Consideration of the Schmid factor on creep behaviors 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 texture in their microstructures [1,2]. In order to investigate the creep anisotropy depending on geometrical orientations, HANA-6 (Zr-1.1Nb-0.07Cu) alloy strips with different orientations were used. The experimental results will be presented in another paper [3]. In this paper, the anisotropic creep behaviors will be interpreted by introducing a basic slip mechanism.

2. Methods and Results

The investigated HANA-6 strips were manufactured according to a commercial process. The final thickness was 0.66 mm, and the chemical composition was Zr-1.11Nb-0.08Cu-0.14O with some impurities. The strips were final annealed at two different conditions, i.e. 600℃ for 10 min and 600℃ for 10 min, in order to vary the microstructural textures. The textural Kearns number for each sample was measured by using X-ray diffraction; the results are presented in Table 1. Other experimental procedures and creep results are shown in an accompanying paper [3].

Table 1. Kearns numbers for studied alloy strips [3]

Samples	600℃ x 10 min	600℃ x 10 min
fn	0.6611	0.7031
ft	0.2502	0.2067
fr	0.0896	0.0906

2.1 Crystallographic Orientation

Correlations between the lattice orientation and sample geometric orientation should be defined prior to the interpretation of texture and mechanical behaviors. If we consider how the direction of the basal pole changed during rotational transformation, the unique function of transformation can be obtained since the other directions in the lattice can be derived from the basal pole. There are two kinds of approaches to identify the orientation of a lattice in a random position. One is the ND–RD–ND rotation in the sample coordination system (Fig. 1), and the other is the *z*–*x*–*z* rotation in the lattice coordination system.

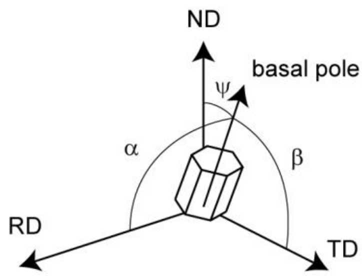

Fig. 1. Orientation of basal pole in the sample coordinate system [4].

The rotation of angle A along ND (Z-axis) is expressed as,

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} \cos A & -\sin A & 0 \\ \sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad (1)$$

where [u v w] is a direction in the RD (X-axis), TD (Y-axis), and ND (Z-axis) coordination system, and [u' v' w'] is the direction after the rotation. Any orientation of the lattice can be defined as a rotation of angle A along ND, and then rotation of angle B along RD, and finally rotation of angle C along ND. The corresponding rotation is expressed as

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} \cos C & -\sin C & 0 \\ \sin C & \cos C & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \qquad (2)$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos B & -\sin B \\ 0 & \sin B & \cos B \end{bmatrix} \begin{bmatrix} \cos A & -\sin A & 0 \\ \sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The rotation can be made in the lattice coordination system. Setting the [100] as an *x*-axis and [001] as a *z*-axis, a particular lattice can be defined with the *z*–*x*–*z* rotation. This rotation process is directly applicable to the ODF (orientation distribution function) texture data. The first rotation along *z*-axis is same as the rotation along TD as presented in Eq. (1). However, the second rotation along *x*-axis differs from the rotation along RD, since the *x*-axis was already rotated during *z*-axis rotation. If the first rotation is identical as Eq. (1) and the *x*-axis was initially aligned along RD, the *x*-axis will have the directional vector of [cos A sin A 0]. Rotational matrix along a general direction is known as Rodrigues' rotation formula:

$$R = P + (I - P)\cos\theta + Q\sin\theta \qquad (3)$$

where $P = \vec{u}\cdot\vec{u}^T$, I the 3x3 identity matrix, Q the skew symmetric representation of a cross product with $\vec{u}$, if the rotation axis is $\vec{u} = [u_x \quad u_y \quad u_z]$ and the rotating angle is θ. Therefore, the *z–x–z* rotation will have the form of

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = R^{\eta}_{z''}\cdot R^{\rho}_{x'}\cdot R^{\psi}_{z}\begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad (4)$$

where the rotational axes are

$z = [0 \quad 0 \quad 1]$, $x' = [\cos\psi \quad \sin\psi \quad 0]$, and $z'' = [\sin\psi\sin\rho \quad -\cos\psi\sin\rho \quad \cos\rho]$, and the rotation matrix is

$$R^{\theta}_{u=[x \;\; y \;\; z]} = \begin{bmatrix} x^2 + (1-x^2)\cos\theta & xy(1-\cos\theta) - z\sin\theta & zx(1-\cos\theta) + y\sin\theta \\ xy(1-\cos\theta) + z\sin\theta & y^2 + (1-y^2)\cos\theta & yz(1-\cos\theta) - x\sin\theta \\ zx(1-\cos\theta) - y\sin\theta & yz(1-\cos\theta) + x\sin\theta & z^2 + (1-z^2)\cos\theta \end{bmatrix}\begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

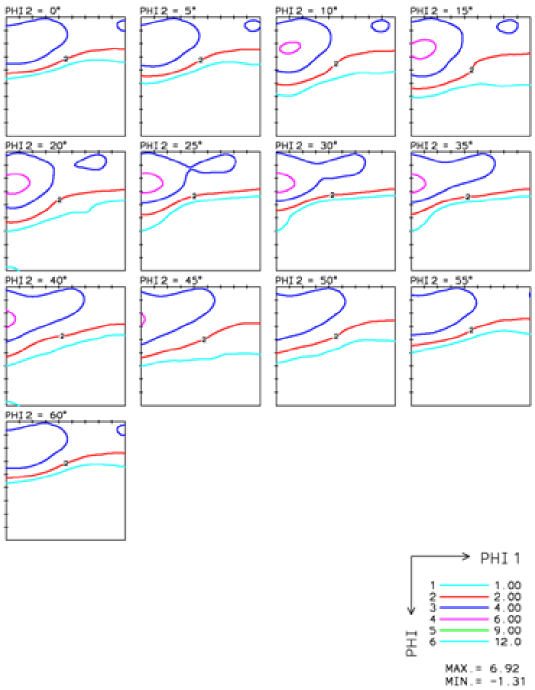

Fig. 2. Orientation distributional function of the HANA-6 strip final annealed at 600°C for 10 min.

Figure 2 shows ODF data for the 660℃ for 4 h annealed strip. It is found that the rotation angles are ψ = ~10°, ρ = ~30°, and η = 10~25° as shown in Fig. 2. The operative slip system can be calculated with the obtained orientational information. In the calculation, critical resolved shaer stress was used as 525 MPa for the basal slip and the pyramidal slip, and 164 MPa for the prismatic slip [5].

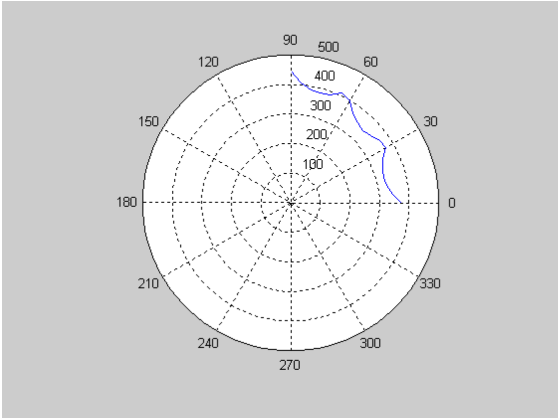

Fig. 3. Yield strength of the strip final annealed at 600°C for 10 min depending on loading directions.

With the given lattice, the Schmid factor depending on the sample orientation and corresponding yield strength was calculated as shown in Fig. 3. According to the calculation, the 45° direction shows the lowest yield strength. This result coincides with the creep behaviors in our experiments [3].

3. Conclusions

The behavior of creep depending on geometric orientations was analyzed by using yield criteria (Schmid factor). The proposed model matched well with the experimental results. Especially, the fastest creep rate in the 45° direction for the 660℃ for 4 h annealed samples was anticipated with the current study.

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