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Creep rupture life and damage evaluation under multiaxial stress state for type 304 stainless steel

Shengde Zhang [a,*], Takashi Wakai [b], Masao Sakane [a]

[a] Department of Mechanical Engineering, Ritsumeikan University, 1-1-1 Nojihigashi Kusatsu, Shiga 525-8577, Japan
[b] Core and Structural Materials Group, Advanced Nuclear System Research and Development Directorate, Japan Atomic Energy Agency, 4002 Narita-cho, O-arai, Ibaraki 311-1393, Japan

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ABSTRACT

The biaxial creep damage of type 304 stainless steel is studied at 973 K. Biaxial tension creep tests were carried out using cruciform specimens under the principal stress ratio (λ) of $0 \leqq \lambda \leqq 1$, where the principal stress ratio is the ratio of y-directional principal stress to x-directional stress in the gage part of the specimen ($\lambda = \sigma_y/\sigma_x$). Creep rupture times under biaxial stress conditions were shorter than those in uniaxial conditions at the same von Mises equivalent stress. Earlier void nucleation and faster void growth were observed in creep tests at larger principal stress ratio tests. Creep rupture times in biaxial stress states were discussed in relation to the void observations.

1. Introduction

Studies of creep life time and damage evaluation in multiaxial stress states are essential for not only designing actual high temperature applications but also studying the creep fracture mechanisms. Historically, von Mises equivalent stress has been used as a parameter for describing the creep deformation in multiaxial stress states, but the applicability of von Mises stress to the multiaxial creep damage evaluation has not been well demonstrated.

There are two major damaging mechanisms operating in elevated temperatures creep. One is the ingrain damage where creep strain rate corresponds to the creep damaging rate in short creep lifetime regimes at relatively low temperatures. The other is the grain boundary damage caused by void formation in long creep lifetime regimes at relatively high temperatures. In recent years, many void growth models [1–3] have been proposed to assess the creep damage evaluation due to void growth and coalescence at grain boundaries. However, there are little experimental works studying the creep rupture and damage development in multiaxial stress states, because of the difficulty of performing multiaxial creep testing [4,5].

The application of internal pressure to tube specimens is a common multiaxial creep testing, but this method enables creep testing in a narrow range of multiaxial stress states. The authors have developed a creep testing machine for cruciform specimens that can perform multiaxial creep tests in much wider multiaxial stress states, and discussed the suitability of typical multiaxial stress parameters for assessing the creep lifetimes [6,7]. However, there still exist many open questions on multiaxial creep rupture lifetime and damage development.

The objective of this paper is to study the multiaxial creep damage evaluation for type 304 stainless steel at 973 K. Biaxial tension creep tests were performed using cruciform specimens of type 304 stainless steel and creep lifetimes were experimentally obtained. The effect of the stress biaxiality on creep rupture lifetimes was discussed in relation to the minimum strain rate. Also, the A-parameter was measured to discuss the grain boundary damage in biaxial creep process. The A-parameter is the ratio of the number of damaged grain boundaries to that of total grain boundaries as defined later and it physically expresses the damage ratio of grain boundary in creep process.

2. Experimental procedure

The material tested was type 304 stainless steel with a solution treatment at 1373 K for 5 min. The chemical composition and heat treatment of the material are listed in Table 1. This paper used a cruciform specimen for biaxial tension creep testing. The shape and dimensions of the specimen is shown in Fig. 1 together with the coordinate system employed in this paper. The specimen shape was determined by finite element analysis to distribute the stress uniformly in the gage part. The variation of stress amplitude was less than 5% up to 8 mm apart from the centre of the specimen under creep loading as reported in the previous paper [6].

* Corresponding author. Tel.: +81 77 561 3970; fax: +81 77 561 2665.
E-mail address: zhangsd@se.ritsumei.ac.jp (S. Zhang).

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Table 1
Chemical composition of the material tested (wt.%).

C	0.05
Si	0.52
Mn	1.31
P	0.28
S	0.02
Ni	8.44
Cr	18.31

Solution treatment at 1373 K for 5 min.

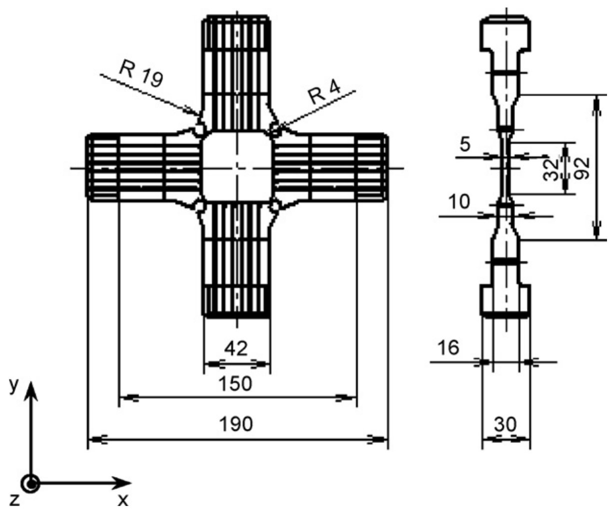

Fig. 1. Shape and dimensions of the specimen tested (mm).

The experimental apparatus used was an originally developed biaxial creep testing machine that has four loading devices and can apply a load to four arms of the specimen shown in Fig. 1 at any loading ratio. The details of the apparatus were also published in the previous paper [7]. Specimens were heated by an electric resistance furnace of 3 kW and the temperature variation in the gage part was within ±2.5 K. The x- and y-directional strains along 16 mm gage length were measured by two extensometers.

Table 2 summarizes the biaxial creep test condition carried out in this study, where λ is the principal stress ratio expressed by the ratio of y-directional principal stress (σ_y) to x-directional stress (σ_x) in the gage part of the specimen, i.e., $\lambda = \sigma_y/\sigma_x$. The $\lambda = 0.0$ test corresponds to a uniaxial tension creep test and the $\lambda = 1.0$ test to an equi-biaxial tension creep test. The relationship between the stress at gage part and loads tabulated in Table 2 was obtained using finite element analysis because the stress at the gage part cannot be directly obtained from the applied load in the case of cruciform specimen. Detailed description of determining the relationship was reported in the former paper [6].

Creep tests were interrupted at every 5% strain increment of von Mises equivalent basis to measure A-parameter. Fig. 2 shows the measuring method of A-parameter with the coordinate system used in this study. A-parameter [8] was calculated by the following

Table 2
Biaxial creep test condition.

Mises equivalent stress σ_{eq} (MPa)	Principal stress ratio λ	Load P_x (kN)	Load P_y (kN)
100		27.8	27.8
90	1.0	24.8	24.8
80		21.8	21.8
80	0.5	22.2	12.6

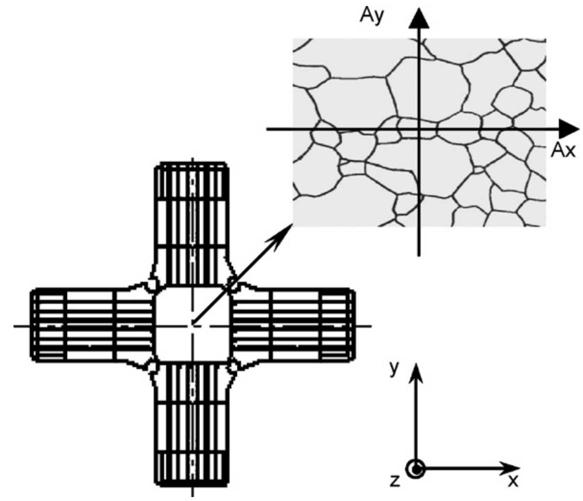

Fig. 2. Observation method of the A-parameter.

equation:

$$A = \frac{n_D}{n_D + n_U} \quad (1)$$

In the equation, n_D is the number of damaged grain boundaries with void formation and n_U the number of undamaged grain boundaries with no void formation. The n_D and n_U values were counted as the number of intersections of the lines parallel to the maximum principal stress and grain boundaries. More than 400 grain boundaries were counted following the recommendation of the Iron and Steel Institute of Japan [8]. The A-parameter was measured in the directions of x (Ax) and y (Ay) in this paper, to discuss the grain boundary damage in each direction. The Ax that is obtained by drawing a line parallel to the x-direction indicates grain boundary damage in the x-direction and vice versa.

3. Experimental results and discussion

3.1. Multiaxial creep lifetime

Fig. 3 correlates the uniaxial and biaxial creep rupture times with the von Mises equivalent stress (σ_{eq}) at 923 and 973 K, where the data at 923 K are quoted from the previous study [7]. Solid lines in the figure are the uniaxial rupture times of solid bar specimens quoted from NIMS creep data sheet [9] at respective temperatures

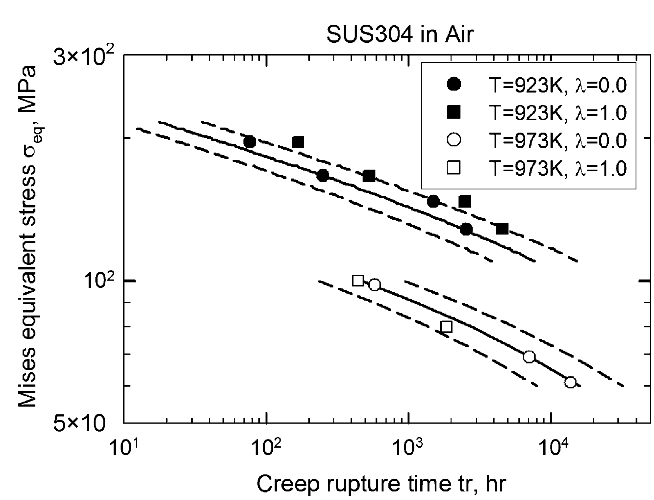

Fig. 3. Correlation of creep rupture time with von Mises stress.