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Slow strain rate tensile tests on notched specimens of copper

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ABSTRACT

In this study, slow strain rate tensile tests have been performed on phosphorus alloyed copper under uniaxial and multiaxial stress states at 75 and 125 °C with two strain rates 10^{-6} and 10^{-7} s^{-1}. Multiaxial stress states have been introduced by incorporating three different notch geometries on the uniaxial specimens. It has shown that the presence of the notches decreased the strength and ductility of copper. Ductility exhaustion was likely to be the dominant rupture mechanism. Finite element analysis was conducted to compare with the experimental results with a physically based model for stress strain flow curves without fitting parameters. The model could successfully describe the experimental data, and it could predict the dependence of acuity, temperature and strain rate in the multiaxial tests.

1. Introduction

Deep geological disposal is believed to be the most appropriate solution for long term management of spent nuclear fuel. In Sweden, a specific concept named KBS-3 is proposed. The spent nuclear fuel will be enclosed in tightly sealed copper canisters surrounded by clay, and buried 500 m down in the bedrock as the final repository [1,2]. The three barriers, copper canister, clay and bedrock, will serve with the principal purpose of delaying the transport of radionuclides. Copper is selected because of its excellent corrosion resistance in reducing ground water and thereby isolating the spent fuel from the surrounding environment. In the repository, the copper canister will also be subjected to mechanical loading at temperatures up to 100 °C. The clay will swell when it comes into contact with underground water. The swelled clay will exert a pressure on the canister. During the swelling process, the load on the canister will gradually increase and it may take centuries before full pressure is reached [3]. In the swelling stage the loading is essentially strain controlled whereas stress control will be activated after full pressure has been reached. In this study, the gradual loading is simulated with slow strain rate tensile (SSRT) tests and full loading with creep tests. In order to describe the role of the deformation of the copper canister, both SSRT and creep tests should be carried out.

Many uniaxial tests (both SSRT and creep) on copper have previously been performed [4–7]. For investigating the role of the complex stress conditions in the repository, it is natural to perform tests also under multiaxial stress state [8–10]. A series of multiaxial creep tests have been conducted [11,12]. However, literatures provide limited information about the performance of copper during SSRT tests under multiaxial stress state.

The purpose of the present work is to perform SSRT tests for copper under multiaxial states. The tests results are used to verify that the basic models which have been successfully developed for uniaxial tests can be used to describe multiaxial tests as well.

2. Material and testing

The canisters used for storage of the spent nuclear fuel are made of oxygen free copper alloyed with 50 ppm phosphorus (Cu-OFP). According to previous research, pure copper was detected to sometimes have extra low creep ductility [13], and phosphorus was added to give copper acceptable creep ductility [14–16]. In order to simulate the multiaxial stress state, double notched Cu-OFP cylinder bars are used in the present tests. The chemical composition of the test material is given in Table 1.

By changing the notch geometry, various stress states can be obtained [17]. Multiaxial SSRT tests were carried out with three kinds of notch geometries. Plain copper bars were also tested as reference. The geometries of the specimens are presented in Fig. 1 and Table 2. To indicate different notch geometries, notch acuity is introduced and defined as the notch root radius divided by the notch throat radius. All the specimens were 7.98 mm in diameter, 47 mm in gauge length and 2.82 mm in notch throat radius. The notch root radii of the specimens were varied in the range from 0.564 to 5.64 mm for achieving different notch acuities.

The specimens were tested at two temperatures, 75 and 125 °C,

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Table 1
Chemical composition of the Cu-OFP cylinder bars, ppm.

Cu (%)	Ag	As	Bi	Cd	Ni	Zn	Fe	Mn
99.992	13.2	0.85–0.87	0.104–0.117	< 0.003	1.1–1.2	< 0.1	1.1–1.2	< 0.1
O	Sb	S	Pb	Se	Sn	H	Te	**P**
1.6–2.4	0.06	5.3–5.6	0.26–0.29	0.1–0.2	0.18–0.19	< 0.1	0.05	**54–56**

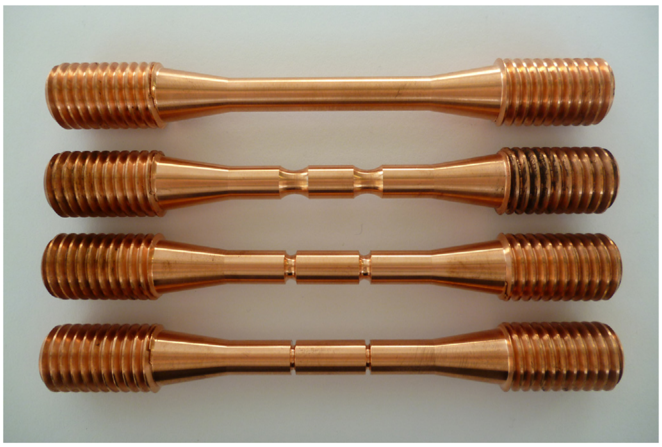

Fig. 1. Geometry of the specimens, from top to bottom notch acuity 0, 0.5, 2, 5.

with two strain rates, 10^{-6} and 10^{-7} s^{-1}. The detailed test parameters are given in Table 2. Test temperatures were chosen according to the working condition of the canister. The maximum temperature is expected to be lower than 100 °C. A higher test temperature 125 °C was chosen for extrapolation purpose [3]. Tests were performed according to standard procedures (SS-EN 10,002-1). All the specimens were tested to rupture, some of which lasted for a few days while others for up to two months. Yield strength was evaluated as the 0.2% offset in strain.

After the tensile tests, one ruptured notch and one unruptured notch were obtained on each double notched specimen. Reduction in area of the ruptured notch was measured. In order to evaluate the reduction in area, fracture images were firstly taken by Hitachi TM3000 scanning electron microscope (SEM) as shown in Fig. 2a and then analyzed with Photoshop CS5. The fracture area was automatically selected by “selected tool” and then adjusted manually. The exact fracture area was highlighted in black as shown in Fig. 2b and the reduction in area of this fracture was accurately calculated through the selected pixels.

In order to examine cavities and observe grain deformation, the specimens were longitudinally sectioned in the middle, ground and polished to 0.06 μm, and finally 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. Microstructure observation was carried out on the etched samples with light optical microscope.

3. Computation

3.1. Model for stress strain curve

It is known that the plastic deformation in creep and SSRT tests represents the same physical phenomenon, i.e. work hardening and recovery. During work hardening, the dislocation density increases by generation of new dislocations and thereby also the strength. Recovery is a process that consists of static (time dependent) and dynamic (strain dependent) recovery. In this process, dislocations with opposite sign annihilate each other and the density is therefore reduced. To describe plastic deformation, the three contributions should be added.

$$\frac{d\rho}{d\varepsilon} = \frac{m}{bL} - \omega\rho - 2\tau_L M\rho^2/\dot{\varepsilon} \tag{1}$$

The three terms in the right hand side of the equation represent work hardening, dynamic recovery and static recovery, respectively. It has been demonstrated that this model can represent the stress and strain rate controlled plastic deformation for pure copper without the use of any fitting parameter [5–7,12,18].

In Eq. (1), ρ is the dislocation density, ε the strain, m the Taylor factor, b Burger's vector and L the "spurt" distance that the dislocation moves in each elementary release during deformation and related to the average distance between the dislocations $L = c_L/\sqrt{\rho}$. The derivation of the constant c_L can be found in Ref [6]. ω is a constant that controls the amount of dynamic recovery; its derivation can also be found in ref [6]. τ_L is the dislocation line tension, $\dot{\varepsilon}$ the stationary strain rate and M the creep mobility. During power-law breakdown, the mobility should take into account glide and climb [4]. A combined mobility for climb and glide is given in Eq. (2), which was derived in [4] using an expression from [19]

$$M_{OF}(T,\sigma) = \frac{D_{s0}b}{k_B T} e^{\frac{\sigma b^3}{k_B T}} e^{-\frac{Q}{RT}\left[1-\left(\frac{\sigma}{\sigma_{imax}}\right)^2\right]} \tag{2}$$

where T is the absolute temperature, σ the applied stress, D the preexponential coefficient for self-diffusion, k Boltzmann's constant, Q the activation energy for self-diffusion, R the gas constant and σ_{imax} the max back stress which is taken as the tensile strength at room temperature. When σ_{imax} is infinity, the expression is the climb mobility of dislocations which was first derived by Hirth and Lothe [20].

This mobility model was used for Cu-OF. The influence of phosphorus is taken into account by introducing the stress σ_{break} [21], which is needed for the dislocations to break away from the Cottrell atmospheres of phosphorus atoms [15].

$$M(T,\sigma) = M_{OF}(\sigma - \sigma_{break}, T) f_Q \tag{3}$$

In Eq. (3) the factor f_Q describing the influence of phosphorus on activation energy is related to the maximum interaction energy between a phosphorus solute and a dislocation U_P^{max} [21].

$$f_Q = e^{-U_P^{max}/RT} \tag{4}$$

Table 2
Specimen geometry and test conditions.

Gauge length (mm)	Stress state	Notch root radius (mm)	Notch throat radius (mm)	Notch acuity	Test temperatures (°C)	Strain rate (s^{-1})
Φ7.98 × 47	Uniaxial	0	0	0	75, 125	1×10^{-6}, 1×10^{-7}
	Multiaxial	5.64	2.82	0.5	75, 125	1×10^{-6}, 1×10^{-7}
	Multiaxial	1.14	2.82	2	75, 125	1×10^{-6}, 1×10^{-7}
	Multiaxial	0.564	2.82	5	75, 125	1×10^{-6}, 1×10^{-7}