac{1}{b}\left[\ell n\left(\dfrac{R\sigma_{UTS} - R\sigma_{PL}}{R\sigma_{UTS} - \sigma}\right)\right]^2, & \text{for } \sigma > R\sigma_{PL},\ R = 1.25\dfrac{S_{Y1}}{S_y}, \\ 0, \quad \text{for } \sigma \le R\sigma_{PL} \end{cases} \tag{3}$$

where b is a temperature dependent coefficient, σ_{PL} and σ_{UTS} are the temperature dependent proportional limit and ultimate tensile stress, respectively, S_{Y1} is the tabulated yield strength in Table Y1 of ASME Section II, Part D, and S_y is the 0.2% offset yield strength extracted from the tensile curves. The creep strain correlation is taken to be of the form

$$\begin{gathered} \varepsilon_c(t,T,\sigma) = a_0(T,\sigma)\, t^{1/3} + mcr(T,\sigma)\, t \\ a_0 \equiv D\sigma \exp\left(V_0\sigma\right)\exp\left(-Q_0 / T_k\right),\ mcr \equiv C\sigma^n \exp\left(V_m\sigma\right)\exp\left(-Q_m / T_k\right) \end{gathered} \tag{4}$$

where D, V_0, Q_0, C, n, V_m and Q_m are material parameters, and T_k is the absolute temperature in Kelvin. All material parameters in Eqs. (2), (3) and (4) are tabulated by Swindeman [3].

For given temperature and time, Eq. (2) can be viewed as a nonlinear algebraic relation between the stress and total strain and it is the basis for the construction of the ISSCs. For a temperature of 593°C, Eq. (2) was used to construct a few ISSCs in *FIG. 1* for illustration. The stress relaxation history for a given total strain range can be obtained by starting at the hot tensile curve and determine corresponding stress levels at varying times for the same total strain. This is illustrated graphically in *FIG. 1*. When ISSCs are used to determine the relaxation history as described in the HBB-T-1443 procedure, the stress is not permitted to relax below a lower bound level of 1.25 times the core stress.

It is noted that in this approach, the algebraic correlation obtained from constant load creep tests is used to predict variable stress histories. Also, according to Eq. (2), the plastic strain will decrease as the stress relaxes at constant total strain ε. But, in a uniaxial stress relaxation setting, the plastic strain is "locked" and remains constant since the stress is within the yield surface and the plastic strain increment is zero as the stress relaxes from a point on the "flow" part of the hot tensile curve. Thus, the stress relaxation history so-determined is an approximation. But it will be demonstrated that the use of such a stress relaxation history would lead to a conservative prediction of the creep damage.

2.2. Use of Stress Relaxation Models

There is very little guidance given in HBB-T-1433 on the selection of the stress relaxation model for the creep damage evaluation. In its most general form, a verified and validated unified constitutive model could be used to determine the stress relaxation history by subjecting the constitutive equations to the cyclic loading and straining history of a creep-fatigue cycle being analyzed. Let the total strain rate $\dot{\varepsilon}$ be represented additively as

$$\dot{\varepsilon} = \dot{\sigma} / E + \dot{\varepsilon}_p + \dot{\varepsilon}_c \tag{5}$$

where E is the Young's modulus in MPa, $\dot{\sigma}$ is the stress rate, $\dot{\varepsilon}_p$ is the plastic strain rate from standard rate independent plasticity model with plastic loading and unloading conditions, and $\dot{\varepsilon}_c$ is the creep strain rate.

To determine the stress relaxation history during strain hold at a strain level ε_h, and a time duration t_h, it is first noted that if the strain hold occurs before the active yield condition is met, the plastic strain rate is zero. If the material is actively yielded before the strain hold takes place, the plastic strain rate vanishes as soon as stress relaxation commences as the material would be unloaded elastically. Thus, after imposing the constant total strain condition, the equation that governs the stress relaxation response is

$$\dot{\sigma} = -E\dot{\varepsilon}_c, \quad \text{for } 0 \le t \le t_h \quad \text{with initial condition: } \sigma\big)_{t=0} = \sigma_0(\varepsilon_h) \tag{6}$$

where $\sigma_0(\varepsilon)$ represents the hot tensile curve. Equation (6) is a <u>nonlinear differential equation</u> and numerical procedure is required to integrate the equation to obtain the stress relaxation history. However, the development of a verified and validated unified constitutive model is challenging and approximate but simpler approaches are usually undertaken.

Let the creep strain correlation in terms of temperature T, stress σ and time t be represented as $\varepsilon_c = g(T,\sigma,t)$. The creep strain rate is determined approximately by differentiating the function g with respect to time, but keeping T and σ constant, leading to $\dot{\varepsilon}_c = (\partial g / \partial t)_{T,\sigma} \equiv h(T,\sigma,t)$. The function h is then assumed to be the creep strain rate that is applicable for varying stress and temperature conditions. The use of h as the creep rate is called the "time-hardening" approximation. Another approximation of the creep strain rate can be obtained as follows. The creep strain correlation can be used to determine the inverse dependence of t as a function of T, σ and ε_c, which is represented as $t = g^{-1}(T,\sigma,\varepsilon_c)$. This can then be used to eliminate t in the function h to obtain

$$\dot{\varepsilon}_c = h(T,\sigma,g^{-1}(T,\sigma,\varepsilon_c)) \equiv y(T,\sigma,\varepsilon_c) \tag{7}$$

which is referred to as the "strain-hardening" approximation of the creep rate. It is quite well established that the "strain-hardening" approximation is more accurate as compared with the "time-hardening" approximation. The JSME procedure employs Eq. (6) and the strain hardening approximation for the creep rate as represented in Eq. (7) to determine the stress relaxation history during the strain hold.

Substituting Eq. (7) into (6), the stress relaxation history can be obtained by solving the resulting nonlinear differential equation using numerical integration schemes. An explicit Euler method to integrate the nonlinear differential equation for two consecutive time steps from t to $t+\Delta t$ can be formulated as

$$\sigma^{t+\Delta t} = \sigma^t - E^t \Delta\varepsilon_c, \quad \Delta\varepsilon_c = y(T^t,\sigma^t,\varepsilon_c^t)\Delta t \tag{8}$$

where the superscripts denote the two time steps. Special consideration might be required for the initial step, depending on the specific form of the creep strain equations.

2.2.1. ASME Strain Equation

Using the creep strain correlation given in Eq. (4) for Grade 91 steel, a so-called "virtual time" $\hat{t}$ can be defined from the nonlinear equation $a_0(T,\sigma)\hat{t}^{1/3} + mcr(T,\sigma)\,\hat{t} - \varepsilon_c = 0$ for given T, σ and ε_c. The "strain-hardening" approximate creep strain rate is then given as $\dot{\varepsilon}_c = a_0\,\hat{t}^{-2/3}/3 + mcr$. The stress at time $t+\Delta t$ is obtained from

$$\sigma^{t+\Delta t} = \sigma^t - E^t\left[a_0^t/3\times(\hat{t}^t)^{-2/3} + mcr^t\right]\Delta t \tag{9}$$

At time $t=0$, the virtual time $\hat{t}$ is also zero and hence the creep rate is infinite and the integration formula in Eq. (9) would not be valid. This can be overcome by using an implicit backward Euler method for the initial step to start the numerical procedure for determining the stress relaxation history. An algorithm was developed to automatically reduce the size of Δt in order to limit the amount of stress drop for each time step. A value of 0.2 MPa was selected for the results shown in the sections below.

2.2.2. JSME Strain Equation

The JSME strain equation for Grade 91 was given by Onizawa et al. [4] and the creep component is similar in form to the ASME correlation, except that the one-third time power for primary creep is replaced by the Blackburn type of expression involving two exponential functions. The JSME strain equation is expressed as

$$\varepsilon = \frac{\sigma}{E} + \left\langle \frac{\sigma - \sigma_p}{K} \right\rangle^{1/m} + \varepsilon_c \tag{10}$$

where the total strain ε is in m/m, σ is the stress and E the Young's modulus, both in MPa, $< \; >$ the Macaulay's bracket, and

$$\begin{aligned} &\sigma_p = \sigma_y - K(0.002)^m, \\ &\sigma_y = 4.94459\times10^2 - 4.59540\times10^{-1}T + 1.73944\times10^{-3}T^2 - 2.68107\times10^{-6}T^3, \\ &K = 1.26156\times10^3 - 1.69234T, \quad m = 0.266556 - 3.14984\times T \end{aligned} \tag{11}$$

The creep strain ε_c is also in m/m and is given as

$$\varepsilon_c(t,T,\sigma) = C_1\left(1-\exp(-r_1 t)\right) + C_2\left(1-\exp(-r_2 t)\right) + \dot{\varepsilon}_{\min} t \tag{12}$$

where

$$\begin{aligned} &C_1 = 2.1382\times\dot{\varepsilon}_m^{0.59235}/r_1, \quad C_2 = 0.92768\times\dot{\varepsilon}_m^{0.81657}/r_2, \\ &r_1 = 317.09\times t_R^{-0.56858}, \quad r_2 = 14.325\times t_R^{-0.82278}, \\ &\dot{\varepsilon}_m = 2.0416\times\exp\left(-\frac{20197}{8.3144T_k}\right)\times t_R^{-1.1548}, \end{aligned}$$

$$
\begin{aligned}
& t_R = \text{smaller of}\,(t_{R1}, t_{R2}), \\
& \log_{10}\left(\alpha_c t_{R1}\right) = -35.25765 + \frac{29368.90}{T_k} + \frac{14217.17}{T_k}\log_{10}\sigma - \frac{5678.093}{T_k}\left(\log_{10}\sigma\right)^2, \\
& \log_{10}\left(\alpha_c t_{R2}\right) = -21.12846 + \frac{26081.50}{T_k} + \frac{818.7218}{T_k}\log_{10}\sigma - \frac{1359.116}{T_k}\left(\log_{10}\sigma\right)^2, \\
& 2\text{MPa} \le \sigma
\end{aligned}
\tag{13}
$$

Here, t is the time in h; σ is the stress in MPa; and $\alpha_c = 1$ is recommended.

Similar to the ASME strain equation, the creep strain correlation given in Eq. (12) can be used to obtain the "virtual time" $\hat{t}$ from the nonlinear equation

$$C_1\left(1-\exp(-r_1\hat{t})\right) + C_2\left(1-\exp(-r_2\hat{t})\right) + \dot{\varepsilon}_{\min}\hat{t} - \varepsilon_c = 0 \tag{14}$$

for given T, σ and ε_c. The approximate creep strain rate from the "strain-hardening" formulation can then be expressed as

$$\dot{\varepsilon}_c = C_1 r_1 \exp(-r_1\hat{t}) + C_2 r_2 \exp(-r_2\hat{t}) + \dot{\varepsilon}_{\min} \tag{15}$$

Using Eq. (15), explicit Euler method similar to that in Eq. (9) can be used to determine the stress relaxation history based on the JSME creep strain equation. The creep rate from Eq. (15) at $\hat{t} = 0$, or $t = 0$, is bounded so there is no issue in using the explicit Euler method to start the numerical procedure to determine the stress relaxation history. Similarly, the amount of stress drop for each time step is limited to no more than 0.2 MPa by an adaptive algorithm to adjust the step size.

3. Results and Discussion

Grade 91 creep-fatigue tests were conducted at the Oak Ridge National Laboratory in the 1980s and efforts were made to retrieve some of the hysteresis loops from strip charts. Since Grade 91 steel cyclically softens, the stress relaxation history during the strain hold from the first creep-fatigue cycle of the test would be the appropriate set of data to compare with the stress relaxation predictions from the methods discussed in the previous section.

A creep-fatigue test with an applied total strain range of 1%, a R-ratio of -1 on the applied strain, a strain rate of 0.4%/s, a temperature of 593°C, and a 60-minute compressive strain hold was selected. The experimental stress relaxation history for the first creep-fatigue cycle, with an initial stress of 334.8 MPa, is shown in *FIG. 2*, part (a). The stress relaxation histories, as predicted from the ASME and JSME strain hardening formulations, are superposed on the experimental data. These two predictions are replotted in *FIG. 2*, part (b), without the data, for clarity.

Another creep-fatigue test with an applied total strain range of 0.51%, a R-ratio of -1 on the applied strain, a strain rate of 0.4%/s, a temperature of 593°C, and a 30-minute tensile strain hold was selected. The experimental stress relaxation history for the first creep-fatigue cycle, with an initial stress of 218.3 MPa, is shown in *FIG. 3*, part (a). The stress relaxation histories, as predicted from the ASME and JSME strain hardening formulations, are superposed on the experimental data. These two predictions are also replotted in *FIG. 3*, part (b), without the data, for clarity.

The stress relaxation histories as predicted from the ASME and JSME strain hardening formulations compare reasonably well with the measured data during both tensile and compressive strain holds, with the stress levels from JSME strain hardening formulation lower than those predicted by the ASME strain hardening formulation.

The data from a uniaxial stress relaxation test at 500°C, with an initial stress of 310 MPa, are shown in *FIG. 4*. The stress relaxation predictions from the two strain hardening formulations are also included in the figure. The JSME prediction compares very favorably with the uniaxial stress relaxation data, while the ASME prediction at this lower temperature is quite conservative.

To compare the use of the two strain hardening formulations in determining the stress relaxation history with that of the ISSC approach, the procedure of ASME Division 5, HBB-T-1433 is applied. Two cases are selected for consideration. The first case is for a temperature of 500°C and a total strain range of 0.2%. Using the monotonic stress strain curve at 500°C, a strain equal to the total strain range leads to an initial stress of 302.5 MPa. The second case has a temperature of 593°C and a total strain range of 0.5%. The corresponding initial stress is 274.9 MPa. A stress relaxation period of 1,000 h, which approximates a typical operating transient, is applied to both cases. The stress relaxation histories from the ISSC approach and the two strain hardening formulations are shown in *FIG. 5*, part (a) for the temperature of 500°C and in part (b) for 593°C.

At 500°C, the predictions from the ISSC approach and the ASME strain hardening formulation are quite close to each other, but are quite conservative relative to the prediction from the JSME strain hardening formulation. For the case of 593°C, which is quite high as compared with the operating temperature of a sodium fast reactor, the ISSC approach gives the most conservative prediction, while the ASME strain hardening formulation comes next, as compared with the prediction from the JSME strain hardening formulation.

4. Conclusion

Based on the limited comparisons with experimental data, it can be concluded that the ASME and JSME strain hardening formulations predict the average stress relaxation response of the first cycle of creep-fatigue tests (short hold time) at high temperature reasonably well. When compared to longer term uniaxial stress relaxation data at lower temperature, the JSME strain hardening formulation still makes good prediction, but the ASME strain hardening formulation over predicts the stress relaxation behavior.

Similar conclusions can be made concerning the stress relaxation predictions using the HBB-T-1433 procedure. While the ASME strain hardening formulation improves upon the conservatism of the ISSC approach, with less improvement at lower temperatures, it is still much more conservative, may be unnecessarily so, as compared with the JSME strain hardening formulation, in the creep-damage calculations.

5. Acknowledgments

The work of T.-L. Sham was sponsored by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357 with Argonne National Laboratory, managed and operated by UChicago Argonne LLC. Programmatic direction was provided by the Office of Nuclear Energy.

The authors would like to thank Dr. T. Onizawa of the Japan Atomic Energy Agency for the discussion on the implementation of the JSME strain hardening formulation.

6. Copyright Notice

7. References

[1] ASME Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors, ASME BPVC.III.5-2015, American Society of Mechanical Engineers, New York, N.Y (2015).

[2] SEVERUD, L.K., “Creep-fatigue Assessment Methods Using Elastic Analysis Results and Adjustments,” J. Pressure Vessel Technology, Vol. 113, Issue 1, pp. 34-40 (1991).

[3] SWINDEMAN, R.W., "Construction of Isochronous Stress-Strain Curves for 9Cr- 1 Mo-V Steel," in *Advances in Life Prediction Methodology, PVP-Vol. 391*, pp. 95-100, American Society of Mechanical Engineers, New York, NY (1999).

[4] ONIZAWA, T., et al., “Development of 2012 Edition of JSME Code for Design and Construction of Fast Reactors (3) Development of the Material Strength Standard of Modified 9Cr-1Mo Steel,” PVP2013-97611, Proceedings of the ASME 2013 Pressure Vessels & Piping Division Conference, Paris, France, American Society of Mechanical Engineers, New York, NY (2013).

8. Figures

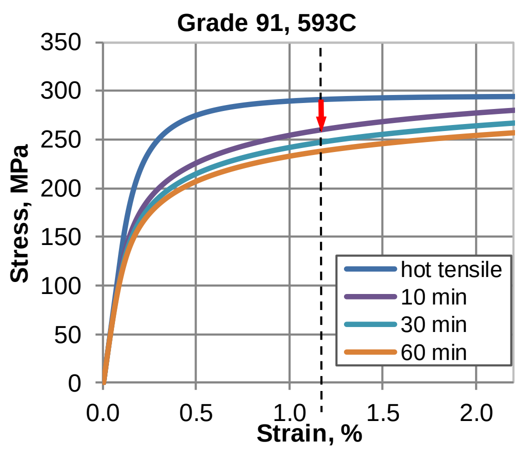

FIG. 1. Determination of stress relaxation using ISSCs

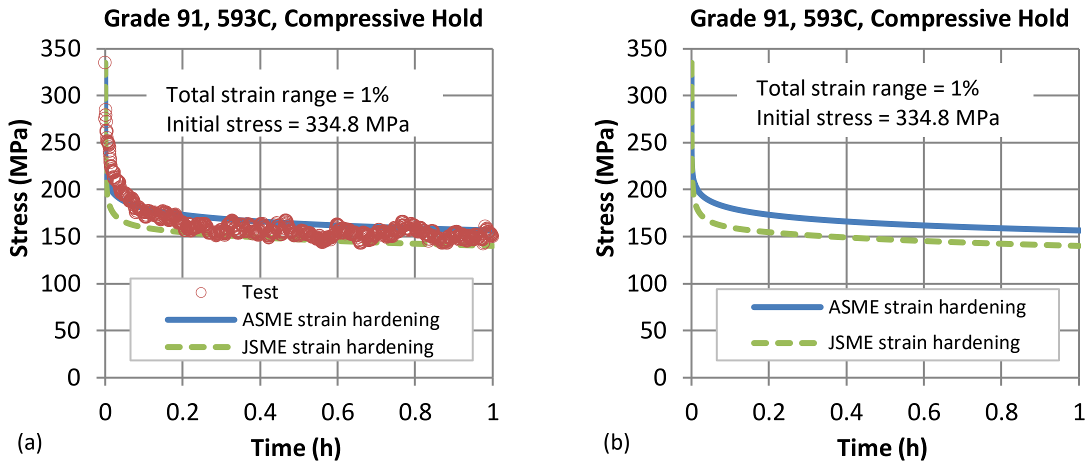

FIG. 2. Predicted stress relaxation histories and 1st cycle hold time data in creep-fatigue

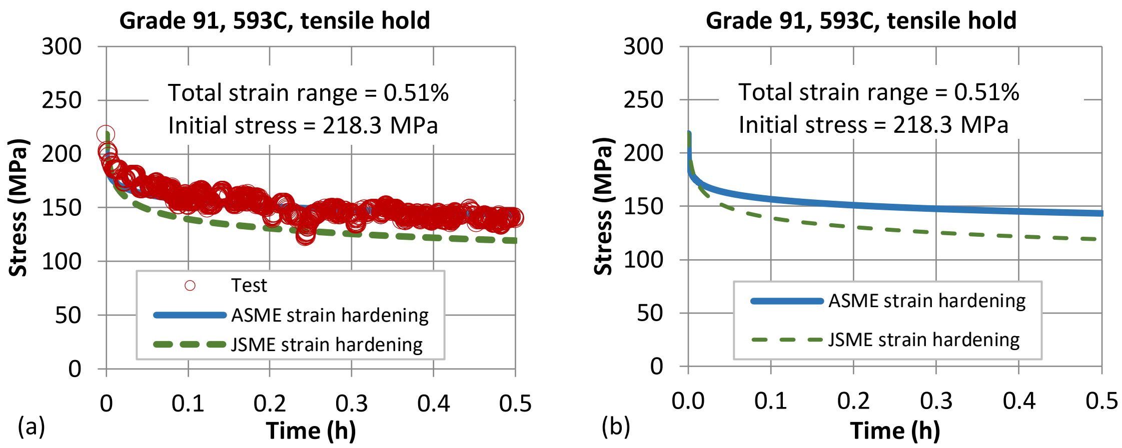

FIG. 3. Predicted stress relaxation histories and 1st cycle hold time data in creep-fatigue

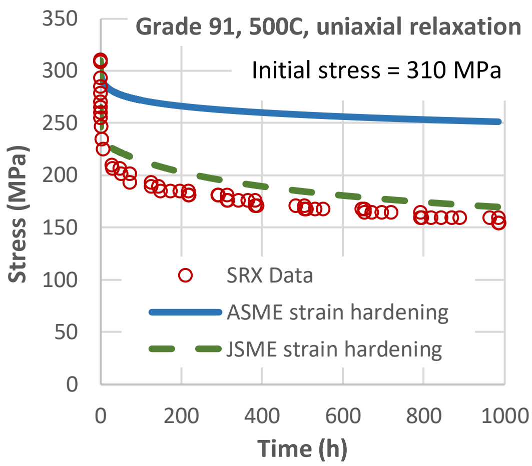

FIG. 4. Stress relaxation behavior of uniaxial relaxation test

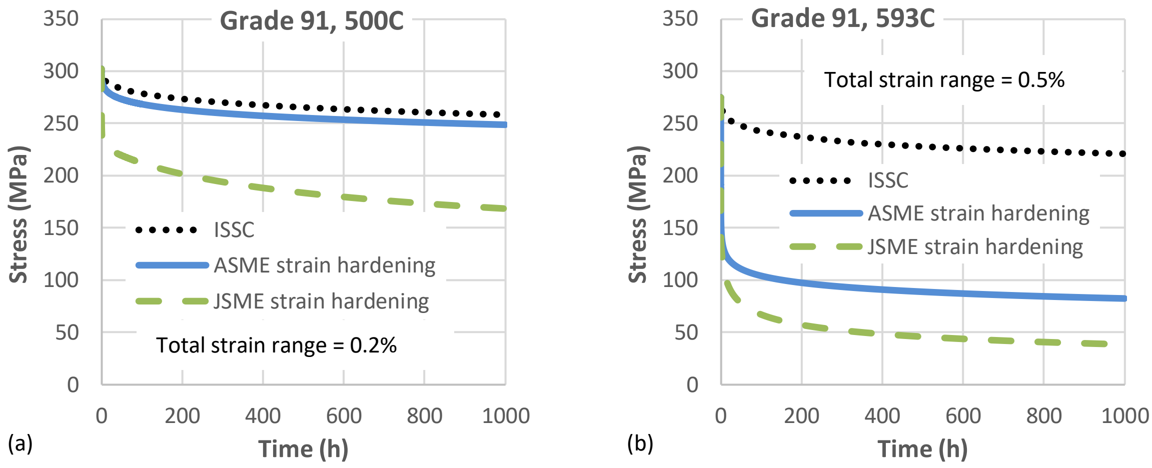

FIG. 5. Stress relaxation prediction per ASME Division 5, HBB-1433 at different temperatures and total strain ranges