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Thermo-mechanical Behavior of a H4 Outer Strip in the Transverse Direction

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1. Introduction

Zirconium alloy shows an anomalous deformation behavior due to a dynamic strain ageing over the temperature range of 200～600°C which includes a reactor operation temperature [1-3]. In the temperature range, the flow stress is not sensitive to the temperature. The athermal behavior of a stress and a strain could be explained by the interaction of a thermally activated dislocation with impurities in α-Zr [1-3]. H4 (Zr-1.5Nb-0.4Sn-0.2Fe) alloy, which had been in a form of tube, showed some characteristics on the dynamic strain ageing behavior when the alloy was deformed in the longitudinal direction in the range of 25°C to 500°C at the strain rate of 8.33×10^{-5}/sec and 1.67×10^{-2}/sec [3]. In addition to the study on the alloy in the longitudinal direction, the dynamic strain ageing behavior of the alloy in the transverse direction was studied through a tensile test with a slow and a fast strain rate in the temperature range of 25°C to 600°C by using a strip material.

2. Methods and Results

Test material was cut from the H4 strip material of a Zr-1.49Nb-0.38Sn-0.2Fe-0.11Cr alloy which was finally heat-treated for about 10 minutes at 580°C. It contained 1,548ppm oxygen, 98ppm silicon, 90ppm carbon, 21ppm hydrogen and 10ppm nitrogen as impurities. With the specimens in the transverse direction with 12.5 mm in gage length, the tensile tests were carried out in a furnace chamber at room temperature, 200, 250, 300, 316, 340, 400, 500 and 600°C after temperature stabilization for 20 minutes. The specimens were deformed with the strain rate of 8.33×10^{-5}/sec and 1.67×10^{-2}/sec. The deformation of the specimens was measured from the displacement of the cross head. The 0.2% offset method was employed to obtain the yield stress. The slop line for getting the yield stress on the stress-elongation curve was shifted to a position where a large load drop occurred on the curve over the ultimate tensile stress. And then the elongation at load zero which intersected the slop line was assumed to be a total elongation.

2.1 Texture analysis

The texture of the H4 strip material had been determined by the X-ray diffraction technique to calculate Kearn's parameters [4] of the specimen which were in the normal, transverse and rolling directions were $f_{ND} = 0.73$, $f_{TD} = 0.20$ and $f_{RD} = 0.07$, respectively.

2.2 Stress-strain curves

Fig. 1 shows the stress-strain curves of the H4 strip material when it was strained with 1.67×10^{-2}/sec and 8.33×10^{-5}/sec in the transverse direction at room temperature to 600℃.

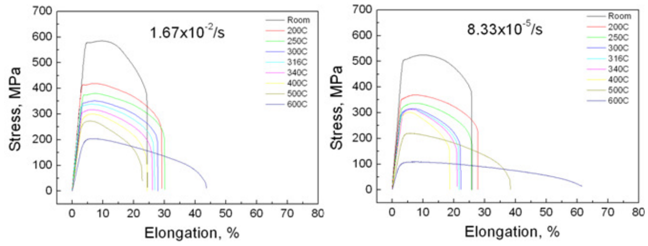

Fig. 1 stress-strain curves of the strip in the transverse direction at the different temperature

With an increase of the temperature, the stress and Young's modulus of the H4 strip decreased but the ductility increased after being decreased in the range of 200～500°C although the range was a little different from each other when the specimens were strained with a different speed.

2.3 Shear stress and strain rate sensitivity

The shear stress τ_T at the absolute temperature T was calculated from the yield stress σ_y, using the relation $\tau = \sigma_y/m$, where m is the Taylor factor. The m is assumed to be equal to 4 [5]. Theoretical shear stress at T [6] is given by:

$$\sqrt{\tau_T} = \alpha - \beta \sqrt{T} \quad \text{------------------------------ (1)}$$

Where, α and β are constants, and T is the absolute temperature.

Fig. 2 shows the change in the τ_T of the H4 strip in the transverse direction with temperature.

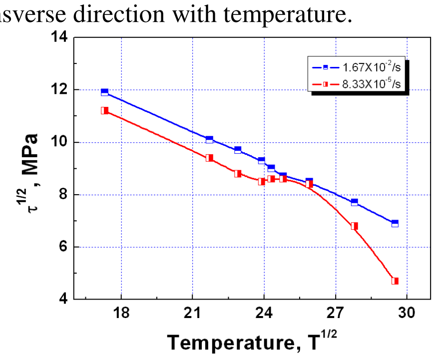

Fig. 2 Change of shear stress of the H4 strip strained with 1.67×10^{-2}/s and 8.33×10^{-5}/s in the transverse direction at the different temperature

The shear stress of the H4 strip was located over a hypothetical slope line when it was strained with a slow speed while the stress decreased almost along another hypothetical slope line when it was strained with a fast speed. The larger τ_T of the strip with temperature could come from the dynamic strain ageing [3, 7].

The strain rate sensitivity *m* can be calculated by:

$$m = \frac{d(\ln\sigma)}{d(\ln\dot{\varepsilon})} \approx \frac{\ln\sigma_2 - \ln\sigma_1}{\ln\dot{\varepsilon}_2 - \ln\dot{\varepsilon}_1} \quad \text{------------------- (2)}$$

Where, $\dot{\varepsilon}_1$ was 1.67×10^{-2} / sec , $\dot{\varepsilon}_2$ was 8.33×10^{-5} / sec

σ_1 and σ_2 were yield stresses at 0.2% offset strain when the alloy was strained with $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, respectively. Fig. 3 shows the elongation and m of the H4 strip in the transverse direction depending on the temperature.

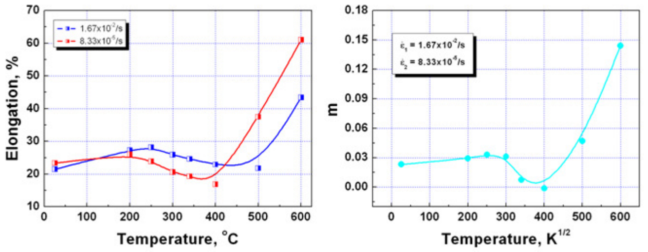

Fig. 3 Change of elongation and strain rate sensitivity of the strip strained with 1.67x10^{-2}/s and 8.33x10^{-5}/s in the transverse direction at the different temperature

The dynamic strain ageing of an alloy would accompany a low ductility and low strain rate sensitivity. The temperature range of dynamic strain ageing moves toward a higher temperature [7] when the alloy is deformed with a faster strain rate. The *m* of the H4 strip decreased from 200°C to 400°C similar to the change of its elongation.

2.4 Ultimate tensile stress and work hardening exponent

After yielding, work hardening of the H4 strip material will be made in accordance with the following the empirical Hollomon's relation.

$$\sigma = A\cdot\varepsilon^n \quad \text{----------------------------- (3)}$$

Where, σ is true stress, *A* is material constant, ε is true plastic strain, *n* is work hardening exponent. The *n* is closely related to the multiplication of dislocation in the plastic range. Because the interaction of dislocation with solute atoms or precipitates, further plastic deformation will need more stress. Fig. 4 shows the change of ultimate tensile stress and work hardening exponent of the H4 strip. The ultimate tensile stress of the strip also decreased with the increase of temperature as the shear stress. The ultimate tensile stress of the H4 strip still shows an athermal behavior especially at 340～400℃ due to the dynamic strain ageing. The accumulation of a dislocation or an increase of its density during a plastic deformation brings about an increase of the *n*. The *n* of the H4 strip would decrease with the increase of temperature by 400～500°C because the *n* at the elevated temperature might be lowered by the dislocation annihilation with the aid of thermal fluctuation. However, the *n* would be higher at 600°C than 500°C because the precipitation of β-Zr was available at 600°C where the effect of the β-Zr precipitates on increasing the *n* value as an obstacle to move dislocations might outweigh the effect of the thermal fluctuation on the dislocation annihilation which decreases the *n* [8].

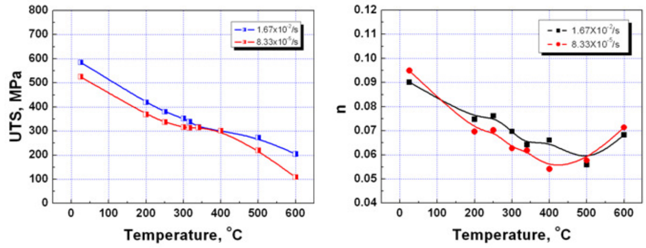

Fig. 4 Change of ultimate tensile stress and work hardening exponent of the strip strained with 1.67x10^{-2}/s and 8.33x10^{-5}/s in the transverse direction at the different temperature

3. Conclusion

H4 strip showed some characteristics of a dynamic strain ageing behavior in the transverse direction when it was deformed with the strain rates of 8.33x10^{-5}/sec and 1.67x10^{-2}/sec in the temperature range of 25°C to 600°C as follows:

(1) The shear stress was higher than the expected one when the H4 was strained with 8.33x10^{-5}/sec and it is remarkable at 340～400℃.

(2) Elongation and strain rate sensitivity were decreased at the temperature range of 200～500℃.

(3) The work hardening exponent was decreased with the increase of the temperature by 400～500°C but it increased at 600°C. An additional precipitation hardening could affect the increase of the exponent due to the β-Zr precipitates at 600°C.

Acknowledgement

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