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Rate Controlling Mechanism on Copper at Very High Strain Rates and High Temperatures

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Abstract. In order to clarify the rate controlling mechanism of FCC metals at the high strain rates, a test is conducted for high-purity polycrystalline copper in the strain rate range from about $1\times10^3 \sim 2\times10^4$/s at temperatures ranging up to 600K. A simplified model for a dislocation kinetics under a dynamic plastic deformation is used to consider the deformation mechanism in the above strain rate and temperature ranges. The increase in the mobile dislocation density with increasing temperature lowers the flow stress and shifts the transition range to the higher strain rate side. The results indicate also that a internal stress decreases slightly with increasing a temperature, which reflects the temperature dependency of *cross-slip* of a screw dislocation. It is confirmed that a steep increase of the flow stress observed at the high strain rates is attributed to the transition in a rate controlling mechanism of a dislocation motion from the thermal activation to the phonon drag.

Key Words : High Strain Rate, Thermal Activation Process, Phonon Drag

1. INTRODUCTION

It is widely recognized that a strain rate sensitivity of the flow stress "$d\sigma/d\log\dot{\varepsilon}$" in the metallic materials increases steeply above a critical strain rate of about 5×10^3/s. In the case of FCC metals, below the critical strain rate the flow stress increases lineally with logarithm of the strain rate, while above the critical strain rate it increases lineally with the strain rate itself. The steep increase in "$d\sigma/d\log\dot{\varepsilon}$" which becomes from the strain rate of about 5×10^3/s has an effect on the mechanical properties of the metallic materials at the high strain rates, however, the deformation mechanism caused the above mentioned phenomenon is not fully understood. For this phenomenon, two contrasting interpretations have been given. One ascribes the phenomenon to the transition in the rate-controlling mechanism of dislocation motion [1]. This is the interpretation based upon the role of the instantaneous strain rate. The other interpretation ascribes the phenomenon to the internal structure evolution which reflects the strain rate history [2]. It has been generally accepted that the flow stress of the metallic materials at a given strain depends upon both the instantaneous strain rate and the strain rate history. For understanding the mechanism of the steep increase in "$d\sigma/d\log\dot{\varepsilon}$" and, further, for deriving constitutive equations which cover a wide range of strain rate, it is indispensable to confirm the relative importance between the above mentioned two roles at the high strain rates. Recently, Sakino and Shioiri [3, 4, 5] developed a new system for the strain rate change test and conducted a decremental strain rate tests for copper at strain rate above about 5×10^3/s. The results indicated that the instantaneous strain rate played a dominant role in the remarkable rise in the flow stress at very high strain rates. Shioiri and Satoh [6] represented that on the basis of the results obtained from their ultrasonic attenuation test made on copper at the high strain rates and high temperatures, the rate controlling mechanism of the dislocation motion shifted from the thermal activation to the phonon drag. The above experiment had been done in the strain rate range only up to 8×10^3/s, whereas the test in the strain rate range above about 1×10^4/s in which the dislocation motion seems to be controlled completely by the phonon drag is required to define whether or not the steep increase in "$d\sigma/d\log\dot{\varepsilon}$" can be expressed by the transition in the rate controlling mechanism.

This paper concerns the transition in the rate controlling mechanism for high-purity copper in the strain rate range from about $1\times10^3 \sim 2\times10^4$/s at temperatures ranging up to 600K. The results obtained are analysed on the basis of the dislocation kinetics.

2. EXPERIMENTAL METHOD

The flow stress measurements were performed on copper (OFHC, annealed in a vacuum for 3 hr at 600 ℃) at 290, 450 and 600K with a modified Hopkinson bar system. Specimens were machined to 1.5 and 2.0 mm in both length and diameter. In this system, a impact bar compresses directly the specimen attached at the end of a pressure bar with silicon grease which is proof against high temperature. The flow stress is measured with two semiconductor strain gauges attached to the pressure bar. The signal from the strain gauges is amplified with a wide-band amplifier and stored in a high-speed digital memory (sampling time: 0.1 μs). The impact bar is

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made of Ti-6Al-4V alloy and the diameter is 13 mm. The output bar was made of tungsten. Its diameter and length are 4 mm and 400 mm, respectively. Using the one-dimensional bar wave approximation and considering elastic deformation of the impact bar and output bar caused by the flow stress of the specimen, the instantaneous strain rate of the specimen is obtained in the following form:

$$\dot{\varepsilon} = \frac{1}{\ell_0}\left(V_0 - \frac{a_0\sigma}{A_1 c_1 \rho_1} - \frac{a_0\sigma}{A_2 c_2 \rho_2} \right) \qquad (1)$$

where V_0 is the initial velocity of the impact bar; ρ, c and A are the density, bar wave velocity and cross-sectional area, respectively; subscripts 1 and 2 correspond to the impact bar and pressure bar, respectively; a_0, ℓ_0 and σ are the initial cross-sectional area, initial length and instantaneous nominal flow stress of the specimen, respectively. The mass of the specimen is neglected. The true stress is calculated assuming the deformation of the specimen to be uniform.

To obtain high time resolution capability in the stress measuring system, an inverse analysis is applied to the stress data recorded in the digital memory using the experimentally determined transfer function of the stress measuring system. The real stress response of the specimen can be obtained from the form of the Fourier transform as follows:

$$X(\omega) = Y(\omega)/G(\omega) \qquad (2)$$

where $X(\omega)$, $Y(\omega)$ and $G(\omega)$ are Fourier transforms of the real flow stress, of the recorded flow stress and of the transfer function (impulse response) of the stress measuring system, respectively.

3. RESULTS AND DISCUSSION

The strain rate change tests after Sakino and Shioiri [3, 4, 5] have shown that the flow stress depends primarily on the instantaneous strain rate and the strain rate history is secondary. This means that the strain rate dependency of the flow stress is caused mainly by the rate controlling mechanism of the motion of the dislocation. In the following, analysis is made on the basis of the dislocation kinetics [6, 7, 8]. In FCC metals, since the Peierls force is negligibly small, the phonon drag is the intrinsic drag upon dislocation motion. As the extrinsic drag in pure metals, the forest dislocations to be cut through with the aid of the thermal activation should be considered. The mobile dislocation segments move repeating the thermally assisted cutting of the forest dislocations and the phonon drag controlled jump motion alternately. By simplifying the above motion of the dislocation segments, the rate of the shear strain can be given by the following type equation [6, 9]:

$$\dot{\gamma} = \frac{NL^2 b}{t_t + t_v} = \frac{NL^2 b}{\nu^{-1}\exp\{-[U-Lb^2(\tau-\tau_a)]/kT\} + LB/(\tau-\tau_a)b} \qquad (3)$$

where t_t is the waiting time for the thermally assisted cutting, t_v is the time required by one jump motions under the control of the phonon drag, N is the number of the moving segments per unit volume, L is the distance between the adjacent forest dislocations, b is the Burgers vector, U is the activation energy of cutting, ν is the frequency factor, k is the Boltzmann constant, T is the absolute temperature, τ is the resolved shear stress, τ_a is the internal stress, and B is the phonon drag coefficient. At lower strain rate (i.e. at lower stresses) $t_t \gg t_v$ and Eq. (3) can be approximated as

$$\dot{\gamma} \fallingdotseq NL^2 b\,\nu \exp\{-[U-Lb^2(\tau-\tau_a)]/kT\} \qquad (4)$$

This is the thermal activation flow rate-controlled by the thermally assisted cutting of the forest dislocations, in which the flow stress depends linearly upon the logarithm of the strain rate. At very high strain rates (i.e. at higher stresses) $t_t \ll t_v$ and Eq. (3) is approximated as

$$\dot{\gamma} \fallingdotseq NLb^2\,\tau/B \qquad (5)$$

This is the phonon drag controlled viscous flow in which the flow stress depends linearly upon the strain rate itself. As seen above, Eq. (3) can cover a wide strain rate range including thermal activation flow range and the phonon drag controlled flow range together with the transition range between them. Figure 1 shows $\tau - \log\dot{\gamma}$ curves predicted from Eqs. (3), (4) and (5). The flow stress curve shown by the solid line increases abruptly at some strain rate in which the transition in the rate controlling mechanism is expected to occur.

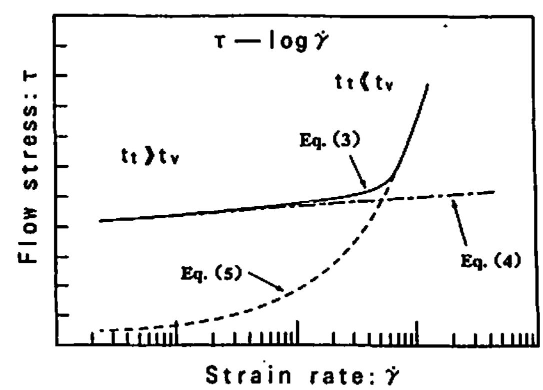

Fig. 1 Theoretical prediction given in Eqs.(3), (4) and (5).

Nowadays, it is possible to use the reliable values for the most of the physical constants and quantities in Eq. (3). The values of B at elevated temperatures are obtained by extrapolating the data given in Ref. [10]. The used values of the physical constants and quantities are presented in Table 1.

Table 1: Physical constants and quantities of copper.

	Copper	Unit
G	44	GPa
b	2.5×10^{-10}	m
ν	1×10^{13}	s^{-1}
B	1.35×10^{-6} (T=290K) [10]	Pa s
	2.02×10^{-6} (T=450K)	Pa s
	2.67×10^{-6} (T=600K)	Pa s
U	$Gb^3/5$ [11]	

The unknown quantities in Eq. (3) are the mean distance between the adjacent forest dislocations, L, the density of moving dislocations, NL, and the long range athermal stress τ_a. Those quantities will depend upon the structure formed during the deformation, and in the present treatment the values of those quantities are determined so that a good fit of the predicted curves to the experimental data is obtained. If L, NL and τ_a are independent of the strain rate, L is determined from the gradient of the σ vs. log $\dot{\varepsilon}$ plot of the experimental flow stress in a relatively low strain rate range where σ is linearly dependent upon log $\dot{\varepsilon}$. NL is determined from the strain rate at which the flow stress begins to rise steeply, and τ_a is determined to obtained a good fit in the stress level. The Taylor factor is assumed to be 3.07. Thus determined L, NL and τ_a at T=290K are shown in Table 2.

Table 2: Determined values of L, NL and τ_a for copper.

	Copper 290K (ε =0.1)	Unit
L	6.56×10^{-8}	m
NL	2.21×10^{11}	m^{-2}
τ_a	46.0	MPa

The curves predicted by Eq. (3) using the above numerical values are shown in Fig. 2 together with the experimental flow stress data. In the calculation, it is assumed that NL, L and τ_a are independent of the temperature. Over the wide range of strain rates, the calculated curves at each temperature except for 290K in both figures are not in agreement with directly measured values and further, a temperature dependency of the flow stress is reverse at higher strain rates in which the motion of the dislocation is controlled in the phonon drag manner.

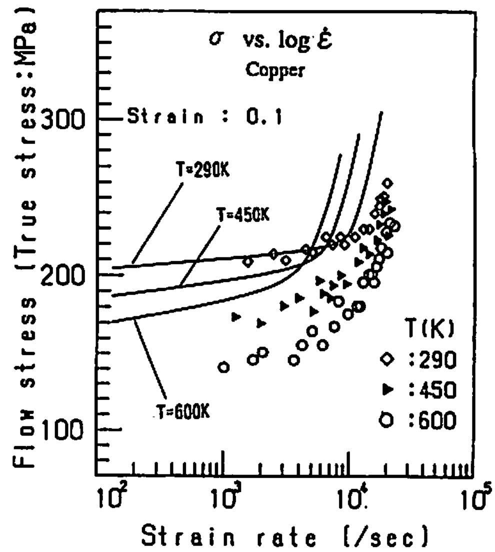

Fig.2 Comparison of measured results (◇▲○) with calculated results (——) for copper.

Such the reverse is not observed in the directly measured data. It may be adequate for this contradiction to consider that the mobile dislocation density is an increasing function of temperature [6]. Because the relative short mobile dislocations caught in the forest dislocations will be also able to move with the aid of thermal fluctuation.

As shown in Fig. 3, it is necessary to take into consideration the temperature dependency not only of the mobile dislocation density but also of the internal stress τ_a. Here, the movement of the screw dislocation from one slip to another takes place by a process known as

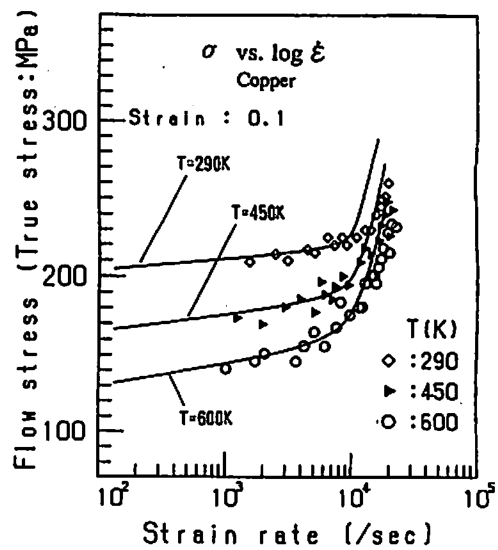

Fig.3 Comparison of measured results with the predictions when NL is an increasing function of temperature for copper.

cross-slip which is easy for a high stacking fault energy material such as aluminium where partial dislocation separation is small. Conversely, a widely separated partial fault energy prevent the screw dislocation from *cross-slip*, dislocations in material such as copper with a low stacking so that a large number of the dislocations pile up against a barrier on the slip plane, thereby increasing the internal stress. It is generally known that *cross-slip* of an extended screw dislocation around obstacles is not permitted without thermally activated processes. It is assumed, therefore, that for copper the internal stress decreases slightly with increasing temperature. On the basis of the above consideration, the determined values of NL and τ_a at each temperature are shown in Table 3.

Table 3: Determined values of NL and τ_a for copper at each temperature.

	Copper (ε =0.1)		Unit
	450K	600K	
NL	3.51×10^{11}	4.93×10^{11}	m^{-2}
τ_a	40	35	MPa

Figure 4 shows the transition in the rate controlling mechanism of the dislocation motion in terms of $t_v/(t_t + t_v)$. The curves in this figure were calculated from Eq. (3) by using the same numerical values as in the calculation of the curves in Figs. 2 and 3. The broken and solid curves correspond to those in Figs. 2 and 3, respectively. The transition gradually occurs through the strain rates from 10^3 to 10^4/s. In the case of phonon drag flow, the value of $t_v/(t_t + t_v)$ is approximately unity. The values are nearly equal to those presented in the other papers [2,6,12].

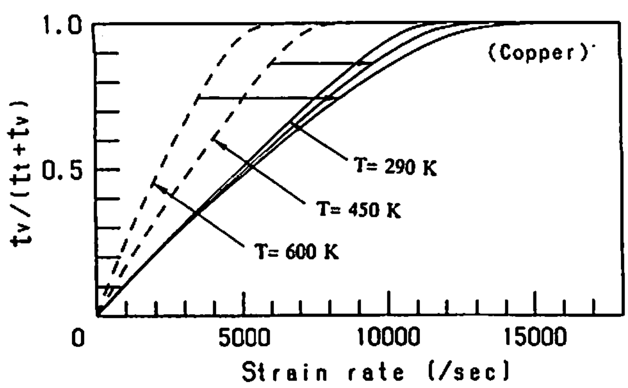

Fig.4 Transition in the rate controlling mechanism of the dislocation motion in Figs. 2 and 3 in terms of $t_v/(t_t+t_v)$: ------ corresponds to the curves in Fig. 2 ; —— corresponds to the curves in Fig. 3 .

It is shown that the increase in the mobile dislocation density caused by increasing temperature expands the transition range to the higher strain rate side. This indicates that at higher temperature the effect of the phonon drag on the flow stress becomes explicit at higher strain rates.

4. CONCLUSION

The high strain rate tests were performed for high-purity polycrystalline copper in the strain rate range from about $1 \times 10^3 \sim 2 \times 10^4$/s at temperatures ranging up to 600K. By analysing quantitatively the obtained results on the basis of the dislocation kinetics, it is concluded that the increase in the mobile dislocation density with increasing temperature lowers the flow stress and shifts the transition range to the higher strain rate side. It is confirmed that a steep increase of the flow stress observed at high strain rates is attributed to the transition in the rate controlling mechanism of the dislocation motion from thermal activation flow to the phonon drag flow.

References

[1] Ferguson W. G., Kumar A., and Dorn J. E., J. Appl. Phys. Vol. 38 (1967) pp. 1863-1869.

[2] Follansbee P. S. and Kocks U. F., Acta Metall., Vol.36 (1988) pp. 81-93.

[3] Sakino K. and Shioiri J., JOURNAL DE PHYSIQUE IV, Colloque C3, supplement au Journal de Physique III, Vol.1, octobre (1991) C3-35-42.

[4] Sakino K. and Shioiri J., Trans. Jpn. Soc. Mech. Eng., Vol. 58, No. 553, A (1992)pp. 1703-1709.(in Japanese)

[5] Sakino K. and Shioiri J., Trans. Jpn. Soc. Mech. Eng., JSME International Journal, Series A, Vol. 39, No. 1 (1996) pp. 135-141.

[6] Shioiri J. and Satoh K., JOURNAL DE PHYSIQUE, Colloque C5, supplement au n° 8, Tome 46(1985)C5-3-10.

[7] Shioiri J. and Sakino K., Proc. IUTAM Symp. Impact Dynamics, Eds. ZHENG Zhemin, TAN Qingming, Pecking Univ. Press, Beijing (1994)pp. 224-233.

[8] Shioiri J., Sakino K. and Santoh S., Proc. IUTAM Symp. Constitutive Relation in High/Very High Strain Rates, Eds. Kawata K. and Shioiri J., Springer-Verlag Tokyo (1996) pp. 49-58.

[9] Kumar A. and Kumble R.G., J. Appl. Phy. 40 (1969) pp.3475-3480.

[10] Hikata, A., Johnson, R.A., Elbaum, C., Physical Review B, Vol.2 (1970) pp.4856-4863.

[11] Ashby M. F., Frost H. J., The Kinetics of Inelastic Deformation above 0 K, Constitutive Equations in Palsticity, Ed. Argon, A. S., The MIT Press (1975) pp.117-147.

[12] Lindholm U. S., J.Mech. Phys. Solids 12 (1964) pp.317-335.