13.2 Modeling of Hot Tensile and Short-Term Creep Strength for LWR Piping Materials under Severe Accident Conditions

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Abstract

The analytical study on severe accident shows the possibility of the reactor coolant system (RCS) piping failure before reactor pressure vessel failure under the high primary pressure sequence at pressurized water reactors. The establishment of the high-temperature strength model of the realistic RCS piping materials is important in order to predict precisely the accident progression and to evaluate the piping behavior with small uncertainties. Based on material testing, the 0.2% proof stress and the ultimate tensile strength above 800℃ were given by the equations of second degree as a function of the reciprocal absolute temperature considering the strength increase due to fine precipitates for the piping materials. The piping materials include type 316 stainless steel, type 316 stainless steel of nuclear grade, CF8M cast duplex stainless steel and STS410 carbon steel. Also the short-term creep rupture time and the minimum creep rate at high-temperature were given by the modified Norton's Law as a function of stress and temperature considering the effect of the precipitation formation and resolution on the creep strength. The present modified Norton's Law gives better results than the conventional Larson-Miller method. Correlating the creep data (the applied stress versus the minimum creep rate) with the tensile data (the 0.2% proof stress or the ultimate tensile strength versus the strain rate), it was found that the dynamic recrystallization significantly occurred at high-temperature.

Keywords: light water reactor, severe accident, reactor coolant piping, stainless steel, carbon steel, tensile strength, creep rupture time, minimum creep rate, microstructure, dynamic recrystallization

1. Introduction

The analyses by Pilch et al.[1] and Hidaka[2] with the SCDAP/RELAP5[3] code showed that failure of the hot leg or pressurizer surge line resulting in the depressurization of the reactor coolant system (RCS) could occur prior to the reactor pressure vessel (RPV) meltthrough at lower head for short-term station blackout scenarios for PWR in severe accident. In such scenarios, the temperature of RCS pipings significantly increased by superheated steam from the degraded reactor core due to countercurrent flows in the hot leg. Therefore, U. S. NRC concluded that the issue of containment failure by direct containment heating (DCH) in PWR, had been mostly resolved. Moreover, the U. S. NRC[4] recently concluded that the pressure- and temperature- induced failure of the steam generator tubes never occur before the failure of the hot legs or surge line in the high pressure severe accident with secondary system depressurization. These important conclusions were made based on the thermal-hydraulics and the creep failure times for each component predicted by using the SCDAP/RELAP5. The model for creep rupture of the structural component in SCDAP/RELAP5 was based on the Larson-Miller theory or the Manson-Haferd theory.

The Larson-Miller and the Manson-Haferd theories using the first degree equation of the logarithms of stress, are used to calculate the creep damage and nearness to rupture of RCS components in best estimate transient simulation of RCS during a severe accident. The Larson-Miller and the Manson-Haferd theories are applicable to extrapolation of creep rupture data using a linear time temperature relationship. If the creep rupture data for the time frame of interest in severe accidents, however, are obtained from the short-term creep tests, the model for creep rupture can be evaluated by interpolation of creep rupture data. It is important to evaluate the model of the high-temperature tensile and creep strength using data obtained from real RCS piping materials in order to assess the risk of severe accident-induced RCS piping failure with small uncertainties.

The present paper describes the high-temperature tensile and creep data for the RCS piping materials. These specimen tests have been performed to obtain the hot tensile properties, the short-term creep rupture time and the minimum creep rate under WIND (Wide Range Piping Integrity Demonstration) project at Japan Atomic Energy Research Institute (JAERI). Before and after the specimen testing, the microstructures were examined by the metallography. The experimental formula of the 0.2% proof stress and the ultimate tensile strength are developed. Also the model of the rupture time and the creep rate are developed by the modified Norton's Law taking into account the microstructural change during the testing. The correlation between the creep data (the applied stress versus the minimum creep rate) and the tensile data (the 0.2% proof stress or the ultimate tensile strength versus the strain rate) are investigated to predict the tensile behavior at high-temperature from its creep behavior using the modified Norton's Law.

2. Experiments

The materials of the test pipes are similar as those of RCS piping used in Japanese LWRs as previously reported[(5)]. The specimen of cold drawn type 316 stainless steel of nuclear grade (here in after, referred to as SUS316(N)), cast duplex stainless steel (CF8M), hot extruded type 316 stainless steel (SUS316) or carbon steel (STS410) were taken circumferentially from as-received pipes, respectively.

The test specimen had the geometry of 30mm in a gauge length and 6mm in a diameter. The tensile and the creep test procedures were reported previously[(5)]. After creep-rupture testing, longitudinal sections of the gauge and head portions of the specimens were polished, etched in either aqua regia for the stainless steel or 5%HNO_3-ethyl alcohol mixture for the carbon steel, and examined by scanning electron microscopy (SEM).

3. Results and Discussion

3.1 Model of Hot Tensile Strength

The logarithms of the 0.2% proof stress and the ultimate tensile strength above 800℃ are evaluated for CF8M and plotted as a function of the reciprocal absolute temperature in **Fig. 1**. There is a decline of the strength properties with increasing temperature. The conventional model of the 0.2% proof stress, $R_{p0.2}$ (MPa), and the ultimate tensile strength, R_m (MPa), is given by Arhenius equation[(5)]

$$R_{p0.2} = 0.0233\exp(73.9/RT) \quad (1)$$

$$R_m = 0.0556\exp(70.9/RT) \quad (2)$$

where R is the gas constant of 8.32 J/mol, T (K) the absolute temperature.

On the otherhand, the present model is given by the equation of second degree as a function of the reciprocal absolute temperature

$$LogR_{p0.2} = -14.7 + 3.44(10000/T) - 0.178(10000/T)^2 \quad (3)$$

$$LogR_m = -9.79 + 2.36(10000/T) - 0.116(10000/T)^2. \quad (4)$$

The conventional model slightly underestimates particularly the 0.2% proof stress at 850℃. This is probably due to the effect of a fine precipitation of carbide, $M_{23}C_6$, on the increase of the strength[(5)]. The prediction by the present model is, however, on the whole in good agreement with the measured stress above 800℃ which is important under severe accident conditions.

3.2 Model of Time to Rupture

Figure 2 plots stress versus logarithmic times to rupture for the tested temperature of CF8M. There is a reduction of the time to rupture with increasing stress. The stress dependence of the time to rupture appears to be split into two regimes: Norton's Law with a linear stress dependence at 600-700℃; and the modified Norton's Law[5] with a nonlinear stress dependence between 800 and 1,000℃. The stress dependence of the time to rupture, t_r (h), at lower temperature is generally expressed as a power law, often called Norton's Law

$$Logt_r = A - nLog\sigma \quad (5)$$

$$A = 0.0904\exp(42.5/RT) \quad (6)$$

$$n = 0.0780\exp(37.2/RT) \quad (7)$$

where σ (MPa) is the stress.

The stress dependence of t_r at higher temperature is expressed as the modified Norton's Law

$$Logt_r = a - b(Log\sigma)^2. \quad (8)$$

The logarithmic stress exponent in Eq. (8) is determined between 1 and 5 by the method of least squares. The temperature dependence of the material parameters in Eq. (8), a and b, are given by the following equations

$$a = -6.66 + 1.34(10000/T) \quad (9)$$

$$b = 7.90\exp(-15.8/RT). \quad (10)$$

The modified Norton's Law seems to take into account the increase of creep strength by a fine precipitation, the decrease of creep strength by a coarse precipitation and the recovery of creep strength by a resolution of the precipitation, occurring in a short time at high temperature[5]. The equation (8) based on the modified Norton's Law is applicable to the stated change of creep strength caused by the microstructural changes above 800℃.

On the other hand, the master rupture curve for the Larson-Miller parameter at high temperature between 800 and 1,000℃ is given by

$$T(Logt_r + 15)/1000 = 26.6 - 5.08Log\sigma \quad (11)$$

where the parameter constant of 15 is optimized between 10 and 25 by the method of least squares.

The uncertainty in the the modified Norton's Law and the Larson-Miller method was discussed in the previous study[5]. The variance, s, about the regression can be estimated from the following equation

$$s = \sqrt{\frac{\sum_i \left(\log t_{r_i} - \overline{\log t_{r_i}}\right)^2}{N}} \quad (12)$$

where $\log t_{r_i}$ is the observed value, $\overline{\log t_{r_i}}$ the value predicted by the the modified Norton's Law or the Larson-Miller theory and N the number of data, 16. **Figure 3** shows the comparison of the variance in the models of t_r for LWR piping materials at high temperature. The variance is smaller in the modified Norton's Law than the Larson Miller method except CF8M. This difference is due to microstructure. The predominant crack occurred on the grain boundary of γ phase in SUS316 and on δ ferrite phase in CF8M. The effect of the microstructural change on creep strength is smaller in δ ferrite phase of CF8M at 800-1,000℃ than in γ phase of SUS316 and SUS316(N) at 800-1,150℃[5].

Photographs 1 shows the change of microstructure before and after the tests for CF8M. The precipitation are almost free in Photo. 1 (a) because the as-received specimen were finally solution-treated and quenched in water. The precipitation in δ ferrite phase was evident and extensive precipitation and particle coarsening occurred at 900 and 1,000℃ within the ruptured gauge lengths in Photo. 1 (b) and (c). The morphology of the intragranular particles at 900 and 1,000℃, were different from each other. On the other hand, the precipitation was almost free due to resolution at 1,000℃ within the undeformed specimen heads in Photo. 1 (d). At 1000℃, the resolution took place within the undeformed region in few tens hours. The precipitates at 900 and 1,000℃ is considered to be various carbides and intermetallic phases which were found in CF8M during aging at elevated temperature. The enhancement of the precipitation occurred by simultaneous creep deformation. The crack occurred in the ferrite phase or along the ferrite/austenite grain boundaries. Therefore, it is considered that the increase of the strength at 850℃ in Fig. 1, is due to the fine precipitation in the ferrite phase or along the ferrite/austenite grain boundaries.

3.3 Correlation between Tensile and Creep Data

The stress and temperature dependence of $\dot{\varepsilon}_{min}$ at lower temperature of 600-700℃ in **Fig. 4**, is expressed as Norton's Law

$$Log\,\dot{\varepsilon}_{min} = -c + dLog\sigma \tag{13}$$

$$c = 0.249\exp(34.5/RT) \tag{14}$$

$$d = 0.171\exp(30.6/RT). \tag{15}$$

The stress and temperature dependence of $\dot{\varepsilon}_{min}$ at higher temperature between 800 and 1,000℃ is expressed as the modified Norton's Law

$$Log\,\dot{\varepsilon}_{min} = -c + d\,(Log\sigma)^2 \tag{16}$$

$$c = -6.97 + 1.43(10000/T) \tag{17}$$

$$d = 8.28\exp(-17.0/RT). \tag{18}$$

This prediction is, also, in good agreement with the measured values. The equation (16) using the modified Norton's Law is applicable to the change of the minimum creep rate caused the microstructural changes above 800℃. Also, this prediction of the minimum creep rate is in good agreement with the measured tensile data except the values at 600-800℃. The modified Norton's Law in Fig. 4, is applicable for the tensile and creep data between 850 and 1,000℃. The results for CF8M of this study are in agreement with the effect of dynamic recrystallization on the deformation at high-temperatute[6].

4. Conclusions

From the evaluation of the tensile and creep data at high-temperature and short-term time which simulate a time-temperature relation for the reactor coolant pipings failure under severe accident conditions of LWR, the following conclusions were obtained:

(1) The prediction of the 0.2% proof stress and the ultimate tensile strength given by the equations of second degree as a function of the reciprocal absolute temperature considering the strength increase due to fine precipitates, is in good agreement with the measured stress above 800℃ for several piping materials of reactor coolant system.

(2) For the short-term creep rupture time and the minimum creep rate, the modified Norton's Law as a function of stress and temperature considering the effect of the precipitation formation and resolution on the creep strength, predicts well the experiments at high-temperature for the above steels.

(3) The range of uncertainty is smaller in the modified Norton's Law than the Larson-Miller method previously used in severe accident analysis except CF8M duplex stainless steel. The modified Norton's Law is suitable to describe the effect of the very rapid formation and resolution of the precipitation on the creep strength.

(4) Correlation of the creep data (the applied stress versus the minimum creep rate) with the tensile data (the 0.2% proof stress or the ultimate tensile strength versus the strain rate), indicated that dynamic recrystallization occurred significantly at temperatures higher than 850℃.

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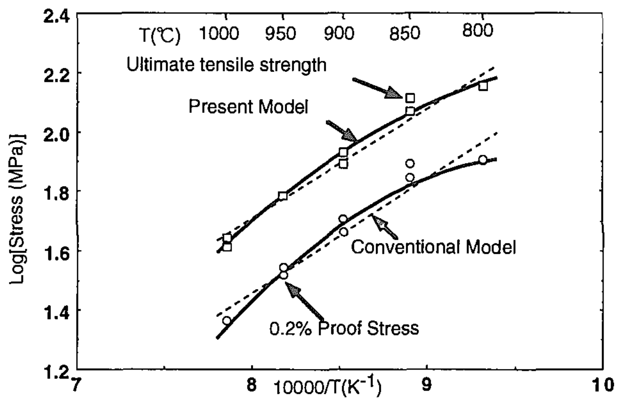


Fig. 1 Modeling of hot tensile strength for CF8M stainless steel

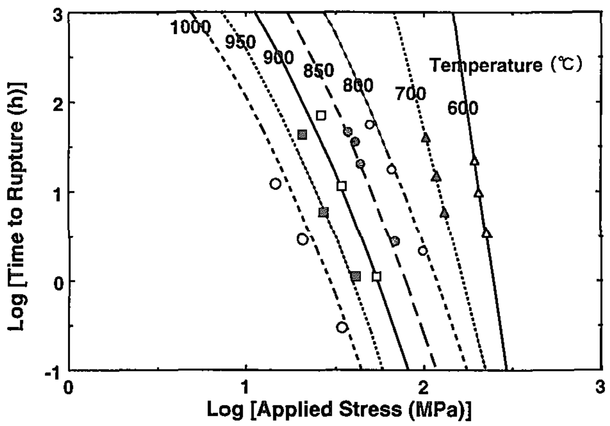
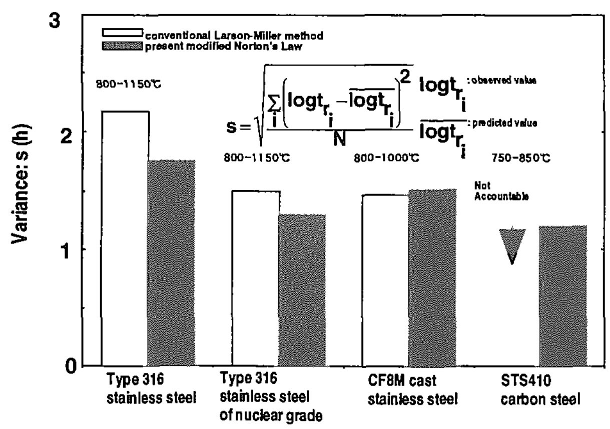


Fig. 2 Modeling of time to rupture given by modified Norton's Law for CF8M



$$s=\sqrt{\frac{\sum_i\left(\log t_{r_i}-\overline{\log t_{r_i}}\right)^2}{N}}$$

Fig. 3 Comparison of variance in model s of time to rupture for LWR piping materials

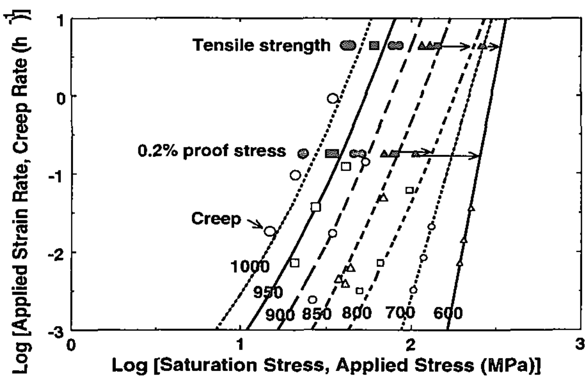


Fig. 4 Modeling of minimum creep rate given by modified Norton's Law for CF8M

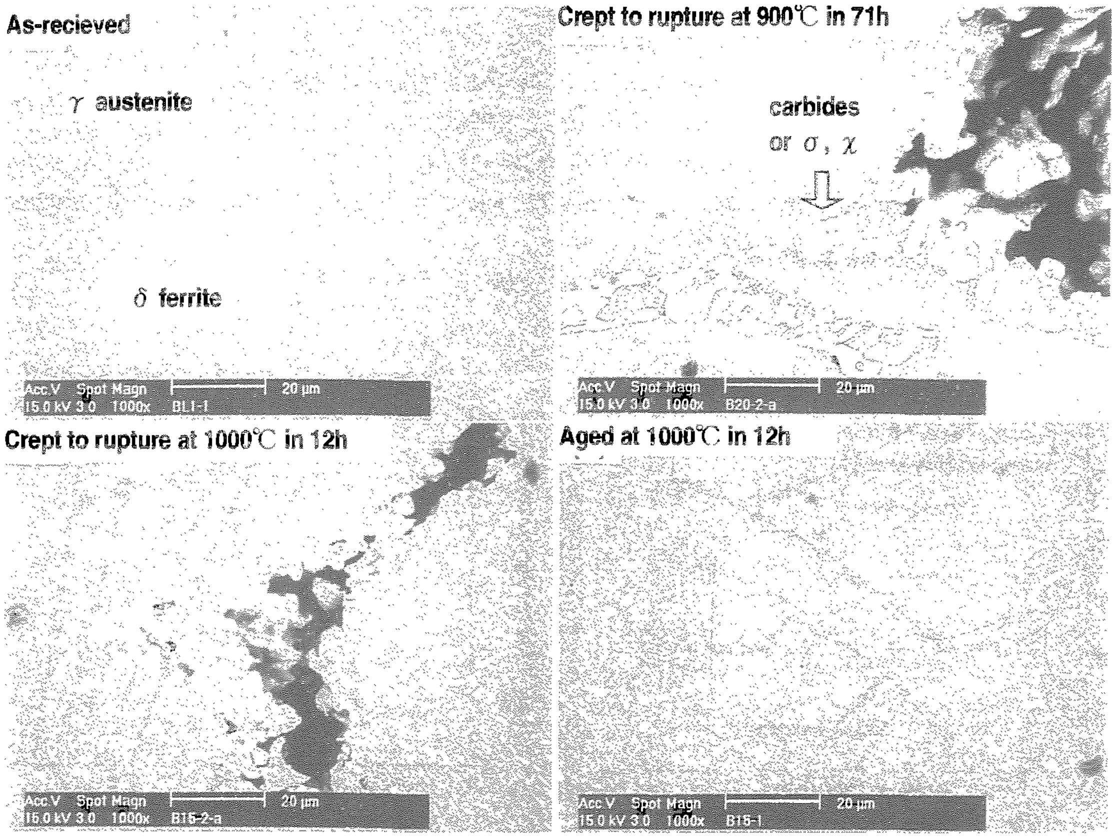


Photo. 1 Microstructural change in CF8M duplex stainless steel at hot-temperature