Creep properties and analysis of creep rupture data of 2.25Cr-1Mo-0.3V steels
Kota Sawada, Yasushi Taniuchi, Kaoru Sekido, Takehiro Nojima and Kazuhiro Kimura
Research Center for Structural Materials, National Institute for Materials Science, Tsukuba, Ibaraki, Japan

ABSTRACT
Tensile properties and creep rupture data were obtained for four heats of 2.25Cr-1Mo-0.3V steels used for high-temperature and high-pressure hydrotreatment reactor vessels. Tensile tests at room temperature to 650°C were performed in accordance with JIS G 0567. Creep tests at 450 to 600°C were conducted in accordance with JIS Z 2271. Large heat-to-heat variations of tensile and creep rupture data were found with the different heat treatment conditions. However, no large difference in creep rupture ductility was observed among the heats. Regression analysis was applied to the tensile test data of each heat because of the large heat-to-heat variations. The creep rupture data of heats VdA and VdB were separately fitted to the regression equation of logarithmic stress using the time-temperature parameters of Larson–Miller, Orr–Sherby–Dorn and Manson–Haferd to estimate the 100,000 h creep rupture strength. The appropriate time-temperature parameter and degree of regression equation were selected based on the fitting accuracy and simplicity of regression equation. The value of 67% of the 100,000 h creep rupture strength was compared with the current allowable stress specified in codes and standards.

1. Introduction
Heat-resistant steels are used for high-temperature components in thermal power plants. In order to design these components safely, the allowable stress of the steels needs to be known. To determine the allowable stress, tensile and creep properties should be evaluated over the range from room temperature to high temperature [1,2]. For example, the 100,000 hours (about 11.4 years) creep rupture strength is needed in the criteria of allowable stress [1,2]. Recently, the allowable stress of high-chromium ferritic steel, ASME Gr.91, has been lowered in Japan because the newly obtained creep rupture strength data were lower than previously anticipated [3]. Therefore, long-term creep rupture strength data can contribute to the safe design of components in power plants. The National Institute for Materials Science started a creep data sheet project in 1966, with the main purpose of obtaining the 100,000 h creep rupture strength for heat-resistant steels and alloys [4]. Recently, we have performed long-term creep tests of 2.25Cr-1Mo-0.3 V steel (JIS SFVCM F22 V [5]), which is mainly used for high-temperature and high-pressure hydrotreatment reactor vessels in the petroleum industry [6]. For the safe design of these reactor vessels, the 100,000 h creep rupture strength should be accurately estimated based on an analysis of creep rupture data.
In this study, we examined the characteristics of creep properties and estimated the 100,000 h creep rupture strength of 2.25Cr-1Mo-0.3 V steel.

2. Experimental procedures

2.1 Material

The steel studied was 2.25Cr-1Mo-0.3 V steel (JIS SFVCM F22 V [5]). The details of the steel such as type of melting, product form, processing and thermal history are listed in Table 1. The four heats, VdA, VdB, VdC and VdD, were sampled for creep testing. The heats VdB and VdD are the same heat as the heats VdA and VdC, respectively. Additional heat treatments were conducted for VdB and VdD after initial heat treatment as shown in Table 1. Therefore, for example, the hardness of VdB is smaller than that of VdA. Table 2 shows the chemical compositions of the steels studied. All the compositions of the steels are in the range of specification of JIS SFVCM F22 V [5].

2.2 Tensile and creep testing

The tensile tests at room temperature and elevated temperatures were performed in accordance with JIS G 0567 [7]. The engineering (nominal) strain rate of the specimen was controlled to 0.3%/min up to about 1.0% proof stress and 7.5%/min beyond that.

The creep tests were carried out in accordance with JIS Z 2271 [8]. Creep strain–time data were obtained using single-type creep testing machines. Solid cylindrical specimens with gauge mark projections were used as shown in Figure 1. The specimen with 10 mm in gauge diameter was used for tensile testing. For creep testing, both types of specimens were used corresponding to stress level.

2.3 Temperature measurement and control

The degree of temperature used in the testing program was based upon the International Temperature Scale of 1990. For tensile and creep

**Table 1.** Details of 2.25Cr-1Mo-0.3 V steel forgings, VdA, VdB, VdC and VdD.

| NIMS reference code | Type of melting | Size of ingot (kg) | Deoxidation process | Product form | Dimensions (mm) | Processing and thermal history | Austenite grain size number | Rockwell hardness (HRC) | Non-metallic inclusion (%) |
|---------------------|-----------------|-------------------|---------------------|--------------|----------------|------------------|--------------------------|------------------------|--------------------------|
| VdA                 | BEA             | 118,000           | Si-Al killed        | Forged       | 4004 OD 264 WT 3918 L | Forged 1020°C/7 h WQ 695°C/11 h AC | 4.8 | 19 | da = 0.01, db = 0.00, dC = 0.01 |
| VdB                 |                 |                   |                     |              |                 | Forged 1020°C/7 h WQ 695°C/11 h AC 625°C/10 h AC 705°C/30 h AC | 4.2 | 12 | |
| VdC                 | BEA             | 120,500           | VOD                 | Forged       | 5070 OD 262 WT 3535 L | Forged 945°C/6.5 h cooling 665°C/9.9 h AC | 8.3 | 30 | da = 0.01, db = 0.01, dC = 0.07 |
| VdD                 |                 |                   |                     | Forged       |                 | Forged 945°C/6.5 h cooling 665°C/9.9 h AC PWHT | 8.2 | 11 | |

1) The forgings were sampled in 2004 (VdA, VdB) and 2007 (VdC, VdD). The details other than grain size number, hardness and non-metallic inclusion were reported by the steel manufacturer.
2) BEA: basic electric arc furnace
3) OD: outside diameter, WT: wall thickness, L: length
4) WQ: water quenching, AC: air cooling, PWHT: post weld heat treatment, cooling: The cooling rate is 20°C/min.
5) JIS G 0551-2020, "Steel-Micrographic determination of the apparent grain size"
6) JIS G 0555-2020, "Microscopic testing method for the non-metallic inclusions in steel"
7) The heat VdB is the same heat as the heat VdA except for the additional stress relieving heat treatment.
8) The heat VdD is the same as VdC, except for the PWHT.

**Table 2.** Chemical composition (product analysis) of 2.25Cr-1Mo-0.3 V steel forgings.

| NIMS reference code | C (%) | Si (%) | Mn (%) | P (%) | S (%) | Ni (%) | Cr (%) | Mo (%) | Cu (%) | V (%) | Ti (%) |
|---------------------|-------|--------|--------|-------|-------|--------|--------|--------|--------|-------|-------|
| Requirement         | ≤0.17 | ≤0.10  | 0.30–0.60 | ≤0.015 | ≤0.010 | ≤0.04  | 2.00–2.50 | 0.90–1.10 | ≤0.40  | 0.25–0.35 | ≤0.015 |
| VdA                 | 0.12  | 0.1    | 0.53   | 0.004 | 0.001 | 0.17   | 2.39   | 0.97   | 0.03  | 0.29  | <0.002 |
| VdB                 |       |        |        |       |       |        |        |        |       |       |        |
| VdC                 | 0.14  | 0.06   | 0.54   | 0.004 | 0.0019 | 0.17   | 2.47   | 1.04   | 0.05  | 0.29  | 0.008  |
| VdD                 |       |        |        |       |       |        |        |        |       |       |        |

| NIMS reference code | Al (%) | B (%) | N (%) | Nb (%) | Ca (%) | As (%) | Sb (%) | Sn (%) | La (%) | Ce (%) |
|---------------------|--------|-------|-------|--------|--------|--------|--------|--------|--------|--------|
| Requirement         | ≤0.003 | ≤0.07 | ≤0.015 | (La+Ce) ≤ 0.015 |
| VdA                 | 0.017* | 0.0001 | 0.0068* | 0.03 | 0.0026 | 0.002 | 0.001 | 0.001 | <0.01* | <0.01* |
| VdB                 | <0.0005 | 0.0004 | 0.0060 | 0.02* | <0.0005 | <0.005* | <0.005* | <0.002* | <0.001* | 0.001* |
| VdC                 |       |       |       |        |        |        |        |        |        |        |
| VdD                 |       |       |       |        |        |        |        |        |        |        |

1) The chemical composition given above was reported by the steel manufacturer except for the elements marked with asterisk, for which the analysis was carried out at NIMS.
2) SFVCM F22 V, JIS G 3206–1993, "High strength chromium-molybdenum alloy steel forgings for pressure vessels under high-temperature service"
tests, the temperature was maintained to within ±3°C for temperatures equal to or higher than 100°C.

2.4 Microstructure observation
For observations by optical microscope, the creep ruptured specimens were cut longitudinally parallel to the stress direction by a water-cooled fine cutter, embedded in hard resin, then polished with emery papers and buffing cloths with paste. The etching was carried out in a solution of 94 cm³ ethanol and 6 cm³ nitric acid.

3. Analysis method
3.1 Short-term tensile data
Short-term tensile data were analyzed and fitted to the following regression equation:

$$\log(S_p \text{ or } S_T) = a_0 + a_1T + a_2T^2 + \ldots + a_kT^k$$  (1)

where $S_p = 0.2\%$ proof stress (MPa), $S_T = $ tensile strength (MPa), $T =$ temperature (°C), $a_0, a_1, a_2, \ldots, a_k =$ regression coefficients estimated by the method of least squares, and $k =$ degree of regression equation.

3.2 Creep rupture data
The creep rupture data were analyzed and fitted to a regression equation of logarithmic stress using the time-temperature parameters (P) of Larson–Miller (LM) [9], Orr–Sherby–Dorn (OSD) [10] and Manson–Haferd (MH) [11].

$$LM\ P = (T + 273.15)(C + \log t_R)$$  (2)

$$OSD\ P = \log t_R - Q/[2.3R(T + 273.15)]$$  (3)

$$MH\ P = (\log t_R - \log t_u)/(T + 273.15 - T_u)$$  (4)

where $t_R =$ time to rupture (h), $T =$ temperature (°C), $C, Q, t_u$ and $T_u =$ optimized constants, and $R =$ gas constant.

The master rupture curve equations for the fit were of the form:

$$P = b_0 + b_1\log S + b_2(\log S)^2 + \ldots + b_k(\log S)^k$$  (5)

$$P = b + b_0S + b_1\log S + b_2(\log S)^2 + \ldots + b_k(\log S)^k$$  (6)

where $S =$ stress (MPa), $b, b_0, b_1, b_2, b_3, \ldots, b_k =$ regression coefficients estimated by the method of least squares, and $k =$ degree of regression equation.

4. Experimental results
4.1 Initial microstructure and tensile properties
Figure 2 shows optical micrographs of as received samples. The microstructure is bainite for all heats. Prior austenite grain size of VdA and VdB is larger than those of VdC and VdD. Figure 3 shows the short-term tensile properties of the four heats listed in Table 1. The tensile strength and 0.2% proof stress decreased with increasing temperature for all heats. However, the difference in tensile strength and 0.2% proof stress was quite large among the heats. This may be due to the difference in heat treatment. There is no large change in elongation and reduction of area at room temperature to 400°C. The elongation and reduction of area increased with increasing temperature above 400°C.
Figure 2. Optical micrographs of as received samples.

Figure 3. Short-Time tensile properties of four heats (a) 0.2% proof stress, (b) Tensile strength, (c) Elongation, (d) Reduction of area.
4.2 Creep properties

Figure 4 shows stress versus time to rupture at 450, 475, 500, 525, 550 and 600°C. There is a large difference in creep strength among the four heats. This may be due to the difference in heat treatment. Therefore, the regression analysis should be performed for each heat, even though the chemical composition is roughly the same for all heats. The creep strength tends to decrease in the long term at 550°C and 600°C for all heats. The creep strength of heat VdA is much higher than that of

![Figure 4](image-url)

**Figure 4.** Creep rupture strength of all heats. (a) Heat VdA, (b) Heat VdB, (c) Heat VdC, (d) Heat VdD.

![Figure 5](image-url)

**Figure 5.** Elongation of creep ruptured samples. (a) 450°C, (b) 475°C, (c) 500°C, (d) 525°C, (e) 550°C, (f) 600°C.
heat VdB at 450 to 525°C. However, the difference in creep strength between them becomes small in the long term at 550°C and 600°C. The 0.2% proof stress and tensile strength of heat VdA are also higher than those of heat VdB, leading to the difference of creep strength at 450 to 525°C. However, the effect of the difference of tensile properties on creep strength is small in the long term at 550°C and 600°C. Creep rupture ductility is shown in Figures 5 and 6. At 450°C there is no large difference in ductility among the steels. The ductility of VdA and VdC is relatively smaller than those of VdB and VdD at 475 to 550°C. At 600°C the ductility of VdA and VdC becomes the same as those of VdB and VdD in the long term. The time to reach the specified total strain and the time to tertiary creep were estimated from the strain and time relation for all heats, as shown in Figure 7. The time to tertiary creep means the time to 0.2% offset strain of the tertiary creep.

Figure 8 shows the relationship between minimum creep rate and stress for all heats. Monkman–Grant relations [12] are shown in Figure 9. The data show heat-to-heat variations, so the relation was evaluated for each heat as shown in Figure 10. The linear relationship between creep rupture time and minimum creep rate (Monkman–Grant relation) was computed from the simple regression equation as listed in Table 3.
4.3 Microstructure of creep ruptured samples

Figure 11 shows microstructures of creep ruptured samples for each heat. The microstructure of the gauge portion of creep ruptured samples was observed. No creep voids were observed for all heats. As shown in Figures 5 and 6, the creep rupture ductility of all heats is basically high, indicating that there was no change in fracture mode. In the case of austenitic stainless steels, the fracture mode changes from transgranular to intergranular with increasing creep rupture time [13,14]. For intergranular fracture, creep rupture ductility is normally low compared with
transgranular fracture; in this case, one should consider the change of fracture mode for analysis of creep rupture data [15]. However, no fracture mode change was observed in the steel studied because creep rupture ductility was high under all testing conditions.

5. Analysis of experimental data

5.1 Analysis of short-term tensile data

Figure 12 shows the results of regression analysis for the short-term tensile data shown in Figure 3. The regression coefficient in Equation (1) for each heat is listed in Table 4. The degree of regression equation of tensile strength and 0.2% proof stress was third and fourth, respectively. We tried several degrees of regression equation. Figure 13 shows an example of the trial for 0.2% proof stress of heat VdD. The fitting was appropriate when the degree of regression equation was fourth and fifth as compared with the third degree. The difference of the fitting curve of the fourth and fifth degrees is very small. To facilitate using the equation for designing components, the equation should be as simple as possible. Therefore, the fourth degree was selected for the fitting curve of 0.2% proof stress of heat VdD. In the same way as heat VdD, the degree of regression equation was selected for each heat as listed in Table 4.

5.2 Analysis of creep rupture data

As shown in Figure 4, there are not enough long-term creep data for estimating the 100,000 h creep rupture strength in the case of heats VdC and VdD, so the creep rupture data were analyzed for heats VdA and VdB. The creep rupture data of heats VdA and VdB were separately analyzed because the difference of creep strength between them was very large due to the difference of heat treatment as shown in Figure 4. Figure 14 shows the results of analyzing the creep rupture data of heat VdA by the LM parameter. (2) and (5) were used for the analysis. In the case of the second degree of regression equation, the fitting is not appropriate at 550°C and 600°C in the long term. The fitting curve is an S-shape in the long term when the degree of regression equation is fourth. However, the fourth degree should not be used because no trend such as an S-shape was observed in the experimental data. The fitting curve of the third and fifth degrees successfully expresses the experimental data. In this case, the third degree is suitable because the fitting curve should be as simple as possible. Figure 15 demonstrates the fitting curve for heat VdA by using Equation (2) and (6). The fitting

Table 3. Regression coefficient of the linear relationship between time to rupture and minimum creep rate for 2.25Cr-1Mo-0.3 V steel.

| NIMS reference code | n*x1 | A  | B  | SEE | CODx² |
|---------------------|------|----|----|-----|-------|
| VdA                 | 50   | 2.728.382 x 10^-1 | -9.968.288 x 10^-1 | 0.125 | 0.9777 |
| VdB                 | 59   | 4.130.861 x 10^-1 | -1.005.346 | 0.210 | 0.9486 |
| VdC                 | 39   | 2.794.308 x 10^-1 | -9.527.603 x 10^-1 | 0.059 | 0.9922 |
| VdD                 | 41   | 7.267.190 x 10^-1 | -9.447.161 x 10^-1 | 0.146 | 0.9636 |

*1 n : number of data points.
*2 SEE : standard error of estimate.
*3 COD : coefficient of determination.
Minimum creep rate : %/h.
tₚ : time to rupture (h).

Figure 11. Microstructure of gauge portion of creep ruptured samples.
by second degree of regression equation is not appropriate at 550°C in the long term. The third degree cannot be used because the S-shape was observed in the long-term. There was no large difference in fourth and fifth degrees. Therefore, the fourth degree of regression equation was selected considering simplicity of equation. The results of analyzing the creep rupture data of heat VdA by the OSD parameter are shown in Figure 16. Equation (3) and (5) were applied to the experimental data. The fitting curve with second degree cannot express the data in the long term. The curve with fourth degree was not selected because the curve was an S-shape. The third degree was selected in terms of simplicity due to the small difference of the third and fifth degrees. In the case of using Equation (3) and (6), we checked the fitting curves by second to fifth degrees. The fitting curve by second degree overestimated rupture time at 550°C in the long-term. The fitting curve by third degree showed the S-shape. In the case of fifth degree, the fitting curve turned back in the long-term. Therefore, the fourth degree was selected for the fitting curve. Figure 17 shows the results of analyzing the creep rupture data of heat VdA by the MH parameter and Equation (5). The fitting curve by second degree cannot express the experimental data. The fitting curve by fifth degree underestimated rupture time at 550°C in the long-term. The fitting curves by third and fourth degrees are not suitable because of S-shape. However, the fitting curve by fourth degree was selected for comparison of MH parameter and others. The second degree was appropriate when Equation (4) and (6)
Figure 14. Results of regression analysis by LM parameter and Equation (5) for heat VdA. (a) 2nd degree, (b) 3rd degree, (c) 4th degree, (d) 5th degree. SEE: standard error of estimate, COD: coefficient of determination

Figure 15. Results of regression analysis by LM parameter and Equation (6) for heat VdA. (a) 2nd degree, (b) 3rd degree, (c) 4th degree, (d) 5th degree. SEE: standard error of estimate, COD: coefficient of determination
Figure 16. Results of regression analysis by OSD parameter and Equation (5) for heat VdA. (a) 2nd degree, (b) 3rd degree, (c) 4th degree, (d) 5th degree. SEE: standard error of estimate, COD: coefficient of determination

Figure 17. Results of regression analysis by MH parameter and Equation (5) for heat VdA. (a) 2nd degree, (b) 3rd degree, (c) 4th degree, (d) 5th degree. SEE: standard error of estimate, COD: coefficient of determination
Table 5. Selected regression coefficient of Laron-Miller, Orr-Sherby-Dom and Manson-Haferd parameters fitted to creep rupture data of heat VdA and VdB.

|       | C                   | Q                   | $T_a$    | log$_{10} T_a$ | b       | SEE*       | COD*      |
|-------|---------------------|---------------------|----------|----------------|---------|------------|-----------|
| VdA   |                     |                     |          |                |         |            |           |
| LM_1  | 1.9,772,343 x 10    | -                   | -        | -              | -       | 0.097      | 0.9874    |
| LM_2  | 1.9,839,873 x 10    | -                   | -        | -              | -       | 0.093      | 0.9888    |
| OSD_1 | 6.2,828,944 x 10    | -                   | -        | -              | -       | 0.088      | 0.9997    |
| OSD_2 | 7.0,486,211 x 10    | -                   | -        | -              | -       | 0.080      | 0.9917    |
| MH_1  | 6.7,390,910 x 10^-2 | -                   | -        | -              | -       | 0.083      | 0.9910    |
| MH_2  | 8.2,261,435 x 10^-2 | -                   | -        | -              | -       | 0.084      | 0.9904    |

| VdB   |                     |                     |          |                |         |            |           |
| LM_1  | 2.1,030,430 x 10    | -                   | -        | -              | -       | 1.3,769,027 x 10^7 | -3.0709862 x 10^7 |
| LM_2  | 2.1,027,308 x 10    | -                   | -        | -              | -       | 6.1,166,864 x 10^6 | -2.0291540 x 10^7 |
| OSD_1 | 6.7,191,140 x 10^7  | -                   | -        | -              | -       | 1.9,502,562 x 10^5 | -4.3,260,160 x 10^7 |
| OSD_2 | 7.3,719,243 x 10^-2 | -                   | -        | -              | -       | 1.9,961,179 x 10^-1 | 1.8,390,501 x 10^-1 |
| MH_1  | 7.4,263,462 x 10^-2 | -                   | -        | -              | -       | 2.3,173,392 x 10^-5 | 2.3,220,460 x 10^-5 |
| MH_2  | 6.0,533,895 x 10^-4 | -                   | -        | -              | -       | 0.087      | 0.9920    |

*1 n: number of data points.
*2 SEE: standard error of estimate.
*3 COD: coefficient of determination.
*4 R: gas constant.
were applied to the data. In the same way as heat VdA, the creep rupture data were analyzed for heat VdB by the LM, OSD and MH parameters. The appropriate degree of regression equation was selected considering extrapolation accuracy and simplicity of fitting curve. The selected degrees of regression equation for heats VdA and VdB are summarized in Table 5. Figure 18 shows the fitting curves based on the results of Table 5 and experimental data. There is no large difference in fitting curve up to around 100,000 h at 450, 475 and 500°C. On the other hand, at 525°C and 550°C the extrapolated 100,000 h creep rupture strength is different among the fitting curves. The fitting curve by the MH parameter shows a faster drop of creep rupture strength at 100,000 h or more as compared with other parameters. For heats VdA and VdB, the fitting curve by the MH parameter underestimates rupture time at 500°C and 525°C in the long-term around 100,000 h. The fitting curve by the MH parameter is appropriate at 550°C for heat VdA. However, it is difficult to recommend MH parameter because the steel studied is normally used at around 500°C [6]. The fitting curves by the LM parameter overestimates the creep rupture strength at 500°C to 550°C in the long
term around 100,000 h. Therefore, the fitting curve by the OSD parameter is appropriate for heats VdA and VdB. In the case of the OSD parameter, there is no large difference in fitting curve by using Equation (5) and (6) for heat VdA. The fitting curve by Equation (5) should be selected because of the simplicity of regression equation. For heat VdB, the fitting accuracy by Equation (5) is appropriate at 600°C in the long term as compared with the fitting accuracy by Equation (6).

Consequently, the fitting curve by using the OSD parameter and Equation (5) was selected for creep rupture data analysis for heats VdA and VdB. The regression coefficients are listed in Table 6. The fitting curves using these coefficients are shown in Figure 19. The maximum creep rupture time extrapolated from the fitting curve is 300,000 h because normally extrapolation should be less than three times the experimental data. The temperature dependence of 0.2% proof stress, tensile strength and creep rupture strength at 100, 1000, 10,000 and 100,000 h as calculated from regression equations listed in Table 6 are shown in Figure 20. The creep rupture strength estimated using the regression equations listed in Table 6 is shown in Table 7. For determining allowable stress, a value of 67% of the 100,000 h creep rupture strength is used [1, 2]. For example, this value at 475°C obtained from Table 7 is about 201 MPa and 148 MPa for heats VdA and VdB, respectively. The allowable stress of JIS SFVCM F22 V is 141 MPa at 475°C [16]. According to ASME SA-336 F22 V [1], the allowable stress at 475°C is the same as that of JIS SFVCM F22 V and is determined by taking a safety factor on tensile property. The estimated value of 67% of the 100,000 h creep rupture strength from Table 7 is higher than the allowable stress determined by short-term tensile properties, indicating that the current allowable stress does not need to be modified.

The tables of data used in this study will be published in the database of https://smds.nims.go.jp/creep/en/as a NIMS Creep Data Sheet. Now, the National Institute for Materials Science is reviewing publication policy of the NIMS Creep Data Sheet. After the review, the NIMS Creep Data Sheet for JIS SFVCM F22 V steel will be published.

### 6. Conclusions

Short-term tensile and creep rupture data were obtained for JIS SFVCM F22 V steels. The regression equation for short-term tensile data was determined for heats VdA, VdB, VdC and VdD. The regression equation using the Orr–Sherby–Dorn parameter can reasonably express the creep rupture data of heats VdA and VdB, and was used to

**Table 7. Summary of creep rupture strength in MPa evaluated from curvilinear regression using Orr-Sherby-Dorn parameter method for 2.25Cr-1Mo-0.3 V steels.**

| NIMS reference number | Number of data points | 450°C | 475°C | 500°C |
|-----------------------|-----------------------|-------|-------|-------|
|                       |                       | 10⁶h  | 10⁷h  | 10¹⁰h |
| VdA                   | 50                    | 496   | 448   | 398   |
|                       |                       | 347   | 455   | 354   |
|                       |                       | 300   | 415   | 311   |
|                       |                       | 252   |       |       |
| VdA                   | 59                    | 525°c |       |       |
|                       |                       |       |       |       |
| VdB                   | 50                    | 777   | 324   | 267   |
|                       |                       | 202   | 340   | 222   |
|                       |                       | 144   | 267   | 201   |
|                       |                       | 116   |       |       |
| VdB                   | 59                    | 288   | 237   | 197   |
|                       |                       | 160   | 249   | 207   |
|                       |                       | 127   |       |       |
|                       |                       | 106   |       |       |
evaluate the 100,000 h creep rupture strength for heats VdA and VdB.

**Disclosure statement**

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

**References**

[1] American Society of Mechanical Engineers (ASME). ASME boiler and pressure vessel code. Section II. Part D; 2019.

[2] The Japan Society of Mechanical Engineers (JSME). Rules on thermal power generation. JSME S TA1-2015.

[3] Kimura K, Yaguchi M, Re-Evaluation of long-term creep strength of base metal of ASME grade 91 type steel. Proceedings of ASME Pressure Vessels and Piping Division Conference, 2016 Jul. 17–21, Vancouver, British Columbia, Canada. ASME, 2016. PVP2016–63355; DOI: 10.1115/PVP2012-78323.

[4] Sawada K, Kimura K, Taniuchi Y, et al. Catalog of NIMS creep data sheets. Sci Tech Adv Mater. 2019;20(1):1131–1149. DOI:10.1080/14686996.2019.1697616

[5] Japanese Industrial Standards (JIS). SFVCM F22V, high-strength chromium-molybdenum alloy steel forgings for pressure vessels under high-temperature service. JIS G 3206; 1993.

[6] Kayano R, Nitta Y, Haga M, et al Recent trends in material properties and fabrication technologies of advanced cr-mo steel for hydrotreating reactors. The Japan Steel Works, Ltd Technical Report. 2005;56:66–75.

[7] Japanese Industrial Standards (JIS). “Method of elevated temperature tensile test for steels and heat-resisting alloys.” JIS G 0567; 1998.

[8] Japanese Industrial Standards (JIS). Method of creep and creep rupture test for metallic materials. JIS Z 2271; 1998.

[9] Larson FR, Miller J. A time-temperature relationship for rupture and creep stresses. Trans ASME. 1952;74:765–771.

[10] Orr RL, Sherby OD, Dorn JE. Correlations of rupture data for metals at elevated temperatures. Trans ASM. 1954;46:113–118.

[11] Manson SS, Haferd A. A linear time-temperature relation for extrapolation of creep and stress rupture data. National Advisory Committee for Aeronautics; 1953. (TN2890).

[12] Monkman FC, Grant NJ, Proc ASTM. 1956; 56:593–597.

[13] National Institute for Materials Science. NIMS Creep Data Sheet, No. M-2; 2003.

[14] National Institute for Materials Science. NIMS Creep Data Sheet, No. M-11; 2016.

[15] Nakakuki H, Maruyama K, Oikawa H, et al. Collective evaluation of temperature and stress dependence of creep rupture life in austenitic stainless steels. Tetsu-To-Hagane. 1995;81(3):220–224. DOI:10.2355/tetsutohagane1995.81.3_220

[16] Ministry of Economy, Trade and Industry. Material specifications in the technical regulation of equipment for thermal power plants. 2016. p. 134.