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Fracture toughness and fracture behavior of CLAM steel in the temperature range of 450 °C–550 °C

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ABSTRACT

In order to analyze the fracture toughness and fracture behavior (J-R curves) of China Low Activation Martensitic (CLAM) steel under the design service temperature of Test Blanket Module of the International Thermonuclear Experimental Reactor, the quasi-static fracture experiment of CLAM steel was carried out under the temperature range of 450 °C–550 °C. The results indicated that the fracture behavior of CLAM steel was greatly influenced by test temperature. The fracture toughness increased slightly as the temperature increased from 450 °C to 500 °C. In the meanwhile, the fracture toughness at 550 °C could not be obtained due to the plastic deformation near the crack tip zone. The microstructure analysis based on the fracture topography and the interaction between dislocations and lath boundaries showed two different sub-crack propagation modes: growth along 45° of the main crack direction at 450 °C and growth perpendicular to the main crack at 500 °C.

1. Introduction

Nuclear fusion is a promising energy producing way in solving the energy crisis with producing abundant clean energy in the future. Reduced Activation Ferritic-Martensitic (RAFM) steel will be used as structural material for the Test Blanket Module (TBM) in the ITER and prospective demonstration reactor due to its high resistance to radiation and low activation features, good strength and thermal conductivity, and mature industrial base [1,2]. CLAM steel has been considered as a top prospect as the structural material for Helium Cooled Ceramic Breeder (HCCB) TBM of ITER in China and blanket for China Fusion Engineering Test Reactor (CFETR) [3–5].

The chemical composition optimization [6,7] and service mechanical properties [8] of CLAM steel have been investigated to evaluate the performance under the design service environment. Among these mechanical properties, fracture toughness is a prerequisite for the material applied to ITER TBM based on the French nuclear reactor construction code [9,10] and a critical technical indicator of damage tolerance design. The fracture behavior of CLAM [11], F82H [12–15] and Eurofer 97 [16] has been studied in room temperature with different loading conditions, however, the facture toughness under the design service temperature has not been covered thoroughly. The service safety of fusion reactor requires a thorough understanding of the fracture toughness and fracture behavior of the material.

The object of this research is to examine the fracture toughness and investigate fracture mechanism of CLAM steel under the design service temperature of ITER. The *J-R* curves were established at 450 °C and 500 °C, respectively, and then the fracture toughness $J_{0.2}$ was determined. The fracture morphology and microstructure after fracture test were analyzed to clarify the mechanism of fracture process.

2. Experimental

2.1. Material

The samples used in this study are from a 55-mm thickness plate of CLAM (HEAT 1506), which is a 6.4-ton ingot fabricated in June 2015. The chemical compositions of the heat are listed in Table 1. Its final heat treatment involved CLAM steel plate was received after normalizing at 1000 °C for 40 min followed with water cooling, and tempering at 740 °C for 90 min followed with air cooling. The tensile properties of CLAM steel at different temperature are listed in Table 2.

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Table 1
Chemical compositions of CLAM (HEAT 1506) (wt %) used in the study.

Cr	W	Ta	V	C	Si	Mn	P	S	O	Fe
9.11	1.52	0.20	0.19	0.12	0.03	0.41	0.003	0.003	0.001	Bal.

Table 2
The tensile properties of CLAM steel at different temperatures.

Temperature °C	Ultimate tensile stress MPa	Yield stress MPa	modulus of elasticity GPa	Elongation after fracture (%)
20	738	608	218	20.5
450	552	496	190	17
500	470	420	177	19.5
550	445	424	161	23.5

Fig. 1 showed the tempered martensitic microstructure of CLAM (HEAT 1506). It is characterized by prior austenite grain boundaries and martensitic laths with 0.24 ± 0.05 μm in width. For the secondary phases, mainly two different types of precipitates (Fig. 1b) have been identified, i.e. Cr rich $M_{23}C_6$ precipitates and Ta or V rich MX precipitates [17]. The $M_{23}C_6$ precipitates were with a size of approximately 125 ± 20 nm, which preferentially located along the grain and lath boundaries, and only a small amount distributed in the subgrains. While, MX precipitates, with sizes ranging from 8 to 40 nm, mainly situated inside the subgrains.

2.2. Methods

The experiment was carried out under the temperatures of 450 °C, 500 °C and 550 °C to study the fracture behavior of CLAM steel under the TBM of ITER operation environment. During the tests, the temperature of specimen was controlled within 1 °C deviation from the setting value. The compact tension specimens with 25 mm thickness were manufactured along transverse-longitudinal orientation according to the international standard ISO 12135 [18], the sample size was shown in Fig. 2. The specimens were pre-cracked at room temperature (RM) with a MTS Landmark 370.10 machine with a frequency of 20 Hz. The target crack length at the end of pre-cracking was 30 mm. The pre-cracking was carried out under the stress intensity factor K decreasing mode. A 19 MPa*m$^{0.5}$ initial stress intensity factor was applied, the stress intensity factor range ΔK (=$K_{\max}$ - $K_{\min}$) was gradually decreased during the crack propagation as prescribed in ISO standard. J tests were carried out through multiple-specimen procedure with the same MTS Landmark 370.10 machine. At least 6 specimens were loaded to selected displacement levels and the corresponding amounts of crack extension to provide the point on the J-R curves. The load-displacement curve was monitored by the high-resolution crack opening displacement gauge, as shown in Fig. 3. The applied load P and corresponding, load line displacement, and crack extension length were on-line recorded with the data acquisition software integrated with the test machine. The samples were then broken after testing with static tension method to determine the crack length occurred during the test. The initial crack lengths a_o and stable crack extension a_f were determined by means of the nine-point average method prescribed in ISO 12135. The typical example of fracture photograph which was tested at 500 °C in present work with SEM was shown in Fig. 4, which revealed precracked zone, stretched zone and quick fracture tested region [18].

2.3. Microstructure

Fracture surface of the samples was rinsed in alcohol with an ultrasonic wave cleaner before observed in a Zeiss Sigma SEM operated at 15 kV. The TEM samples were cut under the fracture surface with 1 mm to avoid the plastic deformation influence. These TEM samples were sliced up to disks with a diameter of 3 mm, grounded to a thickness of about 80 μm and finally electropolished in an electrolyte containing 90% alcohol and 10% perchloric acid by volume at −20 °C. At last, these specimens were observed with a FEI Tecnai G2 F20 S-TWIN TEM operated at 200 kV.

3. Results and discussion

3.1. Fracture toughness

The crack extension data at 550 °C were listed in Table 3, which was too short to analysis the fracture toughness. This may be due to the strength decreased at this testing condition, and the plastic deformation was the mainly mechanical behavior, rather than crack propagation, occurred in the crack tip zone. The similar behavior has been found in the modified 9Cr-1Mo [19]. Therefore, the C^* parameter (i.e. the creep crack growth parameter) may be more suitable for describing the crack growth behavior when the temperature exceeds 550 °C.

The J-R curves of CLAM steel at 400 °C and 500 °C were shown in Fig. 5. For CLAM steel with high work hardening behavior [20], the fracture toughness values of $J_{0.2}$ was determined as the intersection intercept point of 0.2 mm offset from blunting line $J = 3.75 R_m \Delta a$ with the J-R curves. The J values were calculated with the equations listed as followed:

$$J = \left[\frac{F}{(BB_N W)^{0.5}} g_2\left(\frac{a_0}{W}\right)\right]^2 \bullet \frac{1-\nu^2}{E} + \frac{\eta_p U_p}{B_N (W - a_0)} \bullet \left[1 - \frac{\left(0.75\eta_p - 1\right)\Delta a}{W - a_0}\right], \quad (1)$$

$$g_2\left(\frac{a_0}{W}\right) = \frac{\left(2+\frac{a_0}{W}\right)\left[0.884 + 4.64\frac{a_0}{W} - 13.32\left(\frac{a_0}{W}\right)^2 + 14.72\left(\frac{a_0}{W}\right)^3 - 5.6\left(\frac{a_0}{W}\right)^4\right]}{\left(1-\frac{a_0}{W}\right)}, \quad (2)$$