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Numerical Simulation of Creep Crack Propagation for Austenitic Stainless Steel 0Cr18Ni9 at 550°C

Lijie Chen[a], Zunqun Gong[b] and Qi Zhao[c]

School of Physics and Mechanical & Electrical Engineering, Xiamen University,

Xiamen, 361005, China

[a]chenlijie@xmu.edu.cn, [b]gzqhnn@163.com, [c]zhaoqi19850827@163.com

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Abstract. First, tensile creep curve and creep propagation tests are conducted for austenitic stainless steel 0Cr18Ni9, *i.e.* 304 stainless steel at 550°C. The corresponding time hardening creep law is given for stresses ranging from 240 to 320 Mpa and the creep crack propagation length under a tension load of 10kN is measured by using QUESTAR long focus microscope system. Second, with the commercial finite element (FE) code ANSYS, the critical crack tip opening displacement (CTOD) is considered as crack propagation criterion to simulate the creep crack growth in the standard compact tension (CT) specimen. The FE predictions of the creep crack length in the primary and secondary stages are found to agree reasonably with the experimental results. The maximum computational error between the predictions and the experiment results is within 10%. Hence, the critical CTOD is a feasible criterion for crack growth simulations at elevated temperatures.

Introduction

Austenitic stainless steel 0Cr18Ni9 has excellent mechanical properties, corrosion resistance and heat resisting property. It is widely used in chemical industry, petroleum industry and nuclear power plant, etc. For components operating at high temperatures, creep fracture is a main failure mode, which should be considered in the design of high-temperature structures, such as aircraft engine components, nuclear reactor components and steam turbines. Therefore, the experiments and predictions of creep crack growth behavior are fundamental works for safety assessment of structures containing flaws.

With the rapid progress of computer science, the FE method becomes a main prediction method of mechanical behaviors of materials. For high-temperature fracture behaviors, because of the high experimental expenditure, the FE simulation becomes a useful method for researchers. Saxena A *et al* [1] used a node-release approach to model crack growth under creep conditions. By using the FE analysis for CT specimen, Masataka Yatomi *et al* [3] simulated creep crack growth in 316H stainless steel at 550°C. With the FE code ABAQUS, Zhao LG *et al* [2] simulated creep crack growth at 650°C in a standard CT specimen for an elastic/power-law creeping material, a nickel base superalloy. Crack tip parameters, such as stress intensity factor K, C^* integral and $C(t)$ parameter, have been used in most simulations of creep crack growth [2,4,5]. The parameter of crack tip opening displacement (CTOD) is rarely used. From FE simulations of creep crack growth for a nickel base superalloy, Xia *et al* [4] found that the critical value of the CTOD is independent of the initial crack length, the load level and the amount of creep crack growth. Therefore, CTOD is a suitable parameter for simulations of creep crack growth.

In this paper for austenitic stainless steel 0Cr18Ni9, combining with the associated high-temperature experiments, we simulate its creep crack growth behavior with the FE method for a standard CT specimen to illustrate the validity of critical CTOD as a crack growth criterion under creep conditions.

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Material, Specimen and Testing

The chemical composition of austenitic stainless steel 0Cr18Ni9 is given in Table 1. Rods of superalloy GH4049 are used in the heat treatment state. For tensile creep tests, the initial dimension of specimen is: the diameter 6mm and the gauge 50mm, and the applied stresses range from 240 to 320 Mpa. For the creep crack growth test, the standard CT specimen is used and pre-crack length formed by cyclic loading is 5.578mm. Creep crack growth test is performed by using Instron 8560, an electro-hydraulic servo-controlled fatigue testing machine, and the crack growth length is directly measured by QUESTAR long focus microscope system. The applied tension load is P=10kN and the testing temperature is 550°C. The geometry of the CT specimen is shown in Fig. 1 and the thickness B=12.5mm. The testing system is shown in Fig. 2.

Table 1. Chemical composition (*wt.*%) of 0Cr18Ni9

C	Si	Mn	P	S	Ni	Cr	Fe
0.05	0.65	1.57	0.31	0.025	8.02	15.57	Bal.

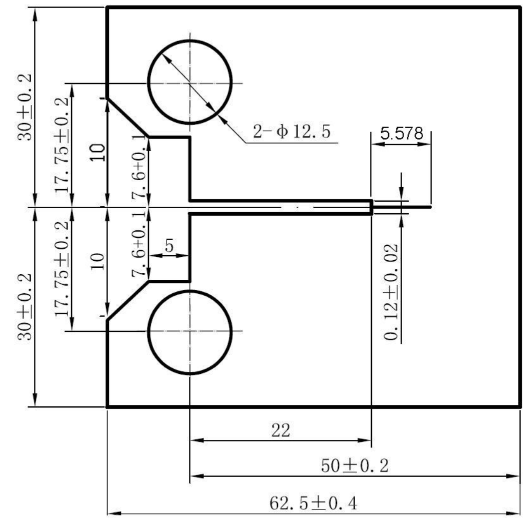


Fig.1. Geometry of CT specimen

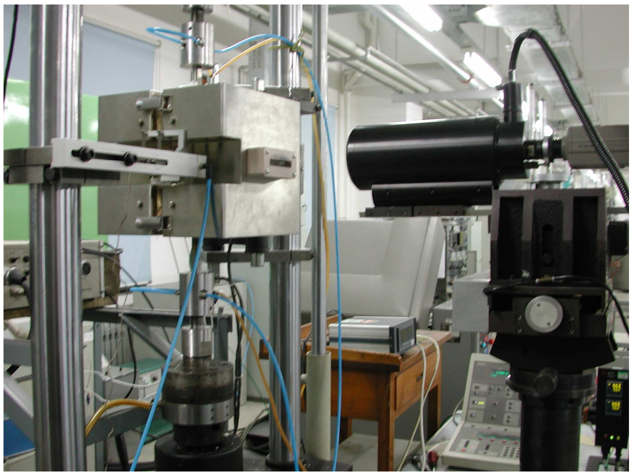


Fig.2 Testing system

Testing Results

Creep curves at different stress levels are presented in Fig. 3. From Fig.3, there obviously exists steady state creep stage at each stress level. The steady state creep rate increases with the increase of the stress. From the testing data, according to the time hardening creep equation, the total strain ε is given as follows:

$$\varepsilon = 8.603\times10^{-11}\sigma^{4.15}t^{0.196}e^{-2909.98/T} - 0.004\sigma^{-0.511}te^{-1898/T} \quad (1)$$

where σ is the applied stress, T the temperature, and t the creep time, which have the units of *Mpa*, *K*, and *h*, respectively. Eq. (1) is used for the FE simulation of creep crack growth behavior.

Fig.4 shows the relationship between the load-line displacement and the loading time, and the relationship between the creep crack growth length and the loading time. Here, the total crack length is equal to the sum of the initial cutting notch depth 22mm and the creep crack growth length in Fig. 4.

Finite Element Analysis

The finite element simulation is performed by using the commercial FE code ANSYS. The material properties are as follows: elastic modulus E=149.103GPa, Poisson's ratio v=0.3.

Because of the symmetry of the geometry and the applied load, the FE model is generated for half a CT specimen by using 4-node element, plane 182, with two degrees of freedom at each node. The FE mesh is shown in Fig.5. The elements size in front of the crack tip is set as 0.005mm. In total, there are 6407 elements and 6851 nodes.

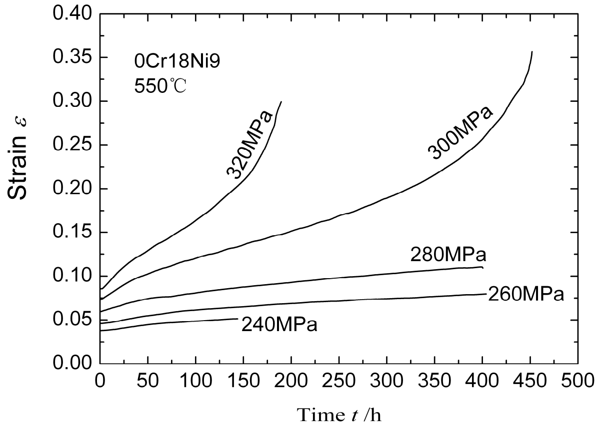


Fig.3. Creep curve of 0Cr18Ni9 at 550° C

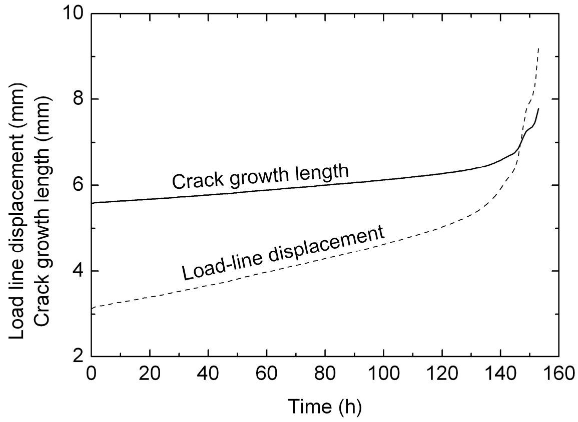
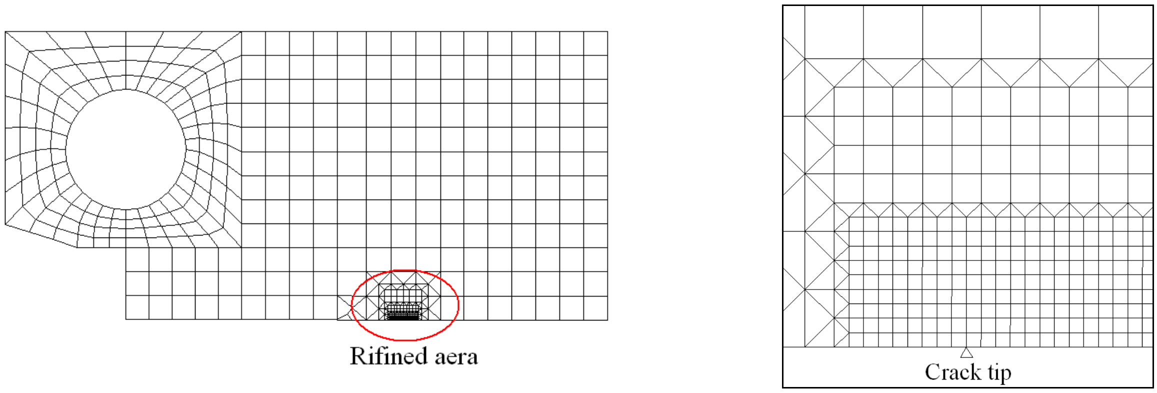


Fig. 4. Load-line displacement and the crack growth length vs. time



(a) The whole mesh model (b) The refined mesh at crack tip

Fig.5. The FE model of CT specimen

Due to the symmetry of the geometry and the applied load, we suppose the crack grow through the ligament of the CT specimen. Then, we can remesh the FE model with node-release technique. That is when the CTOD reaches a critical value at the node ahead of the crack tip, the current crack tip node is released, as shown in Fig.6.

The simulation flow chart for the creep crack propagation with the APDL in ANSYS is shown in Fig.7. Firstly, generate an initial geometrical and physical model of the CT specimen and perform a FE analysis. Secondly, assume the displacement δ of the node ahead of the crack tip as the CTOD. The node at the crack tip will be released when δ reaches a critical value δ_c. Crack growth is therefore simulated by releasing the node through the ligament of the CT specimen. With the crack propagation increment, the simulation time will accordingly increase Δt at the end of the current step. Repeat the above steps until the crack length reaches a pre-set value.

Simulation Results and Discussions

To investigate the accuracy of the finite element model, the creep crack growth length is calculated within 143 hours. The computational results during the loading period are given by Fig. 8. To illustrate the simulation accuracy, we make error analysis and the results are shown in Fig. 9. By comparisons, the maximum error between the experimental and numerical simulation results of crack length is about 8.3%. We can find that combined with node-release technique, the creep fracture behavior can be well simulated by using critical CTOD as a criterion for crack propagation before the unstable crack growth stage.

Conclusions

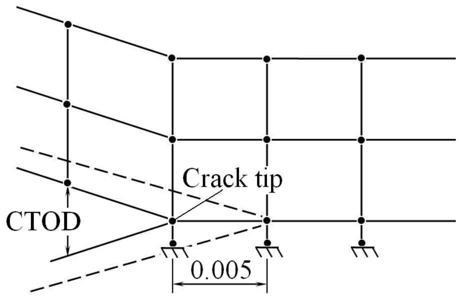


Fig.6. Crack tip node release process

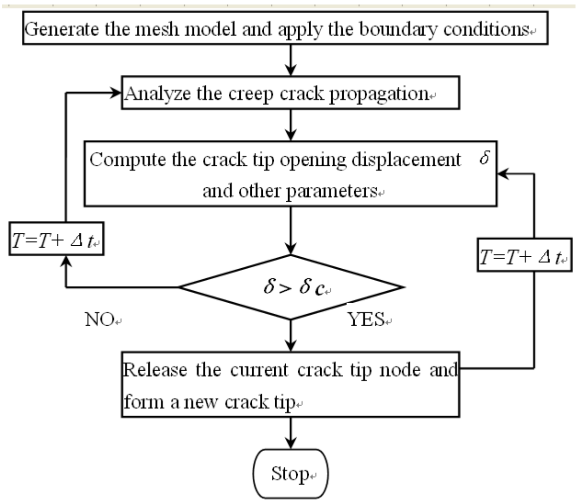


Fig.7. Flow chart of the FEM algorithm of the creep crack propagation

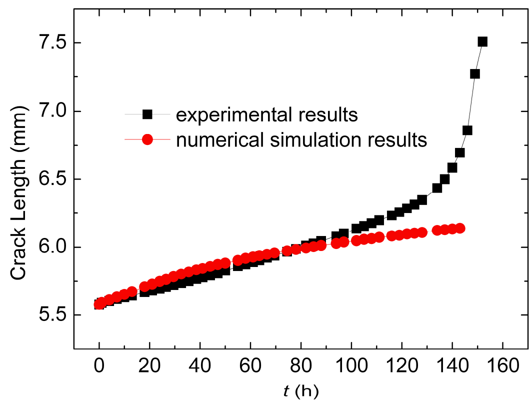


Fig.8. The crack length vs. the time

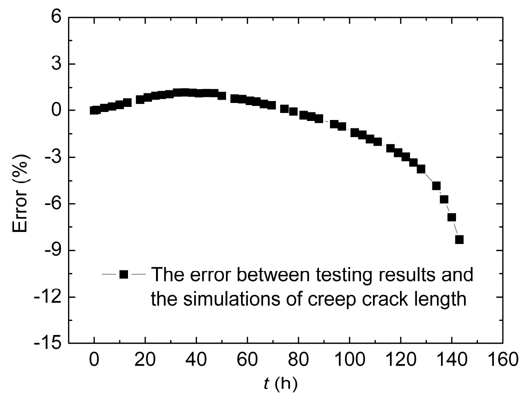


Fig.9. The error between testing results and the simulations of creep crack length

Tensile creep curve and creep crack propagation are tested for 0Cr18Ni9 at 550°C and then creep crack propagation process is simulated for a CT specimen by using the FE code ANSYS. The main conclusions are: (1) The creep curve and the time hardening creep law of 0Cr18Ni9 are obtained. (2) Combined with node-release technique, the creep fracture behavior can be well simulated by using critical CTOD as a criterion for creep crack propagation during the first two stages. (3) The maximum error between the experimental and numerical simulation results of crack length is within 10% for the unstable crack growth stage of creep crack propagation.

Acknowledgements

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