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Experimental and numerical simulation analysis on creep crack growth behavior of CLAM steel

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ABSTRACT

The experiment and numerical simulation were performed to analyze the creep crack growth behavior of China Low Activation Martensitic (CLAM) steel under temperatures ranging from 500 °C to 600 °C with a step of 50 °C. The creep crack growth micro-mechanism under multiaxial state of stress was investigated with the compact tension (CT) specimens. The creep crack growth rates were simulated based on the Nikbin-Smith-Webster (NSW) model. The difference of the crack propagation behavior is correlated with the evolution of two types of precipitates: Cr-rich $M_{23}C_6$ and W-rich M_6C phases. The coarsening of $M_{23}C_6$ carbides and the precipitation of M_6C phase particles lead to dissolving of the solid solution elements and deteriorating the creep properties during the testing processes.

1. Introduction

Fusion energy can provide a CO_2 emission-free, sustainable energy, and has been considered as a radical option for the future energy requirement [1–4]. Reduced Activation Ferritic-Martensitic (RAFM) steels are considered as one kind of structural materials for the future fusion reactor for their high resistance to irradiation swelling, low-activation features, good thermal properties and mature industrial base [5–7]. China Low Activation Martensitic (CLAM) steel [8–12], one kind of the RAFM steels, was developed at the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences. It has been chosen as the candidate structural material for the China test blanket module of ITER (ITER CN TBM), and the breeder blanket of the China fusion engineering test reactor.

The operating temperature faced by the RAFM steel in the fusion system is about 500 °C for a long time; therefore, the viscoplastic performance of materials has become a crucial consideration in order to prevent creep failure [13,14]. In the past years, the creep rupture behavior under uniaxial stress state of the RAFM steel has been studied by many researchers [15–19]. However, the different loading conditions and geometric discontinuity generate multi-axial stress state in the components [20]. It is therefore necessary to investigate the creep deformation behavior under the multiaxial stress state in order to understand the creep failure mechanisms and to predict the life of high temperature components in the future fusion reactors [20]. The creep crack growth tested with the compact tension specimens is an effective way to study the crack formation and crack growth behavior under the multi-axial stress state [21,22]. The creep crack initiation time and the crack propagation rate are important contents for the structural integrity assessment of the components in the nuclear reactor [23].

In the current research, the CLAM steel was studied with the compact tension (CT) specimens to determine the creep crack growth behavior under different testing conditions. The creep crack growth rate was stimulated based on the Nikbin-Smith-Webster (NSW) model with the results of a single uni-axial creep test. The propagation process of the creep crack was explained based on the change of microstructure near the crack tip.

2. Experimental

The research material is the CLAM steel (HEAT 0912). The main chemical compositions are listed in Table 1. The specimens were normalized at 980 °C for 30 min and tempered at 760 °C for 90 min, both followed by air cooling. The creep crack growth specimen was fabricated based on ASTM E 1457 [24] with a thickness of 10 mm, as shown in Fig. 1. A side-grooved with 20% of the thickness was introduced to constrain the crack growth route in the specimen. The detail parameters of creep crack growth experiments are shown in Table 2.

The fracture morphology at different test conditions was analyzed with Zeiss Sigma SEM Scanning Electron Microscope (SEM) operated at 15 kV to expound the mechanisms of the creep crack growth process. The microstructures of the CLAM steel before and after the test were

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Table 1
The main chemical compositions of the steel (wt%).

Element	Cr	W	Mn	V	Ta	C	N	Fe
Content	8.86	1.48	0.48	0.21	0.12	0.094	0.011	Bal.

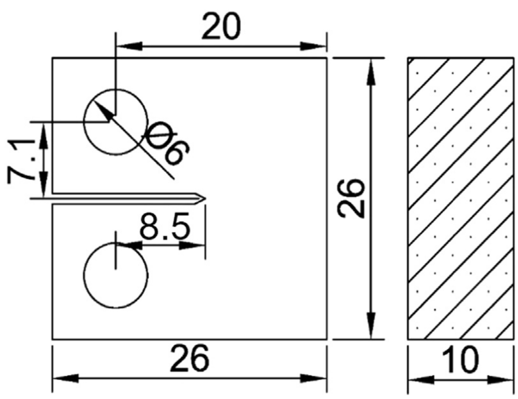

Fig. 1. The geometry and dimensions of the compact tension specimen (unit: mm).

Table 2
The parameters of creep crack growth experiment.

Sample No.	Temperature (°C)	Load (N)	Pre-crack length (mm)	Initial stress intensity factor (MPa $m^{1/2}$)
CT1	500	5, 000	2.50	49.16
CT2	550	4, 000	2.43	32.68
CT3[a]	550	4, 000	2.50	33.05
CT4	550	5, 000	2.58	41.91
CT5	550	6, 050	2.51	50.05
CT6	600	3, 650	2.48	30.10

[a] CT3 was suspended at 666.95 h to analyze the behavior of crack propagation.

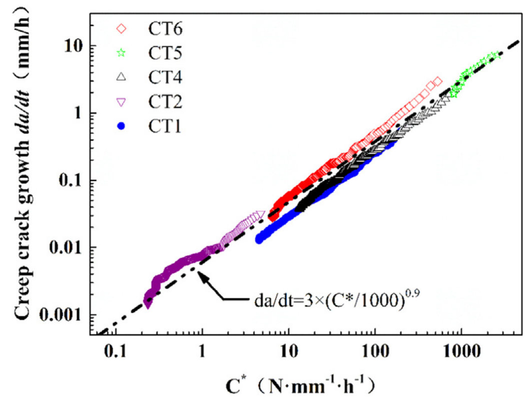

Fig. 3. The creep crack growth rate vs. C* at different testing conditions.

observed with an FEI Tecnai G2 F20 S-TWIN Transmission Electron Microscope (TEM) operated at 200 kV, the precipitates were identified based on the metallic elements composition measured by the Energy Dispersive Spectrometer (EDS). The dislocation density was analyzed with the line intersection method [25], and the precipitates were counted based on the method described in Ref. [26].

3. Results and discussion

3.1. Creep crack growth behavior

The creep crack length and the creep crack growth rate versus time under different testing conditions are given in the review literature [8] to introduce the research progress of CLAM steel. There are three different stages during the creep crack growth process: the crack incubation period, the steady growth period and the accelerated growth period. The incubation period increases with reducing the applied stress and the testing temperature and the initial crack growth rate increases with the increasing of the testing temperature and initial loading. The incubation period has been considered as the progress to build up creep damage to a steady state distribution at the crack tip. Increasing the

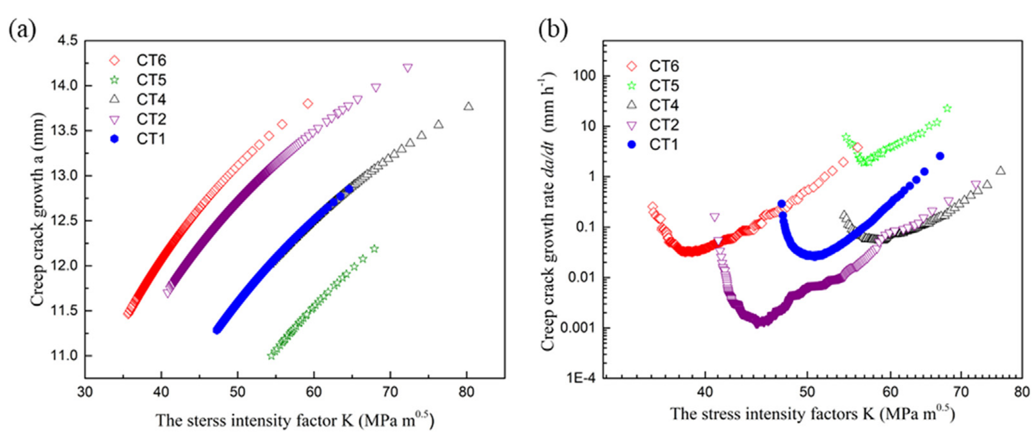

Fig. 2. Creep crack length (a) and creep crack growth rates (b) vs. the stress intensity factor at different temperatures and loads.

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