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Creep constitutive equation of dual phase 9Cr-ODS steel

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Abstract

9Cr-ODS (oxide dispersion strengthened) steels developed by JAEA (Japan Atomic Energy Agency) have superior creep properties compared with conventional heat resistant steels. The ODS steels can enormously contribute to practical applications of fast breeder reactors and more attractive fusion reactors. Key issues are developments of material processing procedures for mass production and creep life prediction methods in present R&D. In this study, formulation of creep constitutive equation was performed against the backdrop. The 9Cr-ODS steel displaying an excellent creep property is a dual phase steel. The ODS steel is strengthened by the δ ferrite which has a finer dispersion of oxide particles and shows a higher hardness than the α' martensite. The δ ferrite functions as a reinforcement in the dual phase 9Cr-ODS steel. Its creep behavior is very unique and cannot be interpreted by conventional theories of heat resistant steels. Alternative qualitative model of creep mechanism was formulated at the start of this study using the results of microstructural observations. Based on the alternative creep mechanism model, a novel creep constitutive equation was formulated using the exponential type creep equation extended by a law of mixture.

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1. Introduction

9Cr-ODS steels developed by JAEA have superior creep properties compared with conventional heat resistant steels. The creep rupture strength (1000 h at 973 K) is about 10 times greater than conventional heat resistant steels [1–5]. The steel can enormously contribute to practical applications of fast reactors and more attractive fusion reactors [6–9]. The superior creep property results from a high number density of small Y–Ti–O and/or Ti–O oxide particles dispersed in the matrix. These particles improve the creep property by pinning and piling up moving dislocations at elevated temperatures. In most of researches on ODS steels, material designs and material processing procedures were accordingly focused to finely disperse oxide particles. Few studies on the creep mechanism are reported [1,6,9] using the power law type equation. Stress exponent values can explain simple creep mechanisms. However, detailed creep mechanisms cannot be interpreted. The power law type equation is an empirical rule and has few physical meanings. Our researches reveal that the 9Cr-ODS steel has an excellent creep property is a dual phase steel which is consist of δ ferrite and α' martensite. [1–5]. The ODS steel has very unique creep behaviors, which were not observed in conventional heat resistant steels. Analyses using the power law type equation cannot consequently

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Nomenclature

List of symbols

α'	martensite
δ	delta ferrite
σ	applied stress
σ_y	yield stress
$\sigma_{0.2}$	0.2% proof stress
$\sigma_{y,i}$	yield stress in i phase ($i = \alpha'$, δ)
$\sigma_{0.2,}$	0.2% proof stress in i phase ($i = \alpha'$, δ)
f_δ	volume fraction of delta ferrite
HV_i	Vickers hardness in i phase ($i = \alpha'$, δ)
R	gas constant
T	temperature in K
$\dot{\varepsilon}$	macroscopic creep strain rate
$\dot{\varepsilon}_i$	creep strain rate in i phase ($i = \alpha'$, δ)
$\dot{\varepsilon}_{\mathrm{disl.},\alpha'}$	dislocation gliding creep strain rate in α'
$\dot{\varepsilon}_{\mathrm{g.b.s.},\alpha'}$	grain boundary sliding creep strain rate in α'
$\dot{\varepsilon}_0$	constant
$\dot{\varepsilon}_{0,i}$	constant in i phase ($i = \alpha'$, δ)
t_{r0}	constant
$t_{r0,i}$	constant in i phase ($i = \alpha'$, δ)
Q	activation energy in the absence of applied stress
Q_i	activation energy in the absence of applied stress in i phase ($i = \alpha'$, δ)
Q_d	activation energy for self-diffusion
$Q_{d,i}$	activation energy for self-diffusion in i phase ($i = \alpha'$, δ)
Q_{int}	elastic interaction energy between movable dislocations and obstacle dislocations
$Q_{\mathrm{int},i}$	elastic interaction energy between movable dislocations and obstacle dislocations in i phase ($i = \alpha'$, δ)
V	activation volume
V_i	activation volume in i phase ($i = \alpha'$, δ)
μ	shear modulus
μ_i	shear modulus in i phase ($i = \alpha'$, δ)
p	characteristic parameter for obstacle dislocation
p_i	characteristic parameter for obstacle dislocation in i phase ($i = \alpha'$, δ)
d	spacing of obstacle dislocations
d_i	spacing of obstacle dislocations in i phase ($i = \alpha'$, δ)
b	length of Burger's vector
v	Poisson's ratio
r_0	length between the nearest neighbor atoms
d/p	EOS: equivalent obstacle spacing
d_i/p_i	EOS: equivalent obstacle spacing in i phase ($i = \alpha'$, δ)

give available information to completely study the creep mechanism. Alternative creep mechanism should be studied using results of microstructural observations, and novel analysis method should be established for the dual phase 9Cr-ODS steel. In addition, R&D on fast reactor fuel cladding tubes is moving to performance demonstrations from material and fuel pin system developments. Key issues are developments of material processing procedures for mass production and creep life prediction methods in the present step.

In this study, formulation of a creep constitutive equation based on detailed microstructural observations was performed to develop reliable life prediction methods against the backdrop.

2. Experimental procedure

The chemical composition of the dual phase 9Cr-ODS steel, as shown in Table 1, was prepared by MA (mechanical alloying) of argon-gas-atomized pre-alloyed metal powder along with Y_2O_3 powder in a high-energy attritor in an argon atmosphere for 48 h at 220 rpm (revolutions per minute). MA powder was then degassed at 673 K in vacuum (0.1 Pa), after which it was canned in mild steel and hot extruded at 1423 K into bar. This bar was drilled and machined to form a cladding tube with real dimension of 8.5 mm outer diameter and 0.5 mm thickness [1]. Normalizing and tempering conditions are 1323 K × 1 h/AC (air cooling) and 1073 K × 1 h/AC, respectively. Creep rupture tests were conducted at 923 and 973 K in air. The dimensions of the specimen used are shown in Fig. 1. This specimen was made from the cladding tube. These creep property data are for specimens taken in the extrusion direction. Vickers hardness tests were performed to investigate hardnesses (yield strengths) in each of matrixes. Microstructural observations were performed using SEM (scanning electron microscope), EPMA (electron probe micro analysis), and TEM (transmission electron

Table 1
The chemical composition of the dual phase 9Cr-ODS steel

	C	Cr	W	Ti	Y	O	Fe	Y_2O_3
(wt%)	0.14	8.9	2.0	0.20	0.27	0.16	Bal.	0.34

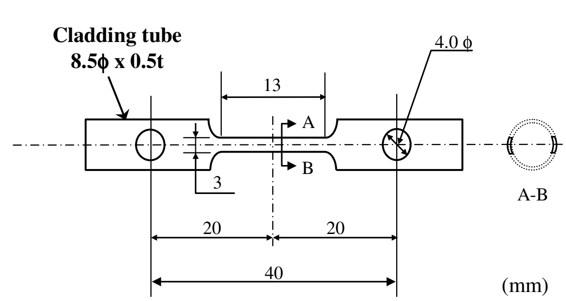

Fig. 1. The specimen dimensions.