Materials Science and Engineering A 527 (2010) 2784–2789

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

A study on influence factors of small punch creep test by experimental investigation and finite element analysis

Zhixiang Zhou, Yangyan Zheng, Xiang Ling*, Ruomei Hu, Jianqiu Zhou

School of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, China

ARTICLE INFO

Article history:
Received 14 November 2009
Received in revised form
29 December 2009
Accepted 5 January 2010

Keywords:
Small punch creep test
Finite element model
Creep damage
Influence factor

ABSTRACT

Small punch creep (SPC) tests for SUS304 and Cr5Mo specimens with dimension Ø10 mm × 0.5 mm were performed at different temperatures, load levels and atmospheres. Based on these tests, a finite element model (FEM) combined with modified Kachanov–Rabotnov (K–R) creep damage constitutive equations was established to simulate the ductile and creep damage of the round specimen during the test procedure. The validity of FEM was proved by the comparison of Center deflection–Time data yielded from finite element analysis (FEA) and experiment. Then, effects of sample thickness, load level, ceramic ball diameter, specimen diameter, temperature and protective atmosphere on SPC test were analyzed by experimental investigation and FEA. The results show that five of the six above-mentioned factors (except specimen diameter) influence the rupture time, center deflection, real creep strain and creep damage of SPC specimen strongly.

1. Introduction

For the past two decades, the small punch test has been used successfully to characterize the mechanical strength, impact toughness, fracture property and creep property of materials with specimens measured only 0.1–0.5 mm in thickness. Okada et al. [1] established the relations between small punch test and uniaxial tensile test by ultimate load and ultimate stress, etc. Based on Okada's researches, Mao [2,3] took specimen initial thickness into account and built similar relations, and predicted ductile fracture toughness J_{IC} and brittle fracture toughness K_{IC} by using small punch test. Bulloch [4] proceeded small punch tests to determine ductile–brittle transition temperature (DBTT) as obtained from Charpy impact test. Kameda and Ranjan [5] studied the deformation and fracture behavior of Al alloy with ceramic coatings by means of small punch test. Komazai et al. [6] and Dobeš [7,8] introduced small punch test to evaluate the creep property of steels. Song et al. [9] utilized small punch test to evaluate the temper embrittlement of CrMo low-alloy steel. Komazai et al. [10] and Blagoeva and Hurst [11] investigated the creep property of welded joint by SPC test. Small punch test has been adopted successfully in the fields of nuclear power, aviation, space flight and petrol-chemical industries. The test materials included metal, mineral [12], composite [13], coating [14], weld zone [15], etc. As a very sensitive novel testing technique, SPC test was susceptible to a lot of factors in the testing procedure. However, few published reports are available on the sensitivity analysis for those factors.

In this paper, SPC tests for SUS304 and Cr5Mo were carried out at elevated temperatures under different constant loads on round specimens. Ar gas was inputted to prevent the specimen from oxidation. Based on these tests, an FEM coupled with modified K–R creep damage constitutive equations was established. Influences of specimen thickness, constant load level, ceramic ball diameter, specimen diameter, temperature and protective atmosphere on SPC test were analyzed by experimental investigation and FEA.

2. SPC test details

SPC tests were carried out on self-made testing system (see Fig. 1), which contains loading unit, electric heating and temperature controlling unit, shielded gas (Ar) supplying unit and support platform [16]. In the test procedure, a constant load was applied to the thin round specimen through a punching rod and a ceramic ball with diameter 2.40 mm. Ar gas with constant flowrate was inputted into the furnace to protect the specimen from oxidation.

3. Numerical simulation

3.1. Model description

The following modified K–R equations for inhomogeneous creep damage are used in the present study [17]:

$$\frac{d\varepsilon_{ij}^{c}}{dt} = \left(\frac{3}{2}\right) B\sigma_e^{n-1} S_{ij}[(1-\rho)+\rho(1-\omega)^{-n}] \quad (1)$$

* Corresponding author. Tel.: +86 25 83243112; fax: +86 25 83600956.
E-mail address: xling@njut.edu.cn (X. Ling).

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doi:10.1016/j.msea.2010.01.010

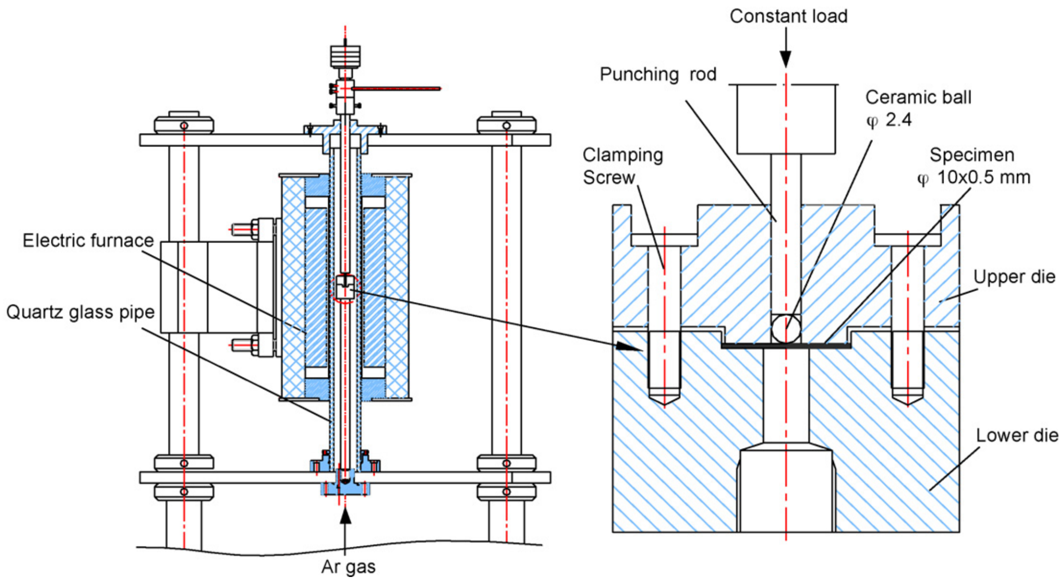

Fig. 1. Detail experimental conditions for SPC tests.

$$\frac{d\omega}{dt} = g\frac{[A/(\varphi+1)][\alpha\sigma_1 + (1-\alpha)\sigma_e]^{\upsilon}}{(1-\omega)^{\varphi}} \quad (2)$$

$$\omega_{cr} = 1 - (1-g)^{1/(\varphi+1)} \quad (3)$$

where ε_{ij}^c is creep strain tensor; σ_e and σ_1 are equivalent and maximum principal stresses, respectively; S_{ij} is the stress deviation tensor; ω is the damage variable which represents cavitations damage varying from 0 (no initial damage) to 1 (complete failure); ω_{cr} is critical damage; α is multiaxial stress parameter ($0<\alpha<1$); B, n, A and υ are material constants related to the minimum creep strain rate and rupture behavior; ρ, g and φ are material constants taking account into the inhomogeneous damage.

The corresponding material parameters (see Table 1) adopted in all the simulations of the SPC tests in this present paper were obtained from uniaxial creep test performed at the temperature of 650 °C. E in Table 1 represents elastic modulus (MPa), and μ is Poisson ratio.

3.2. Finite element modeling

Software ABAQUS provides a general and powerful possibility to add constitutive models to the program library by user subroutine (UMAT) [18]. In the present paper, above-mentioned K–R constitutive equations for creep damage mechanics are implemented into the finite element codes ABAQUS using UMAT.

Since the shapes of SPC test device, shape, deformation and damage evolution of SPC specimen are all axisymmetric, then, a two-dimensional FEM shown in Fig. 2 is sufficient to reproduce the SPC test with reasonable computational cost. According to the actual experimental situations, the displacement boundary conditions simply supported constrain and symmetric constrain are applied to the corresponding edges of this specimen model. The ceramic ball is modeled as a rigid body, and can be moved vertically. Surface-to-surface contact is assigned between the outer surface of ceramic ball and upper surface of specimen. The corresponding mechanical constraint formulation and friction formulation are kinematic contact method and penalty, respectively.

4. Results and discussion

4.1. Comparison of numerical results and experimental data

SPC test for SUS304 specimen with dimension Ø10 mm × 0.5 mm was performed firstly in 650 °C with constant load 463 N and Ar gas flowrate 0.3 L/min. Fig. 3 compares the Central deflection–Time curves obtained from the experiment and simulation. It is clearly observed that the two curves are much close to each other in the first half part, but a difference appears subsequently. The reason might be that the material parameters used in FE calculation were obtained from uniaxial creep tests, in which the corresponding minimum creep rate is a little higher than that of the SPC test. The rupture time is 96 h in the simulation, while 90 h in the experiment. The error is less than 6.67%. Generally speaking, the trends of two curves are basically identical with each other to a large extent, and both of them have three typical stages. This proximity indicates that the FEM in this paper is reasonable.

4.2. Influence of specimen thickness

Specimen thicknesses ranging from 0.1 mm to 0.5 mm were generally chosen by different researchers for SPC test. However, during the specimen preparation process, there would always be deviations, and the specimen thickness of the actual size will be smaller than requested because of oxidation in the practical experiment. According to the numerical results, central deflection, center real strain, rupture time and creep damage were discussed for the specimen with different thicknesses at constant load of 463 N.

The deformation of SPC specimen is different from that of conventional creep test specimen. Previous researches [19] indicated that the deformation of the SPC specimen can be divided into two parts: a bending region and a membrane stretching region. Real

Table 1
Material parameters of SUS304 at 650 °C.

E (MPa)	μ	B	n	g	φ	A	α	ν	ρ
1×10^5	0.29	3.22×10^{-23}	8.297	0.930	1.179	2.665×10^{-21}	0.75	8.135	0.0393