Available online at www.sciencedirect.com

ScienceDirect

International Journal of Pressure Vessels and Piping 85 (2008) 423–440

International Journal of Pressure Vessels and Piping

www.elsevier.com/locate/ijpvp

Study on creep-fatigue evaluation procedures for high chromium steels—Part II: Sensitivity to calculated deformation

Yukio Takahashi

Central Research Institute of Electric Power Industry, 2-11-1 Iwado kita, Komae-shi, Tokyo 201-8511, Japan

Abstract

High-chromium steels containing 9–12% chromium such as ASME SA-213 Grade 91 or Grade 122 are widely used in conventional and combined cycle fossil power plants and are also regarded as candidate structural materials for future nuclear power plants aiming at operation in the creep range. Evaluation of failure life under creep-fatigue conditions constitutes an important part of assessing the structural integrity of these plants. The author has been conducting a series of creep-fatigue tests for three types of high-chromium steels and the validity of life prediction methods has been evaluated using the measured deformation data. Here an additional exercise was carried out in order to evaluate the adequacy of the total life prediction procedure, including the process of predicting stress and strain. After making comparisons of the test data with various existing equations developed for describing deformation and failure behaviour of Grade 91 and Grade 122, prediction of creep-fatigue life was attempted using deformation behaviour analytically estimated by these equations. Many calculations revealed that failure lives predicted by the time fraction approach showed a strong dependency on stress relaxation behaviour, whereas those based on the modified ductility exhaustion method showed a much smaller sensitivity, and therefore some error or uncertainty in stress and strain would be tolerated.

Keywords: High-chromium steel; Creep-fatigue; Stress relaxation; Life prediction; Creep damage; Stress analysis

1. Introduction

Increases in steam temperature and pressure in fossil power plants have been strongly pursued worldwide to improve thermal efficiency, which brings about a reduction of fuel costs as well as undesirable gas emissions. To promote this, high-chromium steels such as modified 9Cr–1Mo steel (ASME SA-213 Grade 91), which have higher creep strength and oxidation resistance than conventional steels, have been widely employed in boilers and piping systems in recent conventional and combined cycle fossil power plants [1] and are also regarded as candidate structural materials for the components of future nuclear power plants aiming at operation in the creep range [2,3]. In addition to simple creep rupture [4–7], prediction of failure due to creep-fatigue interaction is one of the most important subjects in assessing the structural integrity of these plants, and many studies have been conducted on this [8–14].

Under this circumstance, the author has been conducting a series of creep-fatigue tests under a wide range of loading conditions for three types of high-chromium steels used in fossil power plants, including Grade 91 and Grade 122. The applicability of several creep-fatigue life prediction methods was evaluated based on measured stress relaxation data [15]. The validity of the modified ductility exhaustion method as well as the non-conservativeness of the time fraction approach has been made clear as a result.

However, analytical procedures need to be employed for estimating stress/strain states in the assessment of actual components, and the total accuracy is determined as a combination of stress analysis and damage estimation [16–19]. Therefore, the overall judgment on the appropriateness of evaluation procedures has to be made taking both processes into account.

For Grade 91 and Grade 122 steels, various equations have been extensively developed for describing deformation and failure behaviour and incorporated into draft design codes targeted at liquid metal cooled fast breeder

---

E-mail address: yukio@criepi.denken.or.jp

0308-0161/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijpvp.2007.11.006

Nomenclature

$t_{(n)}$	time at nth increment
$\Delta t_{(n)}$	time increment between $(n+1)$th and nth increments
$\varepsilon_{c(n)}$	creep strain at nth increment
$\dot{\varepsilon}_c$	creep strain rate at nth increment
$\tilde{\varepsilon}_c(\sigma, t)$	creep strain at time, t, under the constant stress, σ
t^*	equivalent time based on strain-hardening hypothesis
$\sigma_{(n)}$	stress at nth increment
q	elastic follow-up factor
E	Young's modulus

reactor (LMFBR) plants [19–21] in Japan. A creep rupture equation for Grade 122 was recently developed independently and included in the guideline given by the Ministry of Economy, Trade and Industry (METI) [22] for application to life evaluation of piping in fossil power plants.

In this paper, these equations were applied to simulation of the creep-fatigue tests reported in [15] and predicted lives obtained by applying three damage estimation methods to predicted stress-relaxation curves were compared with the experimental lives. Additional calculations were made to evaluate the sensitivity of creep damage to deformation properties of the material.

2. Comparison of existing equations with test data

2.1. Outline

Various equations have been developed in Japan for describing failure and deformation behaviour of P91 [19,20] and a class of 12% chromium steels (including Grade 122) [21] for the purpose of application to LMFBR design. These equations will be used along with a certain analytical procedure for estimating stress and strain in creep-fatigue evaluation of actual plants. In order to assess the life predictability including the effects of these

Table 1
Monotonic stress–strain equation

(a) Grade 91 [19,20]			
$\varepsilon_e = \sigma/E$			
$\varepsilon_p = 0$ when $\sigma \leqslant \sigma_p$,			
$= \{(\sigma - \sigma_p)/K\}^{1/m}$ when $\sigma > \sigma_p$			
T: temperature (°C), $375 < T \leqslant 600$ σ: stress (MPa) ε_e: elastic strain (mm/mm) ε_p: plastic strain (mm/mm)			
E (MPa)	Tabulated value	175,000 MPa at 550 °C 169,000 MPa at 600 °C 161,000 MPa at 650 °C	
σ_p (MPa)	$\sigma_p = \sigma_y - K(0.002)^m$ $\sigma_y = 504.801 - 0.628569T + 0.00225543T^2 - 0.00000308878T^3$		
K (MPa)	$1347.18 - 1.7848T$	m	$0.556244 - 0.000837514T$
(b) Grade 122 [21]			
$\varepsilon_e = \sigma/E$			
$\varepsilon_p = 0$ when $\sigma \leqslant \sigma_p$,			
$= \{(\sigma - \sigma_p)/K\}^{1/m}$ when $\sigma > \sigma_p$			
T: temperature (°C), $375 < T \leqslant 700$ σ: stress (MPa) ε_e: elastic strain (mm/mm) ε_p: plastic strain (mm/mm)			
E (MPa)	Tabulated value	174,000 MPa at 550 °C 168,000 MPa at 600 °C 161,000 MPa at 600 °C	
σ_p (MPa)	$\sigma_p = \sigma_y - K(0.002)^m$ $\sigma_y = 586.67 - 1.22855T + 0.00380109T^2 - 0.00004412155T^3$		
K (MPa)	$1752.88 - 2.36903T$	m	$0.373980 - 0.000490306T$