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The Effects of Temperature and Strain Rate on the Strength of Polycrystalline Zinc*

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To investigate the compressive strength of polycrystalline zinc, constant strain rate and temperature tests and strain rate and temperature change tests were carried out. The ranges of the strain rate and the temperature of the former tests are from 10^{-4} /s to 7×10^2 /s and from -195°C to 100°C , respectively, and those of the latter are from 10^{-4} /s to 10^{-3} /s and from -195°C to 200°C , respectively. The effects of the temperature and the strain rate upon the strength of polycrystalline zinc are clarified. And, in the static strain rate range, the behaviours at high and low temperatures are interpreted in connection with the thermally activated mechanisms.

1. Introduction

Temperature and strain rate effects upon the strength of zinc single crystals and polycrystals have been studied by many investigators¹⁻⁴. The effects of the temperature and the strain rate on the behaviours of the basal slip of single crystals have been investigated experimentally in wide ranges of the temperatures and the strain rates. The strength of polycrystals at static strain rates has been studied in the ranges of the temperatures above room temperature. It has been discussed in terms of the thermally activated process but is not yet well understood. For polycrystalline zinc, Tegart *et al.*⁵ obtained the activation energy of about 1eV which corresponds to the value of the self diffusion energy of zinc obtained by creep tests with an abrupt change of the temperature, while Cottrell *et al.*⁶ obtained the value of the activation energy of about 0.5 eV from the steady state creep results.

To clarify the effects of the temperature and the strain rate upon the strength of polycrystalline zinc in wide ranges of the temperatures and the strain rates, it is necessary to consider the brittle behaviours and the thermal recovery which affects the strength remarkably even at room temperature. The present paper describes the strength and the deformation behaviours of polycrystalline zinc in the ranges of the temperatures from -195°C to 100°C and of the strain rates from 10^{-4} /s to 7×10^2 /s, and the thermally activated control processes are discussed.

2. Specimen and Experimental Procedure

Material used is zinc ingot of 18mm

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in diameter and the chemical compositions of the material are tabulated in Table 1. Specimens are 6mm both in diameter and in length. Table 2 shows the amounts of pre-strain, the conditions of heat treatment after prestrain and the obtained grain sizes. The conditions of the tests are also tabulated in Table 2.

2.1. Tests at constant temperature and constant strain rate

A 50-ton Amsler universal testing machine and a modified creep testing machine are used for the static (10^{-4} to 10^{-1} /s) and the quasi static (1/s) compression tests, respectively. A split Hopkinson pressure bar apparatus⁷ is used for the dynamic compression tests at the strain rate of $(5 \sim 7) \times 10^2$ /s. The tests were carried out at various constant temperatures. The temperatures are measured by using Alumel-Chromel thermocouples attached to the specimens. The influence of friction between the specimen and the rods is diminished by smoothing the contact surfaces of the rods to the specimen. A cylindrical striker bar of a constant sectional area is used in the split Hopkinson pressure bar apparatus. Because the strain rate is not kept exactly constant during impact, the average values of the strain rates during the deformation are adopted as the strain rates of the specimens. The stress, the strain and the strain rate of the specimen can be calculated as reported elsewhere.

In the present experiment, the stresses on both sides of the specimen are nearly

Table 1 Chemical composition of material

Zn	Cd	Pb	Fe
99.99	0.0009	0.0013	0.0005

Table 2 Condition of heat treatment of specimen and test condition

Prestrain	Annealing condition	Grain size	Test condition
120°C, $\epsilon=10\%$	180°C 30 min	0.21 mm	constant temperature and strain rate
120°C, $\epsilon=20\%$	270°C 40 min	0.25 mm	temperature and strain rate change

identical in the course of the deformation. For convenience of the calculation, the stress is evaluated from the transmitted stress wave. In the following, 'the stress' and 'the strain' represent 'the true stress' and 'the true strain', respectively, and 'the strain rate' is used for 'the nominal strain rate'.

2.2. Tests with abrupt temperature and strain rate changes

To obtain the temperature and the strain rate dependencies on the stress for the identical internal structure, an Instron testing machine was used and the abrupt temperature and strain rate change tests were carried out. The specimens are deformed at 100°C or at -195°C by changing the strain rates from 2.8×10^{-4} /s to 2.8×10^{-3} /s and from 2.8×10^{-3} /s to 2.8×10^{-4} /s periodically. The specimens deformed up to about 7.5% or 15.5% strain at 100°C are rapidly unloaded, and the temperature of the specimen is changed to the required temperature by using the provided vessel. The specimens deformed up to about 4% or 7.5% strain at -195°C are rapidly unloaded, removed from the machine and once kept in

liquid N₂. The specimens are set in the machine again and are heated to the required temperature. After these procedures, the specimens are deformed again at 2.8×10^{-4} /s by periodically changing the strain rate as before. In the experiment, it takes about 2 or 3 minutes to attain the new required temperature.

3. Results and Consideration

3.1.1. Results obtained at constant temperature and strain rate test

Figs.1 and 2 represent some examples of the stress-strain relations at the strain rate of 2.8×10^{-4} /s and $(5 \sim 7) \times 10^2$ /s, respectively. The relations between the stress and the strain rate at 5% and 10% strain are illustrated in Figs.3 and 4, respectively. In the figures, the stresses of 5% and 10% strain linearly increase with an increase of the logarithm of the strain rate in the ranges of the temperatures and the strain rates investigated. The stress of 5% strain at high strain rates ($>10^2$ /s) decreases a little with an increase of the temperature and the stress of 10% strain decreases remarkably with an increase of the temperature.

The strain rate $\dot{\epsilon}$ can be expressed by the equation

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp\{-H(\sigma^*)/kT\}, \quad (1)$$

where T , k and $H(\sigma^*)$ are the absolute temperature, Boltzman's constant and the activation energy, respectively. The thermal component of the stress σ^* is written as

$$\sigma^* = \sigma - \sigma_\mu,$$

Fig.1 Stress-strain relation (static)

Fig.2 Stress-strain relation (dynamic)

Fig.3 Stress-strain rate relation ($\epsilon=5\%$)

Fig.4 Stress-strain rate relation ($\epsilon=10\%$)

where σ and σ_μ are the stress and the athermal component of the stress, respectively. With the assumption that $\dot{\epsilon}_0$ is independent of σ^* and T , the value of the activation energy H_T at constant strain rate can be evaluated⁸ as

$$\begin{aligned} H_T &= k(\partial \ln \dot{\epsilon} / \partial \sigma)_T (\partial \sigma^* / \partial (1/T))_{\dot{\epsilon}} \\ &= k(\partial \ln \dot{\epsilon} / \partial \sigma)_T \{ (\partial \sigma^* / \partial (1/T))_{\dot{\epsilon}} \\ &\quad + (T^2 \sigma_\mu / G)(dG/dT) \} \end{aligned} \quad (2)$$

G is the shear modulus in this equation.

Fig.5 represents the stress of 5% strain to the reciprocal of the temperature relation with the strain rate as a parameter. Above and below room temperature, different kinds of dependencies are observed on the σ to $1/T$ relations and the different kinds of deformation mechanisms may correspond to these different dependencies.

Fig.5 Relation between stress and reciprocal of temperature

Fig.6 Activation energies H_D and H_T to temperature relation

Fig.7 Stress-strain relation (prestrained at 100°C)

Neglecting the temperature variation of G , the temperature dependency of the effective stress, $\partial \sigma^* / \partial (1/T)$, is evaluated from the temperature dependency of the stress, $\partial \sigma / \partial (1/T)$, and Eq.2 becomes

$$H_T = k(\partial \ln \dot{\epsilon} / \partial \sigma)_T (\partial \sigma / \partial (1/T))_{\dot{\epsilon}} \quad (3)$$

The values of H_T can be evaluated by using the values of $(\partial \log \dot{\epsilon} / \partial \sigma)_T$ in Fig.3 and $(\partial \sigma / \partial (1/T))_{\dot{\epsilon}}$ in Fig.5. The values of H_T at 5% strain at various temperatures are represented in Fig.6 in the range of the strain rates from 10^{-4} /s to 10^{-1} /s. In the figure, the values of the activation energy H_D obtained from the abrupt temperature and strain rate change tests which will be mentioned later are also shown. The activation energy H_T of about 0.5eV is obtained in the temperature range from 0°C to 100°C and this corresponds to a half value of the self diffusion energy H_d of about 1eV.

3.1.2. Results obtained at the abrupt temperature and strain rate change tests

(a) Temperature dependent stress increment $\Delta \sigma_T$ and strain rate dependent stress increment $\Delta \sigma_{\dot{\epsilon}}$

Fig.7 shows some examples of the stress-strain relations. The specimens are deformed up to about 7.5% or 15.5% strain at 100°C periodically changing the strain rate, and are unloaded. At the unloaded state, the temperature is abruptly changed from 100°C to a certain required temperature and the specimens are deformed again with the same periodical change of the strain rate. Fig.8 illustrates the stress-strain curve for the specimen which is prestrained at -195°C up to about 7.5% strain and is subsequently deformed at -100°C.

From the detailed study of the results represented in these figures, it will be concluded that at temperatures except -195°C, the stress-strain relations can not be determined only by the temperature and the strain rate at the time but are affected by the strain rate history. In the strain rate change tests, when each amount of the increased strain at 2.8×10^{-3} /s is less than

Fig.8 Stress-strain relation (prestrained at -195°C)

nominal stress to the nominal strain relation accompanied with a change of the strain rate. An abrupt increase of the nominal stress $\Delta\sigma_1'$ (the increment of the true stress $\Delta\sigma_1$) is caused by an increase of the strain rate from $2.8 \times 10^{-4}/s$ to $2.8 \times 10^{-3}/s$. The work hardening rate of the nominal stress to the nominal strain curve at $2.8 \times 10^{-3}/s$ decreases gradually with strain, and then the stress increases with a nearly constant work hardening rate. The nominal stress to the nominal strain relation with the nearly constant work hardening rate is extrapolated to the strain at which the strain rate is abruptly increased. The nominal stress increment $\Delta\sigma_2'$ (the true stress increment $\Delta\sigma_2$) is determined as shown in Fig.9(b). The nominal stress increments $\Delta\sigma_1'$ and $\Delta\sigma_2'$ (the true stress increments $\Delta\sigma_1$ and $\Delta\sigma_2$) at low temperatures are identical in the small strain range, but they differ from each other in the large strain range. At temperatures higher than room temperature, they do not coincide with each other even in the small strain range. In the large strain range, the thermal recovery affects remarkably the compressive strength of polycrystalline zinc even at low temperatures. It may exert an influence upon the stress even in a short time interval in which the strain rate is changed. It is not so unreasonable to adopt the true stress incre-

ment $\Delta\sigma_2$ as the strain rate dependent stress increment $\Delta\sigma_{\dot{\epsilon}}$.

(b) Activation energy for identical internal structures

Fig.11 represents some examples of the stress increments $\Delta\sigma_T$ and $(\Delta\sigma_T + \Delta\sigma_{\dot{\epsilon}})$ to the temperature relations for the specimens prestrained at $100^\circ C$. As was observed two different temperature dependencies of the stress in Fig.5, two respective kinds of temperature dependencies of $\Delta\sigma_T$ and $(\Delta\sigma_T + \Delta\sigma_{\dot{\epsilon}})$ are observed at temperatures above and below room temperature. They may correspond to the different kinds of deformation mechanisms. In Fig.12, full lines represent the yield stress at $2.8 \times 10^{-4}/s$ to the reloading temperature relation for the specimens prestrained up to 4% or 7.5% strain at $-195^\circ C$ or up to 7.5% at $100^\circ C$. Broken lines represent the relation between the yield stress at $2.8 \times 10^{-3}/s$ (AE in Fig.9, the stress at P' in Fig.10) and the temperature. Chain lines show the stress of 4% and 7.5% strain to the temperature relationships in the constant strain rate tests of $2.8 \times 10^{-4}/s$. In the case of the specimens prestrained up to 7.5% strain at $-195^\circ C$, the yield stress increases remarkably with a decrease of the temperature. The amount of the prestrain affects a little the yield stress at high temperatures.

In Fig.12 the values of $(\partial \ln \dot{\epsilon} / \partial \sigma)_T$ are

Fig.12 Yield stress to temperature relation

Fig.14 Relation between activation volume and effective stress

Fig.13 Relation between activation energy and effective stress

Fig.15 Relation between activation volume and effective stress in non-dimensional form

calculated from the difference of the stresses given by the full lines and the broken lines at the same temperatures and the values of $(\partial\sigma/\partial(1/T))_{\dot{\epsilon}} = -T^2(\partial\sigma/\partial T)_{\dot{\epsilon}}$ are derived from the inclinations of the full lines. The activation energy H_D for the identical internal structure can be obtained by using Eq.2'. The obtained values of the activation energy at $2.8 \times 10^{-4}/s$ are shown in Fig.6 for several amounts of the prestrain at 100°C and -195°C. Both in the various constant temperature and strain rate tests and in the temperature and strain rate change tests, the values of the activation energies H_D and H_T decrease remarkably with a decrease of the temperature.

If the athermal component of the yield stress σ_0 is given by the yield stress at a sharp breaking point of (the yield stress)-(the square root of the absolute temperature) curve, the thermal component of the stress, i.e. the effective stress σ^* , can be evaluated as $\sigma^* = \sigma - \sigma_0$. Fig.13 represents the relation between the activation energy H_D and the effective stress σ^* . The values of σ_0 used are written in the figure. The value of $2Uk$ which is the value of H_D at $\sigma^* = 0$ yields (1.3~1.4)eV. Now, the evaluation of the activation volume is necessary to investigate the deformation mechanism corresponding to the obtained activation energy.

(c) Activation volume

The activation energy $H(\sigma^*)$ is expressed as

Fig.16 Stress-strain relation in logarithmic scale (-70°C)

Fig.17 Stress-strain relation in logarithmic scale (50°C)

sed as

$$H(\sigma^*) = H_0 - \int v^* d\sigma^* = H_0 - \int v^* d(\sigma - \sigma_0), \quad (3)$$

where H_0 and v^* are the total activation energy and the activation volume, respectively. Eq.1 can be rewritten by using Eq. 3 and we differentiate both sides of Eq. 1 with respect to σ^* . If the strain rate sensitivity of the effective stress is given by the strain rate sensitivity of the stress, the activation volume can be evaluated as follows.

$$v^* = kT(\partial \ln \dot{\epsilon} / \partial \sigma^*)_T = kT(\partial \ln \dot{\epsilon} / \partial \sigma)_T \quad (4)$$

Fig.14 shows the v^* - σ^* relations for various internal structures. The relation can be represented by a single smooth curve independently of the internal structures.

At low temperatures the migration and the sliding of the grain boundaries are scarcely observed¹⁰ and the simultaneous operations of the various kinds of deformation modes such as basal slip, mechanical twinning, and pyramidal and prismatic slips must be induced in a grain to maintain the homogeneous deformation of polycrystalline zinc. Peierls force of dislocations on these non-basal slip planes might play a significant role in determining the strength, and the deformation behaviours at low temperatures may be controlled by the formation mechanism of double kinks on these non-basal planes. Fig.15 shows the activation volume $(\sigma_p/2Uk)v^*$ to the effective stress σ^*/σ_p relation in non-dimensional forms. The activation volume decreases with an increase of the effective stress. In the figure, the value of σ_p is the effective stress at 0°K derived from the yield stress in Fig.12 and the value of $2Uk$ is the activation energy at $\sigma^* = 0$ in Fig.13. Dorn *et al.*¹¹ investigated the mechanism to produce the double kinks on dislocations and concluded that when the line energies of the dislocations are expressed by various appropriate functions, almost the same relation between the activation volume and the effective stress can be obtained. In Fig.15 a full line represents the relation between the activation volume and the effective stress which is calculated by Dorn *et al.* in the case that the line energy of dislocations is given by a cosine function. The tendency of the present experimental results fairly well agrees with that of the theoretical prediction. Therefore, the formation mechanism of the double kinks which may be on the non-basal slip planes controlled by the Peierls force will contribute to the mechanical behaviours of polycrystalline zinc at low temperatures.

On the other hand, the migration and the sliding of the grain boundaries contribute to the static deformation of polycrystalline zinc at temperatures higher than room temperature, and the basal slip plays an important role¹⁰. The activation energy H_D of about 1eV is obtained at the relatively high temperatures as shown in Fig.6 and this value coincides well with the activation energy of self diffusion. It may be concluded that a climbing of the edge dislocations on the basal plane is in-

duced by diffusion of vacancies and it controls the mechanical behaviours of polycrystalline zinc at temperatures above room temperature.

3.2. Thermal recovery during deformation

Figs.16 and 17 show some examples of the stress-strain curves at constant temperatures and constant strain rates in logarithmic scale. The stress σ (kg/mm²) is expressed as a function of the strain ϵ (%), the strain rate $\dot{\epsilon}$ (1/s) and the absolute temperature T (°K) as follows

$$\sigma = A(\dot{\epsilon}, T)\epsilon^m, \quad m = m(\dot{\epsilon}, T), \quad (5)$$

where both A and m are functions of $\dot{\epsilon}$ and T . Two kinds of values of the strain exponents, m_1 and m_2 , are obtained at strain less than about 10% and at strain more than 10%, respectively. The relations between the strain exponent m_1 and the logarithm of the strain rate are represented in Fig.18 taking the temperature as a parameter. The strain exponent m_1 in the strain rate range from 10^{-4} /s to 1/s is expressed as

$$m_1 = A'(\log \dot{\epsilon} - \alpha)(T + B') + C'.$$

In the relation, the following values are obtained:

$$A' = 0.33 \times 10^3 / ^\circ\text{K} \quad \alpha = 4.6$$

$$B' = 67^\circ\text{K} \quad C' = 1.29$$

The temperature dependency of the strength of the basal slip is not remarkable and the strain rate sensitivity of the stress is not intensive in the strain rate range up to about $10/\text{s}$. The temperature and the strain rate sensitivities of the strength of the mechanical twinning are not well known and the strength of the pyramidal slip as well as the prismatic one may be dependent upon the temperature because the Peierls forces of the dislocations on these slip planes are strong².

The authors reported⁹ previously that the strength of polycrystalline zinc is strongly affected by the thermal recovery. From these facts, it may be concluded that the strain exponent m_1 is influenced by the strength for the non-basal slips and the thermal recovery. The possibility can

Fig.18 Relation between strain exponent and strain rate

not be excluded that the formation of a mechanical twinning which arrests the moving dislocations on the basal and the non-basal planes may depend upon the temperature. The evaluation of the stacking fault energy on the basal plane will be available to make clear the mechanism of the thermal recovery affecting the value of m_1 . The dislocations on the prismatic and the pyramidal planes may be perfect dislocations because of their high stacking fault energies on these planes while the dislocations on the basal plane are split into partial dislocations for their low stacking fault energy on the plane. The partial dislocations pile up against the barriers such as grain boundaries and dislocation dipoles in the course of the deformation. When these partial dislocations are constricted into perfect dislocations, the perfect screw dislocations are able to bypass the barriers and consequently the work hardening rate will decrease. Disregarding the possibility of the occurrence of a cross slip of the screw dislocations on the non-basal planes, it is considered that the change of the strain exponent m from m_1 to m_2 at around 10% strain is related to the occurrence of the cross slip of the screw dislocations on the basal plane. When the stress at which m_2 takes the place of m_1 is denoted as σ_c , it seems the stress corresponds to the starting stress of the stage III of a single crystal¹³⁻¹⁵. The starting stress σ_c of the cross slip is dependent

Table 3 Value of A

T (°K)	373	323	273	203
$\frac{\partial \log \sigma_c}{\partial \log \dot{\epsilon}}$	0.121	0.101	0.096	0.058
$A = kT / \frac{\partial \log \sigma_c}{\partial \log \dot{\epsilon}}$ (eV)	0.27	0.28	0.24	0.30

Fig.19 Relation between logarithm of σ_c and temperature

Fig.20 Relation between logarithm of σ_c and strain rate

upon the temperature and the strain rate. The cross slip process is controlled by a thermally activated mechanism and the strain rate $\dot{\epsilon}$ is expressed as

$$\dot{\epsilon} = \dot{\epsilon}_0 \exp(-U/kT), \quad (6)$$

where U is the activation energy. It is given by Schöck *et al.* as

$$U = -A \ln(\sigma_c(T)/\sigma_c(0)), \quad (7)$$

where $\sigma_c(0)$ and $\sigma_c(T)$ are the values of σ_c at 0°K and T °K, respectively. Eq. 6 and Eq. 7 yield

$$(\dot{\epsilon}/\dot{\epsilon}_0) = (A/kT) \ln(\sigma_c(T)/\sigma_c(0)). \quad (8)$$

The value of A is given by the following equation⁴ on condition of $n \ll 10^3$, where n is the number of the piled up dislocations.

$$A = 0.352Gb^3 / \{(1+(n/900))(1+(180\gamma/Gb))\} \quad (9)$$

In the relation, G , b and γ are the shear modulus, Burger's vector and the stacking fault energy on the basal plane, respectively. The value of $\sigma_c(0)$ is obtained as

$$\sigma_c(0) = 2G(0)(0.056 - \gamma/G(0) \cdot b)/n, \quad (10)$$

where $G(0)$ is the shear modulus at 0°K.

The linear relations between $\ln \sigma_c$ and T hold at given strain rate in Eq. 8. Fig.19 represents the linear relationships between $\ln \sigma_c$ and T taking the value of the strain rate as a parameter. The value of $\sigma_c(0)$ is 81.5 kg/mm² independently of the strain rate. Putting $\sigma_{c1}(T)$ for the value of $\sigma_c(T)$ at $\dot{\epsilon}_1$ in Eq. 8 and also $\sigma_{c2}(T)$ for the value of $\sigma_c(T)$ at $\dot{\epsilon}_2$, two equations are obtained. Eliminating $\dot{\epsilon}_0$ and $\sigma_c(0)$, the value of A is determined as

$$A = kT \ln(\dot{\epsilon}_1/\dot{\epsilon}_2) / \ln(\sigma_{c1}(T)/\sigma_{c2}(T)). \quad (11)$$

Fig.20 shows the $\sigma_c(T)$ - $\dot{\epsilon}$ relations taking the temperature as a parameter and the obtained values of A are tabulated in Table 3. Eliminating n from Eq. 9 and Eq. 10, and using the values of A , the value of the stacking fault energy γ is obtained as (200 $\sim$ 250) erg/cm². In the calculation, the values of the shear modulus of $G = 3.9 \times 10^{11}$ dyne/cm² independent of the temperature and of Burger's vector of $b = 2.66 \times 10^{-8}$ cm on the

basal plane are used. Dobson *et al.*¹⁸ obtained the stacking fault energy of (140 $\pm$ 25) erg/cm² by a direct measurement using an electron microscope. On the other hand, many authors^{5,19,20} obtained from the stress-strain relations of single crystals the values of (74 $\sim$ 300) erg/cm². These values agree well with the results in the present experiment.

Thus, a reasonable value for the stacking fault energy of zinc results and the stress-strain relations having the strain exponent m_1 are supposed to be independent of the cross slip of screw dislocations on the basal plane. The corresponding mechanism to the thermal recovery detected on the stress-strain relations having the strain exponent m_1 may be climbing of edge dislocations on the basal and the non-basal planes. The values of the activation energy for self diffusion in the c -axis direction and in a direction perpendicular to the c -axis are (20 $\sim$ 23) kcal/mol²¹ and (23 $\sim$ 31) kcal/mol²¹ in zinc single crystal, respectively. Therefore, the thermally activated climbing of the edge dislocations on the basal plane may play a predominant role.

3.3. Difference of the activation energies obtained by constant temperature and strain rate tests and by temperature and strain rate change tests

In Fig.6 it is represented that the values of H_D are larger than those of H_T at every temperature. Because the temperature dependency of the yield stress in the temperature and strain rate change tests is similar to that of the stress in the constant temperature and strain rate tests as is seen in Fig.12, the values of $(\partial \sigma / \partial (1/T))_{\dot{\epsilon}}$ in Eq. 2' are almost same in both tests. On the other hand, the stress increment $\Delta \sigma_{\dot{\epsilon}}$, schematically shown in Fig.21, is adopted to evaluate the strain rate sensitivity of the stress increment $\Delta \sigma_{\dot{\epsilon}}$, illustrated in the figure, is used in the constant temperature and strain rate tests. In the present experiment, $\Delta \sigma_{\dot{\epsilon}} > \Delta \sigma_{\dot{\epsilon}}$ holds and consequently $H_D > H_T$ is yielded.

The deformation behaviours at temperatures below room temperature are governed by two thermally activated mechanisms except basal slip. One is the formation of double kinks of dislocations on the non-basal planes and the other is the climbing of the edge dislocations which are on the basal plane. When the strain rate is abruptly increased at point A in Fig.21 where both mechanisms operate, an instantaneous increase of the stress will be caused by the single operation of the former mechanism. In the course of the proceeding deformation, both the processes of the slip on the non-basal planes and of the thermal recovery control the deformation behaviours, and the equilibrium state at point C will be realized.

At temperatures above room temperature, it is inferred that the activation energy H_D of about 1 eV is obtained as the consequence of the process controlled by the thermally produced vacancies, and the activation energy H_T of 0.5 eV is obtained

Fig.21 Schematic representation of stress increment

by the migration process of the vacancies.

4. Conclusions

To investigate the effects of the temperature and the strain rate upon the compressive strength of polycrystalline zinc, constant strain rate and temperature tests and strain rate and temperature change tests were carried out. The ranges of the strain rates and the temperatures of the former tests are from 10^{-4} /s to 7×10^2 /s and from -195°C to 100°C , respectively, and those of the latter are from 2.8×10^{-4} /s to 2.8×10^3 /s and from -195°C to 200°C , respectively.

Results obtained are summarized as follows.

(1) In the constant temperature and strain rate tests, the stresses of 5% and 10% strains linearly increase with an increase of logarithm of the strain rate in the ranges of the temperatures from -195°C to 100°C and the strain rates from 10^{-4} /s to 7×10^2 /s. But the results obtained for the stress of 10% strain at low temperatures and high strain rates are excluded.

(2) Two kinds of strain exponents m_1 and m_2 are found on the stress-strain curve in the ranges of the strains smaller and larger than about 10%, respectively. The temperature and the strain rate dependencies of the strain exponent m_1 are explained by the temperature and the strain rate effects of the slip on the non-basal planes (the prismatic and the pyramidal slips) and by the thermal recovery of the climbing process of the edge dislocation which is on the basal plane. The deformation behaviour corresponding to the change of the strain exponent from m_1 to m_2 can be understood in connection with the cross slip of screw dislocations which are on the basal plane.

(3) Thermal recovery affects the strength at static strain rates and at temperatures from -70°C to 200°C . In the constant temperature and strain rate tests, the value of the activation energy is explained by considering the simultaneous operation of the slip on the basal and non-basal planes and the climbing of edge dislocations on the basal plane.

(4) Considering the results obtained in the temperature and strain rate change tests, the thermally activated control mechanism of the deformation at temperatures from -195°C to room temperature seems

to be the motion of double kinks on dislocations on the non-basal planes.

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