Effect of rolling direction on the creep properties of the HANA-6 strip

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1. Introduction

Zirconium alloys have anisotropic mechanical properties depending on their physical orientations because of the formation of the texture in their microstructures [1,2]. KAERI is developing alloy materials named HANA for high performance fuel cladding tubes. In this study, the creep properties of the HANA-6 (Zr-1.1Nb-0.07Cu) alloy strips with different orientations were investigated under various loading stresses and test temperatures. The creep behaviors were analyzed by examining the crystallographic orientations of the strips.

2. Methods and Results

The chemical composition of the HANA-6 strips for this study was Zr-1.11Nb-0.08Cu-0.14O with some impurities such as 110 ppm Si, 20 ppm H, 35 ppm N. The HANA-6 strips were manufactured to have 0.66 mm thickness by repeating hot-rolling and cold-rolling processes. The strips were cut along the rolling direction (RD) and transverse direction (TD), as well as in the intermediate directions of 30°, 45°, and 60° which were angled from the RD. The test specimens were fabricated as dog-bone shaped with the gage length of 25 mm. For the texture analysis, 15 x 15 mm plate samples were also extracted. Then all the test samples were annealed differently at 600℃ for 10 min or 660℃ for 4 h in order to vary the microstructural textures.

The creep test was performed at 380℃ and/or 420℃ for 10 days under the constant stresses of 90 MPa, 120 MPa, and 150 MPa. The samples for texture analysis were mechanical polished up to 1200 grit emery paper. The polished sections were etched by a scrubbing with a with $10HF–45HNO_3–45H_2O$ (vol.%) solution. The texture was determined by X-ray diffraction in the normal plane.

2.1 Creep and Activation Energy

Creep strain rates are increased by the test temperature and stress increase as indicated in the equation:

$$\dot{\varepsilon} = A\sigma \exp(-Q/RT) \qquad (1)$$

where $\dot{\varepsilon}$ is the creep strain rate, A the constant, σ the applied stress, Q the activation energy for creep process, R the gas constant, and T the absolute temperature. The activation energy can be obtained from the Eq. (1) by applying logarithm [2,3]:

$$Q = -R\left(\frac{\partial \ln \dot{\varepsilon}}{\partial (1/T)}\right) \qquad (2)$$

In the case of RD, the activation energies were obtained as 74.8 kJ/mol and 190.7 kJ/mol under the stress of 120 MPa and 150 MPa, respectively. On the other hand, the activation energies for TD were 123.8 kJ/mol and 221.7 kJ/mol under the stress of 120 MPa and 150 MPa, respectively. The activation energy was higher in the RD than TD.

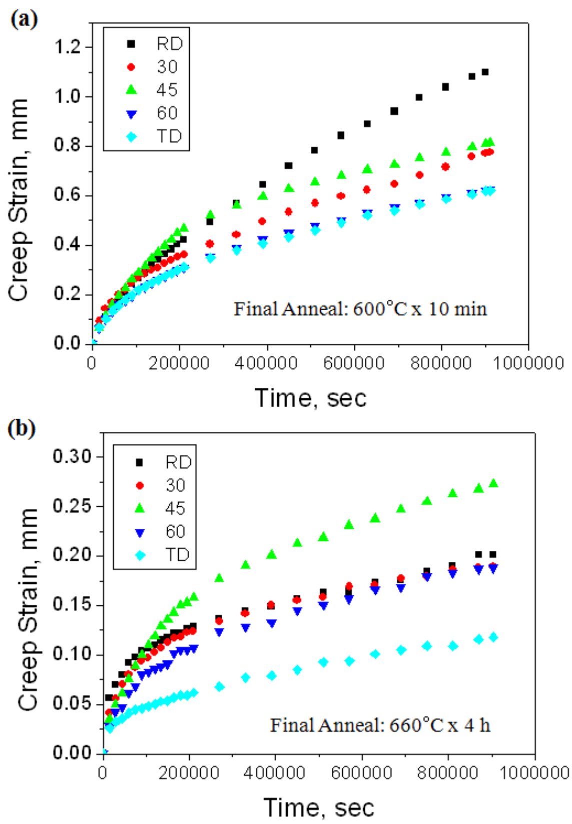

Fig. 1. Relationship between the creep curves and sample directions (a) finally heat-treated at 600℃ for 10 min, (b) finally heat-treated at 660℃ for 4h, respectively.

Figure 1(a) shows the creep curves for the strips finally annealed at 600℃ for 10 min. The strain rate for RD was higher than that of TD. In particular, the 45° strip revealed the highest primary creep rates, but the creep rate was decreased to its lowest after the saturation of initial creep deformations. Figure 1(b) shows the creep curves for the strips finally annealed at 660℃ for 4 h. Unlike Fig 1(a), 45° direction specimens showed the highest creep strains. TD showed the lowest creep strain, and the other specimens showed similar values among them.

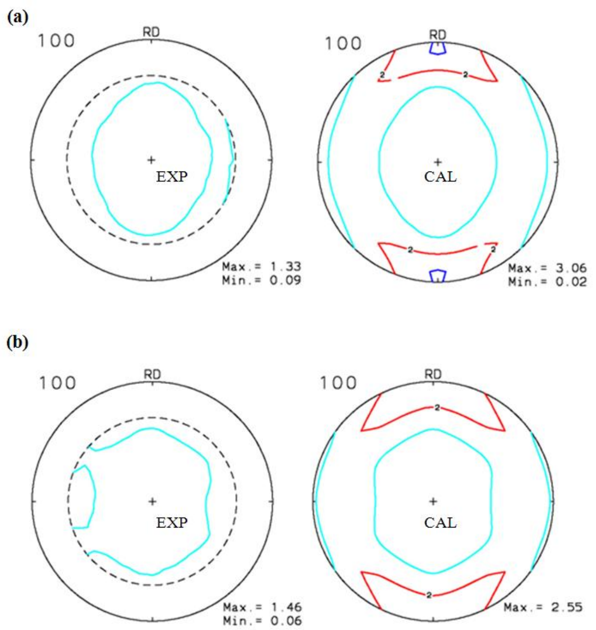

Fig. 2. Pole figure for HANA-6 (a) finally heat-treated at 600℃ for 10 min, (b) finally heat-treated at 660℃ for 4h, respectively.

2.2 Texture and Kearns-number

Kearns proposed an orientation parameter, f (Kearns-number), defined in terms of the effective fraction of grains with their basal poles aligned in a particular direction given by,

$$fi = f_0^{\pi/2} I(\Phi)\sin\Phi\cos^2\Phi d\Phi \qquad (3)$$

where $I(\Phi)\sin\Phi$ is the volume fraction of the grains with their c-axes oriented at a tilt angle Φ from the reference direction, with if expressed in the units of times-random. The f value can be evaluated from either the indirect or direct pole figure data but in general it is more complicated to use direct pole figures since the values of $I(\Phi)$ for each Φ must be determined over 2π of the rotation angle in the specimen plane. Thus the θ–2θ scans are commonly used in determining the Kearns parameter which is given for the three orthogonal directions (RD, TD, ND for strips), and it is satisfied that

$$fn + ft + fr = 1 \qquad (4)$$

where fn, ft, and fr are the Kearns numbers for the sample directions along normal (ND), transverse (TD)m and rolling (RD), respectively.

Kearns-number for the samples final annealed at 600℃ for 10 min was obtained by fn : 0.6611, ft : 0.2502, fr : 0.0896, and the samples underwent final annealing at 660℃ 4 h was fn :0.7031, ft : 0.2067, fr : 0.0906.

Figure 2 shows the pole figure in the (100) plane of the samples final annealed at 600℃ for 10 min and 660℃ for 4 h. The (100) planes were calculated to be aligned along the RD; however, final annealing at 660℃ mitigated the concentrated distribution of (100) planes.

3. Conclusions

The behavior of creep and activation energy, textures, along with Kearns numbers, were investigated in HANA-6 strips with various geometric orientations. The creep strain rate was increased as the test stress and temperature increased. The rate was higher along RD than TD irrespective of annealing conditions. However, the samples with 45° direction showed different behaviors depending on the annealing temperature. When strips finally annealed at 600℃ for 10 min, the primary creep rate of the 45° strip was the highest among the various orientations although the saturated creep rate was the lowest. In the case of final annealing at 660℃ for 4 h, the highest creep rate occurred during the whole creep test in the 45° strip. It is considered the fraction of (100) planes along the direction of creep deformation affect the creep rates.

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