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Modeling the effect of creep deterioration on magnetic properties in heat-resistant steels

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ABSTRACTS

The hysteresis parameters of the Jiles–Atherton model are modified to elucidate the variation of magnetic properties with creep deterioration based on a consideration of the effect of pinning of magnetic domain walls on the grain boundaries, dislocations as well as precipitates in short-term creep process. Experiments are carried out to evaluate the magnetic hysteresis curves of 10CrMo910 specimens with controlled levels of creep-induced damage. An intelligent optimization algorithm is used to determine the hysteresis parameters of Jiles–Atherton model. The microstructure parameters of the crept specimens are determined by a quantitative metallographic analysis. The modified model is applied to correlate the experimental data of both 10CrMo910 and 410 stainless steel creep specimens. The calculated results are in good agreement with the measured data of the hysteresis parameters.

1. Introduction

The long term and safe operation of the high temperature plants is generally limited by creep damage. Non-destructive evaluation (NDE) techniques have been thus employed to detect the damage. As many ferromagnetic steels have been used in high temperature components, the magnetism-based NDE may possibly be developed by taking advantages of magnetic characteristics. During the last decade, some results have been obtained to describe the relation between microstructure features and magnetic properties such as coercivity and remanence [1–4]. For high temperature applications, however, doubts persist due to the lack of a strong correlation between measured parameters and creep damage [5,6]. Chen et al. [7] predicted the trend of the magnetic property of Cr–Mo steel creep specimen by simply changing two parameters in the Jiles–Atherton (J–A) model, but the quantitative study of how the magnetic signals change with the progress of the creep damage was not given.

The impedance to the changes in magnetization is provided by pinning sites inside the solid in the form of imperfections like grain boundaries and inhomogeneities within a grain, such as dislocations and precipitates, which oppose the motion of domain walls [8]. Therefore, the hysteretic behavior of magnetic properties is directly affected by the microstructure evolution. Research shows that magnetic domain structure in ferrite phase of 10CrMo910 specimens consists of stripe pattern for as-received one, and turn to maze pattern for the crept one due to microstructure evolution [9]. It can also be found in literature [10,11] that the observed microstructure evolution plays an important role in the variations of magnetic domain structure and magnetic properties in creep specimens of the heat-resistant steel after creep. However, these effects have not yet been taken into account in the theoretical modeling of magnetic hysteresis.

In the present work, the J–A model is hence modified to take into account the effect of microstructure changes during creep on the magnetic property. To verify the modified model, magnetic measurements are preformed first on the heat-resistant steel specimens with different levels of creep damage. Then numerical determination of hysteresis parameters for the J–A model is carried out. Furthermore, quantitative metallographic analysis is made to evaluate the microstructure evolution of each crept specimen and determine the microstructure parameters related to dislocations, grain size and precipitations. Finally, a comparison of the experimental results with the modified model calculations is discussed.

2. The model

2.1. Magnetic hysteresis model

The J–A model is now widely accepted and has been applied to incorporate microstructural changes [8,12]. The differential

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Nomenclature

M	magnetization
H	magnetic field intensity
H_e	effective field
M_{an}, M_{irr}	anhysteretic magnetization, irreversible magnetization
M_s	saturation magnetization
k	domain wall pinning parameter
a	effective field scaling parameter
c	reversible parameter
α	domain coupling parameter
δ	directional parameter
d	average grain diameter
ρ	dislocation density
f_p, D_m	volume fraction, mean diameter of precipitation
t/t_r	creep life fraction
G_1, G_2, G_3, G_4	constants in Eqs. (3) and (4)

susceptibility according to the J–A model can be expressed as follows:

$$\frac{dM}{dH}=(1-c)\frac{M_{an}-M_{irr}}{k\delta-\alpha(M_{an}-M_{irr})}+c\frac{dM_{an}}{dH} \quad (1)$$

where M_{an} is the anhysteretic magnetization, which follows the Langevin function

$$M_{an}=M_s\left(\coth\left(\frac{H_e}{a}\right)+\left(\frac{a}{H_e}\right)\right) \quad (2)$$

The five parameters of J–A model are domain coupling α, domain density a, pinning site density and pinning site parameter k, reversible coefficient c, and M_s. The directional parameter δ takes the value $+1$ when H increases and -1 when H decreases. And $H_e=H+\alpha M$is the effective field taking into account the domain interactions.

2.2. Modeling the effects of creep on magnetic properties

Sablik [13–16] found that there exists a relationship between microstructure features of steels and material parameters in the J–A mode. The pinning effects and effective field scaling parameter follow the following equations:

$$k_i=k_0\left(G_1+\frac{G_2}{d}\right)\sqrt{\rho} \quad (3a)$$

$$a_i=a_0\left(G_1+\frac{G_2}{d}\right)\sqrt{\rho} \quad (3b)$$

where G_1 and G_2 are constants. The remaining parameters in the J–A model are independent of average grain size d and dislocation density ρ. The equations allow the prediction of magnetic properties after mechanical testing under room temperature. However, it is questionable whether the equations can be used for materials after high temperature creep.

It is widely accepted that the dominant deformation mechanism changes with creep test condition, diffusion creep and power law (dislocation) creep are dominant in the low and intermediate stress regimes, respectively in the deformation mechanism maps [17]. The deformation mechanism of the steel specimens which are processed with accelerated creep test under high stress is mainly dislocation creep. The time of the whole accelerated creep test is usually so short that dislocation structure as well as precipitation undergoes considerable change all along. The impedance which is so called pinning sites to changes in magnetization is assumed to be uniform in establishing the hysteresis model. As indicated by Kronmuller and Fahnle, the coercivity is also proportional to the square root of number density of the non-magnetic pinning particles in the metal materials [18]. In addition, the number density of precipitates can be substituted by a function of volume fraction and mean diameter of the precipitates based on the McCall–Boyd's metallographic theory [19], the equations for pinning parameter and effective field scaling after the short-term creep should be modified as follows:

$$k_i=k_0\left(G_1+\frac{G_2}{d}\right)\sqrt{\rho}\frac{\sqrt{f_p}}{G_3D_m^{3/2}} \quad (4a)$$

$$a_i=a_0\left(G_1+\frac{G_2}{d}\right)\sqrt{\rho}\frac{\sqrt{f_p}}{G_4D_m^{3/2}} \quad (4b)$$

where f_p is the parameter for the volume fraction of the precipitates, D_m the particle mean diameter, G_3 and G_4 are constants.

3. Materials and experiments

3.1. Creep test

The chemical compositions of the as-received heat resistant steel 10CrMo910 cut out from pieces of a steam pipe $\Phi273\times28$ mm^2 are listed in Table 1. Samples cut from 10CrMo910 piping component were machined into standard tensile specimens with a diameter of 10 mm and a gauge length of 100 mm (Fig. 1) according to China National Standards of GB/T 2039-1997 (equivalent to ISO 204:1997). Accelerated creep tests were carried out in air at a temperature of 560 °C under constant tensile load of 190 MPa. Creep test under the stress of 190 MPa was carried out until the specimen fractured, the rupture time t_r was 157 h. Another three specimens were tested under the same load and temperature but with different testing hours which were 0 h, 40 h, and 100 h, corresponding to a creep expended life fraction t/t_r of 0, 0.25, and 0.63. The interrupted creep tests are stopped by furnace cooling.

3.2. Microstructure characterization

The samples for microstructure evaluation were cut from the uniform deformation area of the crept specimen, and all samples were milled, polished and etched with an etchant of alcohol solution 4% of nitric acid (volume fraction). A scanning electron microscope (SEM, with type of ZEISS EVOMA 15) was used for metallographic observations. Optical micrographs (OM, ZEISS) for each specimen were taken, and then examined by an image analyzer to measure the grain size. A transmission electron microscope (TEM, H-800 Hitachi type) was used for observing the dislocation variations within thin film specimens which were prepared by twin jet electron-polishing in an electrolyte containing

Table 1
Chemical composition of as-received 10CrM910 (wt%).

Sample	C	Si	Mn	P	S	Cr	Mo
10CrMo910	0.10	0.25	0.49	0.008	0.010	2.35	1.09