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《Original》

The Influence of Temperature and Strain Rate on the Mechanical Behavior in Uranium

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Abstract

The effect of temperature and strain rate on the deformation behavior of α-uranium was investigated in the temperature ranged 300° to 550°C by strain rate change test. Strain rate sensitivity, activation volume, strain rate sensitivity exponent and dislocation velocity exponent were determined. The strain rate sensitivity exponent and dislocation velocity exponent were determined. The strain rate sensitivity exponent increases with strain below 400°C, while the exponent decreases with strain above 500°C. It is believed that the increase of strain rate sensitivity exponent with strain below 400°C can be attributed to an increase in internal stress as a result of work hardening while decrease of the exponent with strain above 500°C is due to predominance of thermal softening over work hardening because more slip system are active in defor- mation above about 500°C.

요 약

온도 및 연신율변화 (strain-rate change)가 α-uranium의 변형거동에 미치는 영향을 300°C에서 550°C까지 연구하였으며, strain rate sensitivity, activation volume, strain rate sensitivity exponent 및 dislocation velocity exponent을 조사하였다. 400°C 이하에서 strain rate sensitivity exponent는 strain의 증가에 따라 증가하였으나 500°C 이상에서는 strain의 증가에 따라 감소하는 경향을 나타냈다. 400°C 이하에서는 strain에 의해 생기는 가공경화로 인한 내부 응력의 증가가 strain rate sensitivity exponent에 영향을 미치나 500°C 이상에서는 많은 slip system이 변형에 기여하게 되므로 가공경화 보다는 thermal softening이 더 큰 영향을 미쳐서 strain rate sensitivity가 감소된다고 추측된다.

1. Introduction

The mechanical properties of metallic uranium have been investigated extensively[1-8], because the metallic uranium and its alloys are widely used in the research and experimental reactor as nuclear fuels. However comparatively few data have been reported on the thermally activated flow, strain-rate sensitivity, dislocation velocity exponent and activation volume for the deformation.

The dynamic theories of yielding[9,10], which are based on the concept of intrinsic relation between dislocation velocity and stress, make it possible to interpret the strain-rate change data in term of properties of dislocation. The dynamic theories of yielding are derived from the following well known two relationships:

$$\dot{\varepsilon}=Nbv \quad\cdots\cdots(1)$$

and $$v\sim\left(\frac{\sigma}{2\tau_c}\right)^m \quad\cdots\cdots(2)$$

where $\dot{\varepsilon}$ is strain-rate, N is the number of mobile dislocations, b is Burgers' vector, v is dislocation velocity, σ is true stress, τ_c is critical resolved shear stress, and m are constants for a given material and temperature.

The parameter, m, is strongly related to the dislocation velocity and it has been shown that the smaller dislocation velocity exponent will give the larger yield drop in stress-strain test and delay time in creep test[11]. The dislocation velocity exponent is also used to interpret crack propagation[12,13].

Therefore the dislocation velocity exponent is very valuable to determine the mechanical behaviors of crystal.

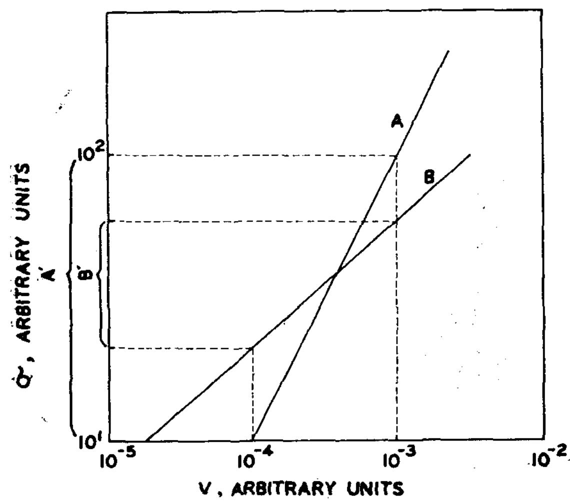

Fig. 1. Illustrative deawing relating stress to the dislocation velocity exponent

In the dynamic theories of yielding, the stress dependence of dislocation veloity can be determined from the strain-rate sensitivity. As shown in Fig. 1, if a strain-rate is chosen to correspond to a dislocation velocity of 10^{-4} and then the strain-rate is increased by a factor of 10, the dislocation velocity must increase to 10^{-3} if no more mobile dislocations are created. Therefore it is evident that the stress change to create same change in dislocation velocitty is much greater for material A than or material B, i.e. the strain-rate sensitivity of material A is much greater.

The dislocation velocity exponent can be directly measured by using etch pit methods[10,14,15], but this method is a very difficult and tedious work. Therefore Guard[16] has suggested it would be desirable to obtain information regarding the dependence of dislocation velocity on stress from measurement of strain-rate sensitivity.

In the present work, the effect of strain-rate and temperature on the mechanical behavior of polycrystalline uranium was investigated by the strain-rate change experiments.

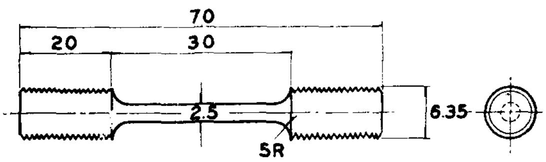

Fig. 2. Uranium tensile specimen (dimension in mm)

2. Experiment

The material used in this investigation was extruded high purity uranium rod of 1/4 inch in diameter, chemical composition of which is in Table 1. The rod was milled into tensile specimen of the dimension as shown in Fig. 2 and the specimen was then polished with emery papers. In order to get a fine and homogeneous grain size the specimen was annealed in vacum of 2×10^{-4} mmHg at 640°C for 15 hours and furnace-cooled to room temperature.

Table 1. Chemical composition of uranium (all ppm except U)

Element	Content	Element	Conte t
U	99.9%	Ni	1C0
Al	20	C	500
Cu	20	N	25
Fe	100	O	100

Tensile test was made on an Instron tensile testing machine equipped with a push-button gear box used for the strain-rate changes. The experiment was carried out in a helium atmosphere at several temperatures in the range of 300° to 550°C, after holding the specimen for 30 min at each testing temperature. For changes in strain rate, the cross-head speed of the Instron tensile testing machine was cycled between 0.1 and 1mm/min, which corresponds to a nominal strain rate of 8.3×10^{-4} and 8.3×10^{-5} sec^{-1}, respectively.

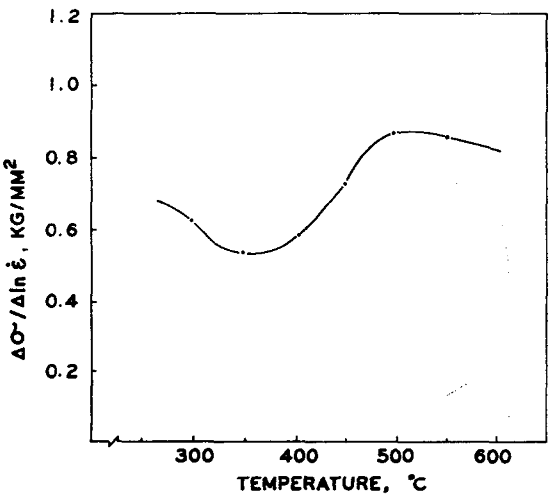

Fig. 3. Temperature Dependence of the strain rate sensitivity, $\Delta\sigma/\Delta\ln\dot{\varepsilon}$, of uranium

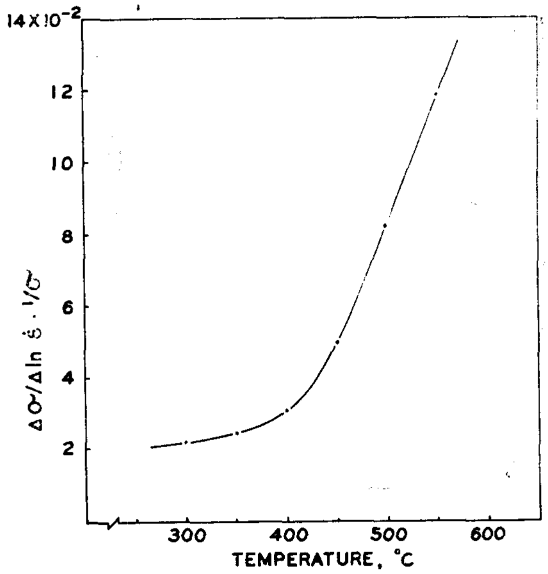

Fig. 4. Temerature dependence of the selative strain rate sensitivity $\Delta\sigma/\Delta\ln\dot{\varepsilon}\cdot1/\sigma$ of uranium

3. Results and Discussion

The strain-rate sensitivity, $\Delta\sigma/\Delta\ln\dot{\varepsilon}$, is plotted in Fig. 3 as a function of temperature. The stress change, $\Delta\sigma$, is the mean increase of true stress that is measured when strain-rate is changed for upward in the range of plastic deformation. A maximum of the strain-rate sensitivity is found near 500°C and then the rate sensitivity decreases slightly with increasing temperature, while the minimum of rate sensitivity is appeared at approximately 350°C. These reduction of stress change due to strain-rate change above 300° to 400°C is believed that the low viscosity of grain boundaries are significant factor in the flow stress in the range of 300° to 400°C as shown in creep experiment[17].

The fluctuation of rate sensitivity dependent on temperature also appeared in the Fe—Ni alloy. By the Hildebrandt[18] a maximum of the rate sensitivity is found in the range of

100° to 200K and the minimum is appeared between 400° and 500°K dependent on Ni—content. Fig. 4 shows the relative strain-rate sensitivity, $1/\sigma$. $\Delta\sigma/\Delta\ln\dot{\varepsilon}$, as a function of temperature. The value of $1/\sigma$. $\Delta\sigma/\Delta\ln\dot{\varepsilon}$ increases with temperature, especially it increases rapidly above 400°C.

Since the strain rate sensitivity exponent, m^*, is proportional to $(\Delta\ln\sigma)^{-1}$ as shown in equation (3) and Δ ln σ is equal to ln $[(\sigma+\Delta\sigma)/\sigma]$, it follows that the sensitivity exponent, m^*, is proportional to ln $[1+\Delta\sigma/\sigma]^{-1}$. Therefore, strain-rate sensitivity exponent have a maximum value where strain-rate sensitivity has a minimum. Fig. 5 shows the strain-rate sensitivity exponent as a function of true strain. The value of senstiivity exponent, m^*. increases with strain below 400°C, while slightly decreases above 500°C. Friedel[19] has sueggsted that the change of certain physical properties of uranium with increasing temperature are due to the weakening of covalent bonds because α-structure contains a significant degree of covalent bonding between atoms.

This theory can interpret the main features of variation of τ_c/μ_b, τ_c is critical resolved shear stress and μ_b is shear modulus, with temperature for different slip systems as shown in Fig. 5[8]. At low temperature (010) [100] and (110) $(1\bar{1}0)$ slip system are mainly contributed in deformation, but above about 500°C, (010) [100], [110] $[\bar{1}\bar{1}0]$ and (001) [100] slip system are active and (021) $[1\bar{1}2]$ slip system is also operate. Considering these results, it is not conclusive but believed that the increase of sensitivity exponent, m^*, with strain below 400°C can be attributed to an increase in in ternal stress as a result of work hardening, while decrease of the exponent, m^*, above about 500°C is due to predominance of thermal softening process over work hardening because more slip systems are active during deformation.

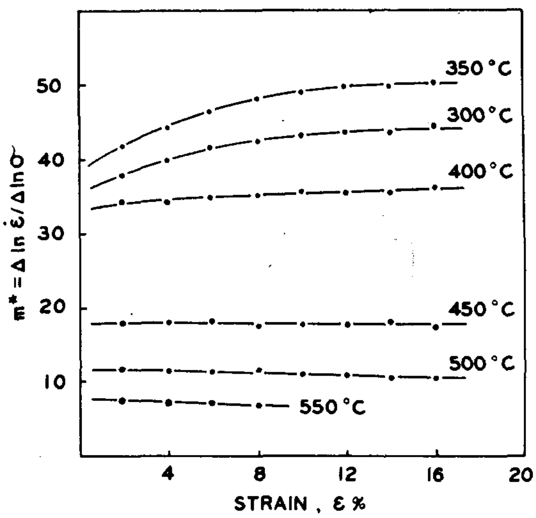

Fig. 5. Strain rate sensitivity exponent m^* as a function of true strain

On the basis of dynamic theories of yielding [9,10], the dislocation velocity exponent can be obtained from the strain rate sensitivity. If we take logarithms of both sides of equation (1) and differentiate with respect to stress we obtain

$$\frac{\partial\ln\dot{\varepsilon}}{\partial\ln\sigma}=m^*=\frac{\partial\ln v}{\partial\ln\sigma}+\frac{\partial\ln N}{\partial\ln\sigma}\quad\cdots\cdots\cdots(3)$$

From equation (2) it is seen that $\partial\ln v/\partial\ln\sigma=m$, so that

$$m^*=m+\frac{\partial\ln N}{\partial\ln\sigma}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

where $m^*$is strain-rate sensitivity exponent, m is dislocation velocity exponent, and N is number of mobile dislocations. Since the strain-rate sensitivity exponent, m^*, is a function of $N[\sigma(\varepsilon)]$ Guard[16] points out that strain-rate sensitivity exponent, m^*, is equal to dislocation velocity exponent, m, if the second term, ln N/∂ ln σ, in equation (4) is negligible. Therefore extrapolating the strain-rate sensitivity exponent, m^*, to zero strain gives dislocation velocaity exponent. In Fig. 5, the intersection of the strain-rate sensitivity exponent, m^*, with the ordinate at zero strain gives dislocation velocity exponent, m, of polycrystalline uranium. The obtained maximum value of velocity

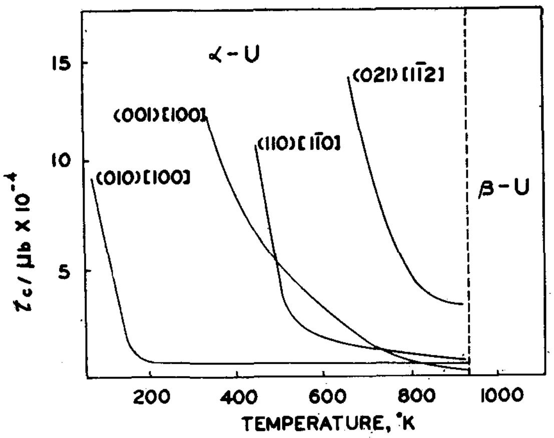

Fig. 6. The variation with temperature of τ_c/μ_b (C. R. S. S/shear modulus) for the slip modes (after daniel[8])

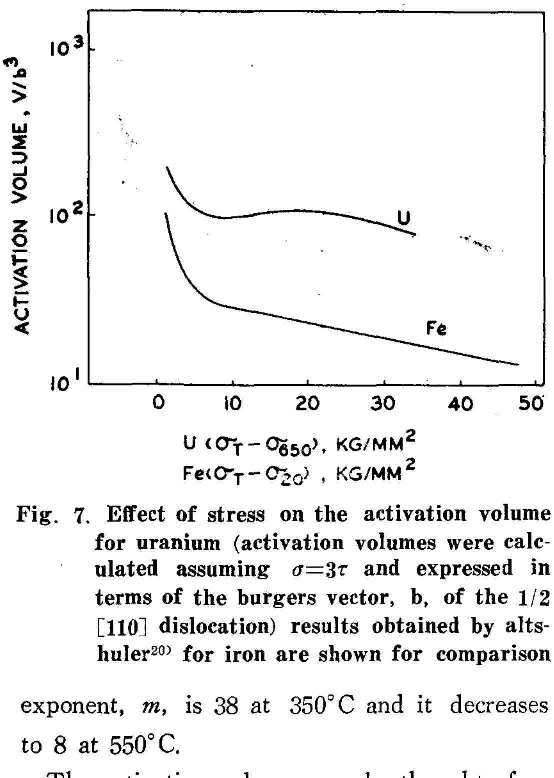

Fig. 7. Effect of stress on the activation volume for uranium (activation volumes were calculated assuming $\sigma=3\tau$ and expressed in terms of the burgers vector, b, of the 1/2 [110] dislocation) results obtained by altshuler[20] for iron are shown for comparison

exponent, m, is 38 at 350°C and it decreases to 8 at 550°C.

The activation volume may be thought of as the product of the Burgers' Vector of a dislocation and the area swept by the dislocation in overcoming a barrier to motion. This volume can be calculated using the following relationship:

$$V=KT\left(\frac{\partial \ln \dot{\varepsilon}}{\partial \tau}\right)_T \quad \cdots\cdots(5)$$

where V is activation volume, K is Boltzmann's constant, $\dot{\varepsilon}$ is strain-rate and $\sigma\tau$ is the change of shear stress during change of strain-rate. Therefore, activation volume can be obtained using the data obtained by strain-rate change test at constant temperature, provided that the relationship between the applied stress, σ, and the shear stress, τ, is known. The calculated value of activation volume is shown in Fig. 6 as a function of stress. At 550°C the activation volume is approximately $110b^3$ (where b is Burger's vector for the 1/2 [110] dislocation) and it seems likely that the larger value would be obtained at higher temperatures.

4. Conclusion

From the experimental results, the specific observations are:

(1) The strain-rate sensitivity, $\Delta\sigma/\Delta\ln\dot{\varepsilon}$, has a minimum at near 350°C and a maximum at 500°C, but relative strain-rate sensitivity, $\Delta\sigma/\Delta\ln\cdot 1/\sigma$, increases with increasing temperature.

(2) Below 400°C the strain-rate sensitivity exponent, m^*, increases with strain while decreases above 500°C. It is believed that the increase of strain-rate sensitivity exponent with strain below 400°C can be attributed to an increase in interal stress as a result of work hardening and the decrease of the exponent with strain above 500°C is due to predominance of thermals oftening over work hardening during deformation.

(3) Activation volume is approximately $110b^3$ (where b is Burger's vector for the 1/2 [110] dislocation) at 550°C, but it seems likely that the larger value would be obtained at higher temperature in α-uranium.

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