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Multiregion analysis of creep rupture data of 316 stainless steel

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Abstract

A creep rupture data set of 316 stainless steel containing 319 data points at nine heats was subjected to a conventional single-region analysis and a multiregion analysis. In the former, the conventional Larson–Miller analysis was applied to the whole data set. In the latter, a data set of a single heat is divided into several data sets, so that the Orr–Sherby–Dorn (OSD) constant Q takes a unique value in each data set, and the conventional OSD analysis was applied to each divided data set. A region with a low value of Q appears in long-term creep of eight heats. Predicted values of the 10^5 h creep rupture stress of three heats were lower than the 99% confidence limit evaluated by the single-region analysis, suggesting that the single-region analysis is error prone. The multiregion analysis is necessary for the correct evaluation of the long-term creep properties of 316 stainless steel.

Keywords: 316 stainless steel; Creep rupture life; Time–temperature–parameter methods; Extrapolation of rupture life; Heat-to-heat variation

1. Introduction

Long-term creep properties of structural materials used in high-temperature plants are evaluated from short-term data with the aid of time–temperature–parameter (TTP) methods [1]. However, the conventional TTP methods sometimes overestimate long-term creep rupture life. The overestimation has been pointed out on austenitic stainless steels [2–4], and recognized more seriously on advanced high Cr ferritic steels: for example 11Cr–2.6W–0.1Mo–CoVNb steel [5], 9Cr–1Mo–VNb steel [6], and 11Cr–2W–0.3Mo–CuVNb steel [7–9]. Conventional TTP methods always make a crucial assumption that the TTP constant, such as C for the Larson–Miller (LM) parameter or Q for the Orr–Sherby–Dorn (OSD) parameter, is unique in a given creep rupture data set. In other words, the temperature T dependence of rupture life t_r, namely $d\ln t_r/d(1/T)$ should not change in a data set. However, this is not always true. Maruyama et al. [2,9] have pointed out that the change in $d\ln t_r/d(1/T)$ is the cause of the overestimation, and have proposed a multiregion analysis of creep rupture data. In the analysis, a set of creep rupture data is divided into several data sets so that C or Q is unique in each divided data set, and each divided data set is analyzed by the conventional TTP method. The multiregion analysis can properly evaluate the long-term creep rupture life of 304 stainless steels [2]. The multiregion analysis is applied to multiheat creep rupture data of 316 stainless steel in the present study.

The allowable stress of a structural material to be used in the creep regime is usually determined by its creep rupture properties: 2/3 of the average stress to cause creep rupture in 10^5 h or 80% of the minimum stress to cause creep rupture in 10^5 h. Since the 95% confidence limit of the scatter band of creep rupture data provides the minimum stress, a large scatter in data, in other words large deviation from the mean value, lowers the allowable stress. The deviation of rupture life Δ is defined

$$\Delta = \log t_r - \log t_m, \tag{1}$$

where t_r is the measured rupture life, and t_m is the mean value defined by the regression curve. Various items contribute to the scatter in creep rupture data; heat-to-heat variations, true scatter in data within a heat, and so on. As will be shown later (see Fig. 3(b)), regression curves obtained by a conventional TTP method depart from the

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trend of data points measured at each temperature, when the Q value changes within a given data set. In such a case, the deviation Δ is artificially enlarged due to the departure of the regression curve from the trend of the data. The artificial deviation lowers the minimum stress of the scatter band, and such an artifact should be eliminated. The seriousness of the artificial deviation will be evaluated through the rupture data analyses of the multiheat data set of 316 stainless steel.

2. Conventional single-region analysis of creep rupture data

The creep rupture data of 316 stainless steel to be analyzed in the present paper have been reported in Creep Data Sheet no. 6B [10] published by National Institute for Materials Science, Japan. The data set contains 319 data points of nine heats of materials; heats A–F and L–M. Long-term rupture life t_r of a material is usually evaluated from short-term data with the aid of TTP methods. The followings are the representative parameters [11,12]:

$$P(t_r, T) = (\log t_r + C)T \quad \text{(LM)}, \tag{2}$$

$$P(t_r, T) = \log t_r - (Q/RT)\log e \quad \text{(OSD)}, \tag{3}$$

where T is the absolute temperature, C is a LM constant, Q is the apparent activation energy, and e and R have their usual meanings. A master curve independent of testing temperature is obtained with the aid of the time–temperature parameters P. The master curve is represented by

$$P(t_r, T) = f(\sigma), \tag{4}$$

where $f(\sigma)$ is a function of stress and defines the master curve. Once $f(\sigma)$ is determined, one can readily evaluate t_r at any σ and T. Polynomials of logarithmic stress are often employed for $f(\sigma)$:

$$f(\sigma) = \sum_{k=0}^{l} a_k(\log\sigma)^k, \tag{5}$$

where a_k is a constant, and l is less than 6.

The LM method was applied to the whole data set of 316 stainless steel, and the master curve obtained is drawn in Fig. 1 together with the regression curve (solid line). The value of the LM constant giving the best fit was $C = 18.2$. The standard error of the estimate, SEE, is defined by

$$SEE = \sqrt{\frac{\Sigma(\log t_r - \log t_m)^2}{N - q}}, \tag{6}$$

where N is the number of data points, and q is the total number of adjustable parameters included in the regression equation. The conventional single-region analysis of the present data set by using the LM parameter gives $SEE = 0.233$. This value suggests a large scatter in the data as evident in Fig. 1. The cumulative probability of deviation from the regression curve is shown in Fig. 2. The abscissa is normalized by the value of SEE. The deviation of data points follows the log-normal distribution represented by the solid curve.

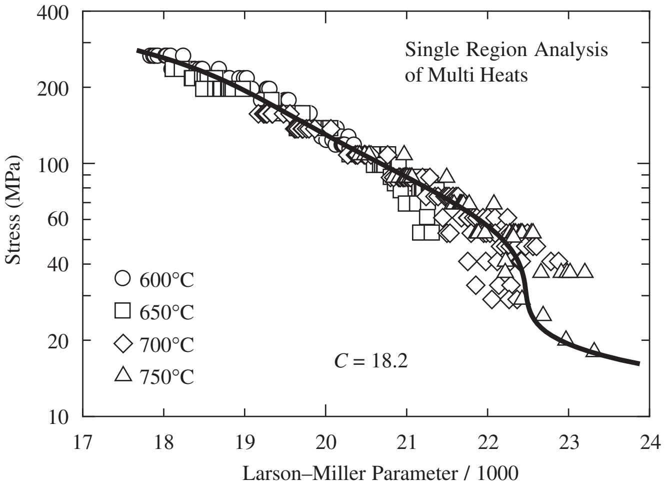

Fig. 1. Stress vs. rupture life for the whole data set based on the Larson–Miller parameter with the regression curve (sold line) determined by the conventional single-region analysis of the whole data.

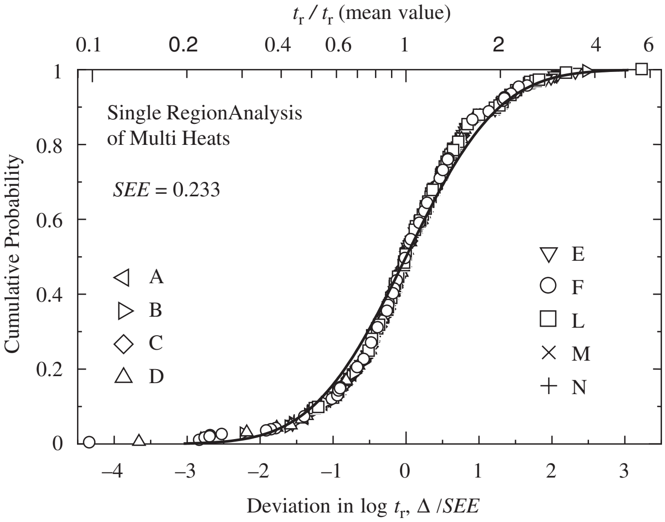

Fig. 2. Cumulative probability as a function of deviation Δ defined by Eq. (1). The abscissa is normalized by SEE given by Eq. (6). The solid curve represents the log-normal distribution.

In order to examine causes of the large deviation of data points in the conventional LM analysis, a single heat of data (heat F) was subjected to a single-region analysis based on the LM parameter. Fig. 3(a) shows the master plot together with the regression curve. In Fig. 3(b) a comparison is made between the data points and the regression curve at each temperature. The value of SEE is 0.145 in terms of $\log t_r$, and not small. As is evident in Fig. 3(a), the regression curve passes through the centre of the data points. It is expected that this is true at each temperature. However, the regression curves drawn in Fig. 3(b) depart from the data points and cannot describe