Journal of Nuclear Materials 509 (2018) 62–72

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Creep tests on notched specimens of copper

Fangfei Sui [a, *], Rolf Sandström [a], Rui Wu [b, 1]

[a] Materials Science and Engineering, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden
[b] Swerea KIMAB, Drottning Kristinas Väg 38, 11428, Stockholm, Sweden

ARTICLE INFO

Article history:
Received 9 March 2018
Received in revised form
15 May 2018
Accepted 11 June 2018
Available online 13 June 2018

Keywords:
Multiaxial stress state
Creep
Notched specimen
Finite element modelling
Copper

ABSTRACT

In Sweden, spent nuclear fuel is planned to be disposed off by placing it in canisters which are made of oxygen free copper alloyed with 50 ppm phosphorus. The canisters are expected to stay intact for thousands of years. During the long term disposal, the canisters will be exposed to mechanical pressure from the surroundings at temperatures up to 100 °C and this will result in creep. To investigate the role of the complex stress conditions on the canisters, creep tests under multiaxial stress state are needed. In the present work, creep tests under multiaxial stress state with three different notch profiles (acuity 0.5, 2, and 5, respectively) at 75 °C with net section stresses ranging from 170 MPa to 245 MPa have been performed.

To interpret the experimental results, finite element computations have been conducted. With the help of the reference stress, the rupture lifetime in the multiaxial tests was estimated. The prediction was more precise for the higher acuities than for the lower one. In order to predict the creep deformation of the canisters for the long service period, fundamental creep models are considered. Previously developed basic models are used to compute the creep deformation in the multiaxial tests. Although the scatter is large, the agreement with the experiments is considered as acceptable, indicating that the basic models which have been successfully developed for uniaxial creep tests can also be used to describe multiaxial creep tests. Notch strengthening was observed for copper.

1. Introduction

Deep geological disposal is generally considered as a suitable solution for long term management of spent nuclear fuel. It is based on adopting multi barrier methods; different barriers can serve to reduce an overall risk of leakage of radionuclides. A designed concept in Sweden, denoted as the KBS-3 concept, means that the spent nuclear fuel assemblies are placed in iron inserts inside sealed copper canisters which are in turn placed in deposition holes, embedded in a bentonite clay, and buried 500 m down in the bedrock as the final repository [1]. The repository is planned to be functional for thousands of years until the radioactive waste is no longer hazardous. After disposal, the bentonite will gradually be saturated by ground water and swell. The copper canister will be subjected to hydrostatic pressure from the ground water and swelling pressure from bentonite. The heat from radioactive waste will raise the temperature in the repository to up to 100 °C. The pressure at elevated temperature will give rise to creep deformation of the copper canisters.

The canister is 5 m long with a diameter of 1 m. It is composed of three parts, the lid, tube and base. The lid and base are sealed to the tube by friction stir welding. At the connections between lid/base and tube there exists slits about 75 mm in length and 0.15–0.33 mm in width. Considering the existence of slits, large stress concentration will appear. The top section of the canister is exposed to horizontal and vertical loads that give rise to complex multiaxial stresses [2,3].

To simulate the service condition of the canisters, creep tests under multiaxial stress state have been performed. Practically, creep tests of components are difficult and expensive to perform. A well-established way to introduce multiaxial stress state is to subject circumferentially notched bars to axial load [4,5]. Extensive studies have been carried out with notched bars to examine the notch sensitivity of materials with respect to creep failure [6–9].

Finite element modelling (FEM) has been widely used for estimating stress distribution and damage evolution around the notches under creep conditions [5,10–13]. To interpret the

* Corresponding author.
E-mail address: fangfei@kth.se (F. Sui).
[1] Present address: Avesta Research Center, Outokumpu Stainless, Sweden.

https://doi.org/10.1016/j.jnucmat.2018.06.018
0022-3115/© 2018 Published by Elsevier B.V.

experimental results, finite element computations have been conducted. For safe extrapolation, the controlling mechanisms of creep deformation should be fully understood. Considering the extensive periods that the copper canisters have to stay intact in the repository, the use of fundamental models is of major importance [14]. Fundamental models based only on deformation mechanisms have been developed [15,16]. It has been demonstrated that the models can successfully reproduce uniaxial creep tests and stress strain curves under both uniaxial and multiaxial stress state for different kinds of materials [14,17–19].

The purpose of the present work is to perform creep tests under multiaxial stress state and use the data to verify that the basic models can be used to interpret creep tests under multiaxial stress state.

2. Material and testing

The test materials used in this study were extracted from a forged lid provided by Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company, SKB). The lid was made of oxygen free copper doped with about 50 ppm phosphorus (Cu-OFP). The test material is the same as used in Ref. [20], where its chemical composition is specified. The microstructure of the material before testing is shown in Fig. 1. Grains with different sizes and twin boundaries were observed. The grain size was ranging from 85 μm to 156 μm.

In order to simulate multiaxial stress states, double notched cylindrical specimens were used in this study. These specimens were made with a gauge length of 47 mm and a total length of 129 mm. The gauge length for both notched and unnotched specimens are defined to be the same as the distance between the two knife edges (shown in Fig. 2). Creep strain was measured from the deformation within the whole gauge length. To represent different stress states, different notch acuities were introduced. The notch acuity was defined as the notch root radius (a) divided by the notch throat radius (R). The specimens with three notch acuity 0.5, 2 and 5 were tested. The geometry of the notched specimens and detailed notch sizes are shown in Fig. 2.

The specimens were tested at 75 °C under constant dead load. The temperature was chosen to represent the in-service condition of copper canister. The maximum temperature is computed to be 90 °C or below. If a maximum temperature of 90 °C is reached, the temperature will be about 75 °C after 100 years and stay about there for extended periods of time. So at about 75 °C, most creep

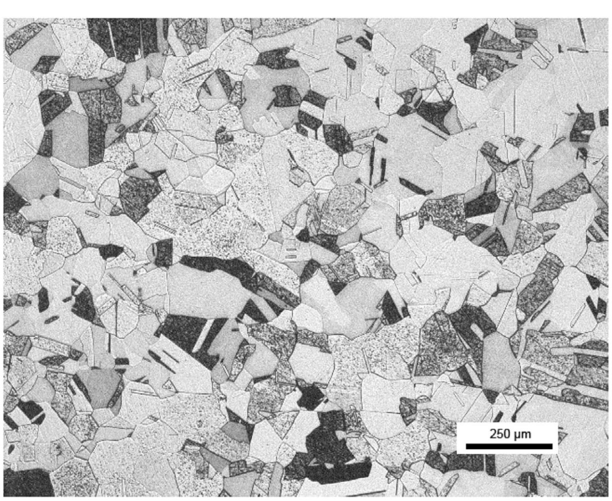

Fig. 1. Microstructure of Cu-OFP material.

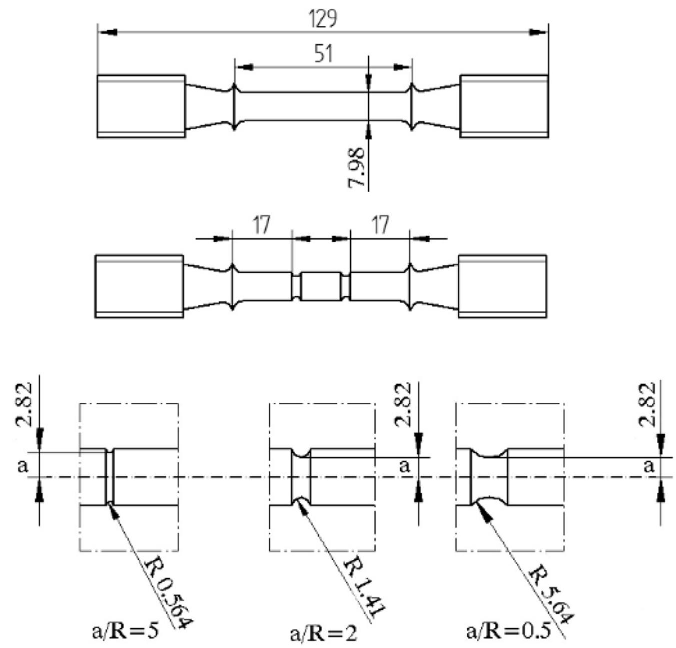

Fig. 2. Specimen geometry used in creep tests.

exposure is expected [21]. The initial applied net section stress was calculated by the load divided by the minimum notch cross section area. The stresses are listed in Table 1. The tests were planned to run to rupture, but some tests were interrupted due to unexpected long test duration. A few uniaxial creep tests were also conducted for the same batch of material.

The specimens were double notched. After creep testing, only one notch was ruptured. Creep cavitation investigation was carried out using light optical microscope on both ruptured and unruptured notches, representing rupture state and near rupture state, respectively. Samples were taken from longitudinally sectioned creep specimens. The samples were mounted, grinded, polished to 0.25 μm and etched in a solution containing 4 g CrO_3, 0.75 g HN_4Cl, 5 ml H_2SO_4, 5 ml HNO_3 and 190 ml H_2O.

3. Computation

3.1. Model for creep curve

The uniaxial model for the creep curve that is used in the FEM computations has been derived and analysed in several papers [16,22,23]. Only a brief summary will be given here. A typical creep curve shows three stages. The creep rate decreases during the primary stage, reaches a steady state value in secondary creep, accelerates during tertiary creep and terminates at rupture. For many materials the high initial creep rate is due to a low starting dislocations density and the accompanying low back stress. The work hardening gives rise to a decreasing creep rate. At the same time the recovery due to the annihilation of dislocations starts to

Table 1
Specimen test conditions.

Notch acuity	Test temperatures (°C)	Net section stresses (MPa)
0	75	170,175,180
0.5	75	170, 180, 195, 200, 215
2	75	170, 180, 200, 215, 225, 230
5	75	170, 180, 200, 215, 230, 245