Engineering Failure Analysis 93 (2018) 317–329

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Phase field analysis and simulation for remaining creep life assessment of H13 steel

Zohair Sarajan, Said Nategh*, Hamidreza Najafi

Department of Materials Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Keywords:
Creep
Remaining life
Microstructures
Simulation tests
Structural steel

ABSTRACT

A traditional phase field model was used to develop and improve the remaining creep life assessment of H13 steel. In this modified phase field model, the microstructure was characterized by order parameter ϕ. The changes of ϕ were considered to be a function of subgrain formation or growth during creep. Due to the linear relationship between yield strength and hardness in steel, hardness was used in equation of motion for studying material flow at steady state creep. Creep tests consist of fracture and 1% creep ductility, were conducted according to ASTM E139 at 500, 550 and 600 °C and stress levels of 872–926.5 MPa. The mechanical properties and microstructural characteristics of H13 steel were examined and used through simulation process.

1. Introduction

Creep life assessment is a major issue in the design and inspection of industrial parts composed of high-temperature alloys. Replacement of critical parts having short life spans is essential to minimizing human and material risk. H13 is a medium-carbon, high-alloy steel which is resistant to hot corrosion and creep [1, 2]. Austenitizing, quenching and double tempering as the main strengthening mechanism of this steel causes martensitic phase transformation and carbide formation (mainly $M_{23}C_6$) around the lath boundary [3–6]. In the tempered martensite the dislocations move into the lath wall and form the cell structure. The dislocation cell structure with embedded fine carbides acts as an obstacle against free dislocation movement and, consequently, the fixed cell walls change to subgrain during creep [7–9]. Their increased tensile and yield strength makes them suitable for applications such as hot shear blades, pipelines for liquids and gases, gate and pressure valves, boilers, high-pressure chambers at temperatures of 500–600 °C [10].

Several models have been developed based on creep tests to estimate the remaining life of alloys [11–19]. However, most of the suggested models do not predict the remaining creep life accurately because they do not consider the microstructural changes including matrix and precipitates evolutions [14, 20, 21]. Therefore, the use of a criterion which is strongly affected by microstructural evolutions play a vital role in developing a model for creep life assessment. Among various mechanical properties, yield strength and hardness are directly affected by microstructural changes. Changes in the yield strength have been used in several studies to estimate the remaining life some alloys [4, 5, 20, 22]. On the other hand; since hardness test can be carried out in situ, non-destructively and more quickly, it seems that the substitution of hardness for yield strength could be an appropriate alternative for creep life assessment [11, 23, 24]. The phase field method is an effective approach employed for modeling the phase transformations involving progressive interface. This method developed by Cahn and Hilliard for free energy of heterogeneous systems [25] and Allen and Cahn for the mobility of anti-phase boundaries [26]. Phase field method depends on phase transformation variables and the

* Corresponding author.
E-mail addresses: zohairsarajan@srbiau.ac.ir (Z. Sarajan), s.nategh@srbiau.ac.ir (S. Nategh), hnajafi@srbiau.ac.ir (H. Najafi).

https://doi.org/10.1016/j.engfailanal.2018.07.010
Received 16 February 2018; Received in revised form 2 May 2018; Accepted 5 July 2018
Available online 17 July 2018
1350-6307/

related free energy changes in a metallurgical process. The Gibbs free energy functional (F) for a heterogeneous system is usually expressed as a function of ϕ, the order parameter, according to Eq. (1):

$$\frac{\partial \phi}{\partial t} = M_{\phi}\left(-\frac{\delta F}{\delta \phi}\right) \tag{1}$$

Where M_{ϕ} can be considered as interface mobility. Moreover, the free energy of the system depends on the free energy density, free energy per unit volume, (f) as expressed by Eq. (2):

$$\frac{\partial F}{\partial \phi} = \frac{\partial f(\phi)}{\partial \phi} - \alpha^2 \nabla^2 \phi \tag{2}$$

Hence:

$$\frac{\partial \phi}{\partial t} = M_{\phi}\left[\alpha^2 \nabla^2 \phi - \frac{\partial f(\phi)}{\partial \phi}\right] \tag{3}$$

α^2 in Eq. (2) is the gradient energy coefficient depending on the changes of free energy density of homogeneous phases with order parameter. With a uniform reduction in energy, the free energy can be used to determine the kinetics of recovery i.e. $\frac{\delta F}{\delta t} \leq 0$. Furthermore, Eq. (1) can be utilized for material flow as a function of applied driving force ($\frac{\delta F}{\delta \phi}$) for steady state process ($\frac{\delta F}{\delta t} = 0$) [27, 28]. The main objective of the present study was to estimate the remaining creep life using hardness evolution during service life of H13 steel. Creep tests and microstructural observations were conducted to evaluate the models employed for predicting the remaining creep life by hardness tests. Furthermore, the mechanical tests results along with microstructural observations were utilized through phase field analysis to simulate the creep process.

2. Materials and methods

2.1. Materials

H13 steel plate with thickness of 1.5 mm and chemical composition given in Table 1 was used for this study. Creep samples were then prepared according to ASTM E139 [29] with the dimensions shown in Fig. 1.

Then, the samples were heat-treated using an argon-controlled atmosphere furnace. The heat treatment was carried out in five steps: (1) Initial heating of the samples to 800 °C with a holding time of 20 min; (2) Austenitizing at 1050 °C for 60 min; (3) Quenching in oil at 25 °C; (4) First tempering at 500 °C and; (5) Second tempering at 500 °C (total time of 120 min for two steps of tempering). Fig. 2 schematically illustrates the thermal cycle utilized for heat treatment [2, 33].

2.2. Creep test

Creep tests were carried out according to ASTM E139 at 500, 550 and 600 °C; and in the stress range of 872–926.5 MPa. While some tests (short-term creep) were continued until rupture of samples, the others were interrupted at the strain of 1% (1% creep ductility). 1% creep ductility tests were performed based on the data obtained by creep fracture tests at the same temperature and stress level. Creep conditions of interrupted tests are given in Table 2. At least three samples were tested under each condition to ensure the quality of the results [30]. Samples obtained in this step are used for tensile and hardness tests.

2.3. Tensile and hardness tests

Tensile tests were performed on creep ductility samples according to ASTM-E8 to determine the yield strength and elastic modulus. Vickers hardness testing was done according to ASTM E92–82 with a test load of 31.25 Kgf at room temperature. The reported hardness values are the average of at least three indentations.

2.4. Microstructural characterization

The microstructures were studied by Olympus optical microscope (OM), Phenom ProX scanning electron microscopy (SEM) equipped with a Silicon Drift Detector (SDD) energy dispersive spectrometer (EDS), Nanosurf Easyscan 2 atomic force microscope (AFM) and JEOL JEM-2100 transmission electron microscope (TEM). OM and SEM were used to study grain size, size and distribution of carbides formation and growth. Contact-mode AFM was used to study the surface topography showing subgrain formation and

Table 1
Chemical composition of tested steel in wt%.

C	Si	Mn	Cr	Mo	V
0.405	0.857	0.377	4.920	1.310	0.939