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Analysis of long-term creep curves by constitutive equations

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ABSTRACT

Long-term creep curves up to the secondary stage (time >10^5 h) for carbon steel, 1.25Cr–0.5Mo–Si steel, 2.25Cr–1Mo steel, and SUS316 steel were analyzed by means of constitutive creep equations. A power-law equation well fitted the actual long-term creep curves for all the steels, whereas the exponential-law equation, logarithmic-law equation, and Blackburn's equation could not represent the beginning of primary creep during long-term testing. All the equations reproduced short-term creep curves for all the steels. For carbon steel, the parameters obtained from data analysis at higher stresses were extrapolated to lower stresses to predict the long-term creep curve. However, none of the creep curves predicted by the equations agreed with the actual long-term creep curves, although the prediction of the power-law equation was better than those of the other equations.

1. Introduction

The residual life of high-temperature components in power plants are evaluated by means of destructive and nondestructive testing methods based on the damage mechanisms for each material [1]. Creep deformation is one reason for failure of high-temperature components after long-term service. It is possible to predict residual creep life by measurement of the creep strain of components [2]. If a constitutive creep equation existed that could express actual creep-strain data, we could predict creep life from measurements of strain. Furthermore, the design of components in nuclear power plants requires creep-strain data for long-term conditions in order to determine the allowable stress [3]. In next-generation fast-breeder reactors, it is expected that components could be in use for 60 years [4], so there is a need to know their long-term creep-deformation behavior from experimental studies, calculations, or both. It is, however, difficult to obtain long-term creep-strain data for more than 10^5 h (11.4 years). We must therefore obtain a valid constitutive creep equation by analyzing short-term creep-strain data and then predict long-term creep-deformation behavior by numerical extrapolation based on the equation.

The National Institute for Materials Science (NIMS) has conducted a large number of long-term creep tests to obtain creep rupture and strain data for various materials. In many of these tests, the creep time exceeds 10^5 h. In these cases, the creep strain was continuously measured during testing. Applied stresses for these tests were very low and mimicked the actual conditions in power plants. These data are useful for investigating whether the constitutive creep equation obtained from analysis of short-term data can be extrapolated to long-term conditions. Many constitutive equations have been proposed [1,5–9]. These equations describe creep curves up to the secondary and/or tertiary stage. The longest creep time studied by our institute is about 330,000 h for carbon steel, ferritic steel, and austenitic heat-resistant steel. These tests are in the range of the secondary stage and are still running. To analyze these data, constitutive creep equations for the primary and secondary stages should be used. We selected four constitutive creep equations that are widely accepted as basic equations [10,11].

$$\text{Power law} \quad \varepsilon = \varepsilon_i + at^b + \dot{\varepsilon}_M t \tag{1}$$

$$\text{Exponential law} \quad \varepsilon = \varepsilon_i + a[1 - \exp(-bt)] + \dot{\varepsilon}_M t \tag{2}$$

$$\text{Logarithmic law} \quad \varepsilon = \varepsilon_i + a\ln(1 + bt) + \dot{\varepsilon}_M t \tag{3}$$

$$\text{Blackburn} \quad \varepsilon = \varepsilon_i + a[1 - \exp(-bt)] + c[1 - \exp(-dt)] + \dot{\varepsilon}_M t \tag{4}$$

where ε, ε_i, t, and $\dot{\varepsilon}_M$ are the strain, the initial strain, the time, and the minimum creep rate, respectively; a, b, c, and d are the constants obtained from the analysis.

By analyzing experimental creep-strain data relating to periods of more than 10^5 h, we determined a constitutive creep equation that can accurately reproduce creep curves. We also discuss whether the constitutive creep equation obtained from the analysis of short-term creep data is also applicable for long-term creep exposures.

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2. Materials and creep tests

The steels under study were a carbon steel, 1.25Cr–0.5Mo–Si steel, 2.25Cr–1Mo steel, and SUS316 steel. Creep rupture data for these steels have already been published [12–15]. Creep tests were performed under a constant load in air on specimens with gauge diameters of 6 and 10 mm, and gauge lengths of 30 and 50 mm. Displacements during creep exposures were measured directly by an extensometer suitable for high-temperature use. The test conditions and creep times selected for the analysis are summarized in Table 1. At the given test temperatures listed in the table, the longest duration of testing for each steel exceeded 100,000 h.

The creep tests with the longest duration are still running, and are now in the range of the secondary stage. To permit a systematic comparison to be made between the results of analysis for short-term creep data and those for the longest term, creep-strain data up to the secondary stage were analyzed, even when the results of the test included data for the tertiary stage. In short, we focused on the primary and secondary stages of creep deformation using Eqs. (1)–(4). An initial strain, ε_i, in Eqs. (1)–(4) represents the value obtained experimentally. Experimental values of ε_i are used to analyze the time-dependent strain change $(\varepsilon - \varepsilon_i)$. The strain used for analysis was the nominal strain. Eqs. (1)–(3) have three parameters, whereas Eq. (4) has five parameters.

Table 1
Test conditions of data considered in the analysis.

Material	Temperature/°C	Stress/MPa	Time to rupture/h
Carbon steel	400	294	336324.7[a]
		314	20886.1
		333	19952.6
		353	998.7
1.25Cr–0.5Mo–Si steel	550	53	311940.5[a]
		61	111887.0
		74	85889.2
		88	29801.5
		108	7056.8
		137	1118.1
2.25Cr–1Mo steel	550	69	115274.0[b]
		88	67392.3
		98	24224.4
		108	8013.8
		137	857.0
SUS316 steel	600	88	315972.8[a]
		108	152758.0
		127	61463.9
		137	42079.8
		157	19646.2
		177	11007.5
		216	2444.5

[a] The test is running.
[b] The test was stopped due to accident.

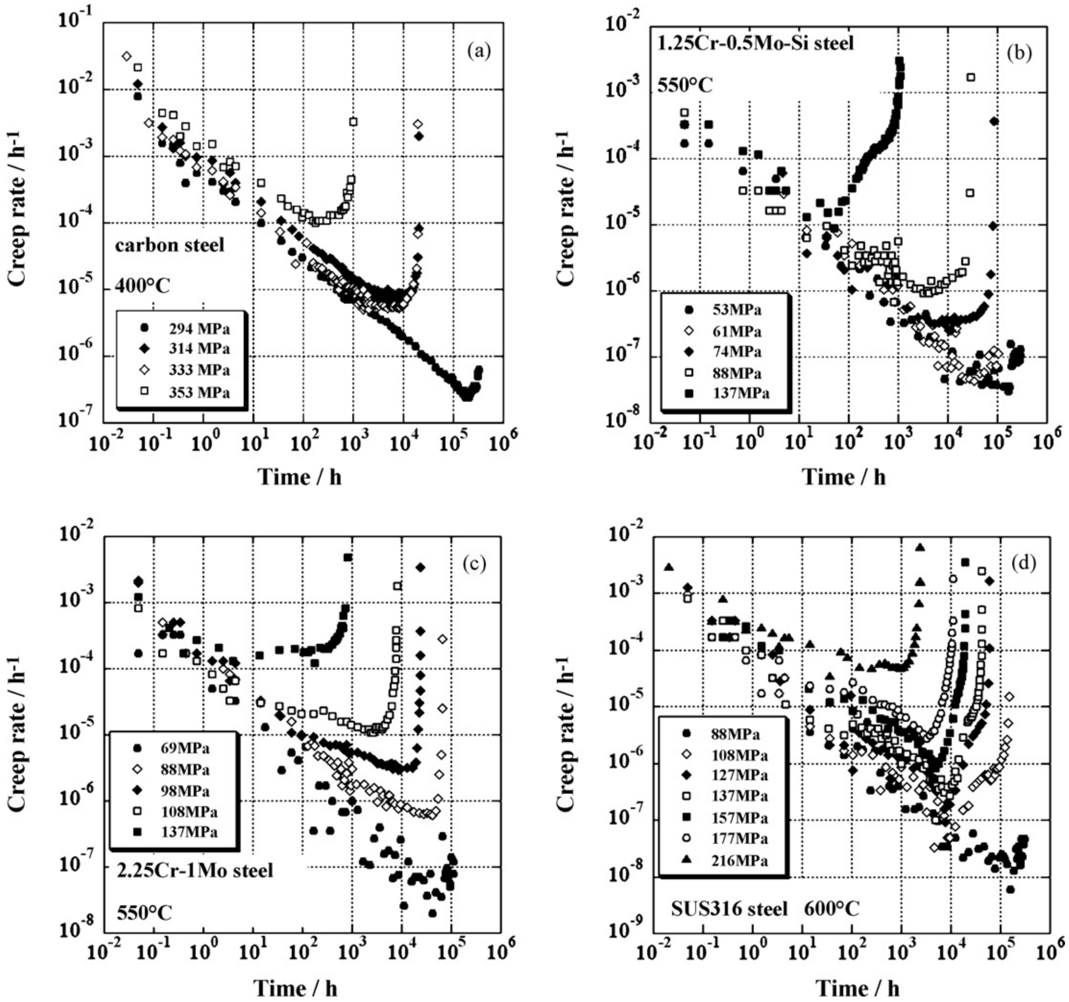

Fig. 1. Creep rate versus time curves under various stresses. (a) Carbon steel, (b) 1.25Cr–0.5Mo–Si steel, (c) 2.25Cr–1Mo steel and (d) SUS316 steel.