

《Original》 **Theoretical Considerations on Effect of
Environments on Strain Hardening**

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Abstract

The part of the work of plastic deformation of metal goes into the changes in the total surface free energy. This contribution is dependent on the specific surface free energy, which is affected by the environment.

Based on thermodynamical approach, volume constancy requirement and adsorption induced two distinct dislocation interaction mechanisms for strengthening or weakening of metals at surface, theoretical derivation has been made to show that the environmental contribution on the strain hardening, the stress and the energy required for plastic deformation can be expressed in terms of solid surface tension in vacuum (γ_s), interfacial tension (γ_{se}), surface dislocation density (ρ_s), internal dislocation density (ρ_i) and fraction of surface site uncoverage (f). On the basis of theoretical derivation, the various mechanical behaviours under different environments are predicted.

요 약

금속의 소성변형에 필요한 일의 일부는 전표면자유에너지 (Total Surface Free Energy)의 변화에 소모된다. 전표면자유에너지 변화는 비표면 자유에너지 (Specific Surface Free Energy)에 의해 변화하며 비표면자유에너지는 분위기에 따라 달라진다.

열역학적규명, 체적불변율과 흡착으로 인한 두개의 관이하게다른 강화 혹은 약화를 초래하는 전위 (Dislocation) 상호작용기구를 기반으로 금속의 소성변형으로 인한 가공경화, 응력 및 에너지에 미치는 분위기의 영향을 이론적으로 도출했다.

이론식은 진공중금속표면장력 (γ_s), 개면장력 (γ_{se}), 표면전위밀도 (ρ_s), 내부전위밀도 (ρ_i)와 표면노출율 (f)의 함수로 표시할 수 있었다. 이론식을 이용하여 자기 다른 분위기내에서의 금속의 기계특성을 예측 비교해왔다.

I. Introduction

The basic consequences of the physical discontinuity existing the surface of metal include

the surface energy, the adsorption of environmental atoms or molecules, the formation of surface film, the existence of image forces on dislocations, and the revelation of plastic dis-

placements during deformation.

The surface area and the volume to area ratio change during plastic deformation of metal. The part of the work of plastic deformation goes into the changes in the total surface free energy. This contribution is dependent on the specific surface free energy, which is affected by the environment. Due to the change in the specific surface free energy of metal, the interactions of egressing dislocations with adsorption locked surface dislocations or defect free surface behave differently. Consequently, the changes in mechanical behaviour of metal take place under the different environments.

The surface energy may be thought of as an excess energy that exists because a surface has been created. Benedicks¹⁾ offered a simple explanation on this excess energy which was based upon atomic bonding at surface. Some of this excess bonding energy will be used by foreign atoms adsorbed on the surface, but the remaining excess energy becomes an increased bonding energy between the atoms at the surface, (Fig. 1).

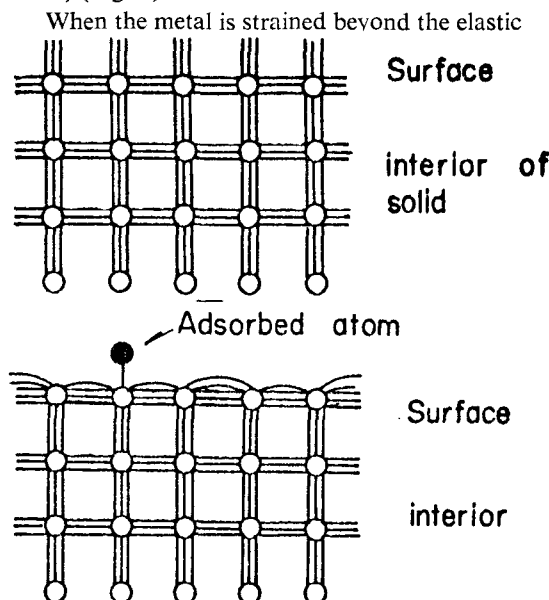


Fig. 1-(a) Schematic view showing excess bonding energy available at surface
(b) schematic view showing adsorption and excess bonding between surface atoms.

limit, the dislocations move along the plane of easy slip in the crystal and disappear at the surface leaving surface steps. As the dislocation approaches free surface of metal, it will encounter an attraction toward free surface due to image force and, at the same time, the resistance from surface due to greater bonding energy of surface layer atoms. The attraction due to image force is inversely proportional to the distance from free surface²⁾ and the resistance due to the excess bonding energy of surface layer would be proportional to the surface tension of solid.

Since the image force is long range and becomes almost infinite whereas the surface tension is short range and finite at the free surface of solid; the resultant force acting on near surface dislocation would be an attraction toward the surface. Therefore, once the internal dislocation slip out the near surface, the force required to move dislocation would be less compared to that of internal dislocation. Accordingly, the surface dislocation density is expected to be less than the internal dislocation density. The newly generated fresh surface step would attribute to the larger surface energy and promote the adsorption of environmental atoms or molecules. Through different modes of adsorption, the environments definitely play an important role in changing surface tension of solid³⁾. With different environment, the resistance for egress of internal dislocation to free surface is altered. However, the environments can not influence the image force since it is merely geometry induced force due to free surface.

Consequently, the resultant attraction on near surface dislocation would be different depending on different environments and increases with increasing the adsorption of environmental atoms or molecules. Thus the adsorption induced weakening of solid or Rebinder effect occurs.

On the other hand, if the adsorption of polar molecule or ionic species take place preferentially at the surface dislocation sources such as Fisher source⁴, the adsorption strengthening of solid occurs.

The concept for preferential adsorption is plausible in light of the fact that the region around the dislocation becomes the higher energy lattice.

The strain hardening behaviour of solid would be governed by internal dislocation density⁶⁻⁷ as well as surface tension or surface dislocation density as well as interfacial tension. There are three cases of surface imaginable as shown in Fig. 2-A, B and C. Fig. 2-A shows pure clean metal surface in which almost no dislocation pile-up occurs at near surface. Fig. 2-B shows coherent oxide or metal film in which little dislocation pile-up would be expected at the boundary between film and substrate. On the other hand, when the film is incoherent, great pile-up dislocation takes place at the boundary between film and substrate as shown in Fig. 2-C. In all of three cases, the surface step would be formed when the solid is strained as shown in Fig. 2-D.

There are many conflicting evidences of strengthening or weakening effect of environments with various explanations.⁸⁻¹³ The reason for those variations would be due to the

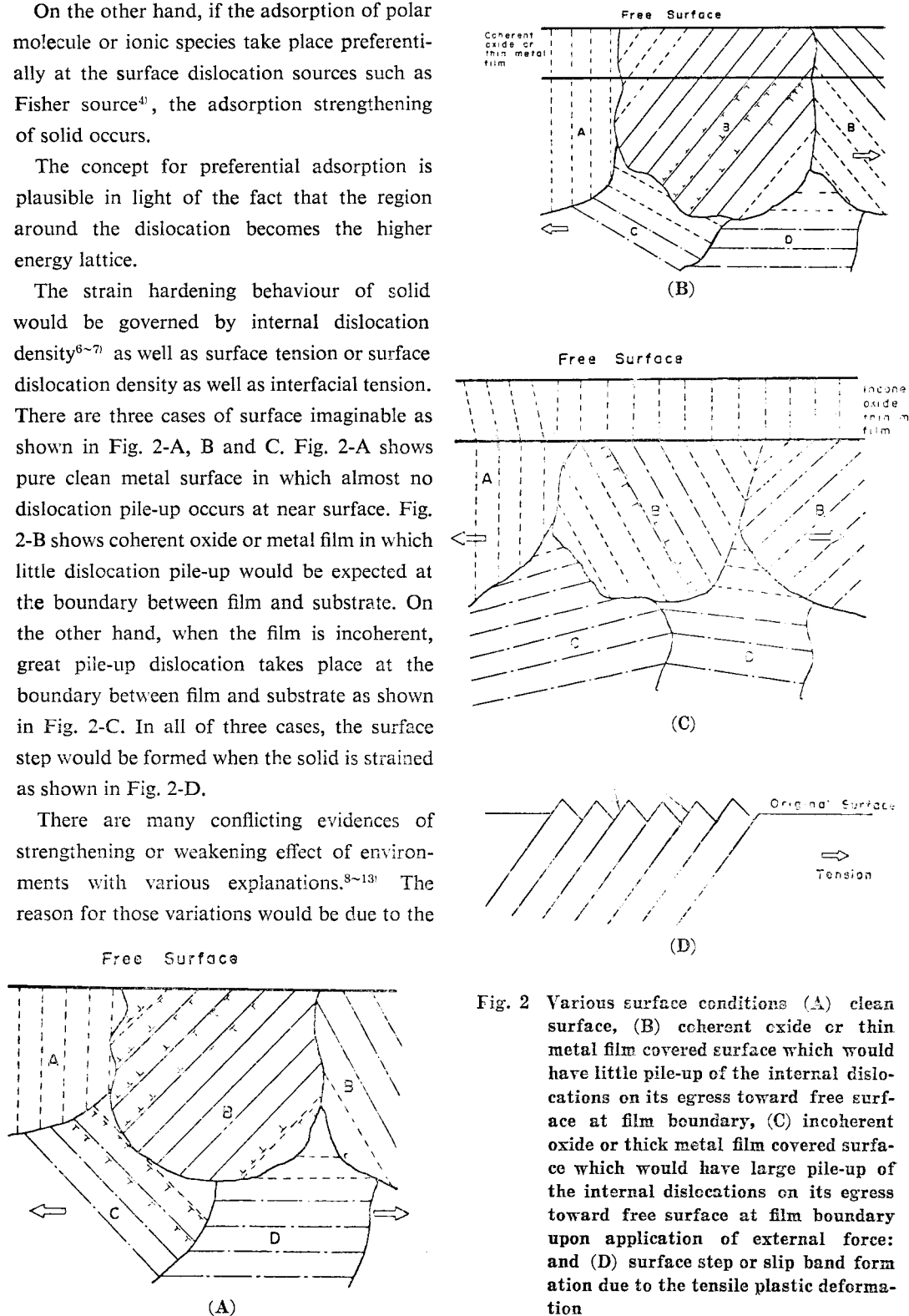


Fig. 2 Various surface conditions (A) clean surface, (B) coherent oxide or thin metal film covered surface which would have little pile-up of the internal dislocations on its egress toward free surface at film boundary, (C) incoherent oxide or thick metal film covered surface which would have large pile-up of the internal dislocations on its egress toward free surface at film boundary upon application of external force; and (D) surface step or slip band formation due to the tensile plastic deformation

differences exist among the experiments especially on interface conditions as well as the parameters used for comparing. Therefore, if the consistent surface conditions were kept or, in other words, the surface tension or interfacial tension is used for major parameter, the effect of environment can be compared very clearly. The attempt is made to make a quantitative expression for environmental effects on strength properties of metals making use of thermodynamics, volume constancy requirements of solid during plastic deformation, dislocation behaviours, surface tension and the mode of adsorption as parameters.

Table I. List of Symbols

α	: proportionality constant
f	: fraction of surface site uncoverage
A_o	: solid-environment interfacial area
A_{xo}	: solid cross sectional area
A_o/A_{xo}	: specimen geometry factor
γ_{se}	: interfacial tension between solid and environment
γ_s	: solid surface tension
ρ_s	: surface dislocation density
ρ_i	: internal dislocation density
E_E	: excess energy required for plastic deformation due to environment
E_s	: excess energy required for plastic deformation due to surface dislocation source locking by adsorbed environment
E_{si}	: excess energy required for plastic deformation due to the blocking of internal dislocation escape from the surface by desorption of environments
σ	: true stress
ϵ	: true strain
σ_B	: bulk stress
σ_E	: excess stress for plastic deformation due to environment
σ_s	: excess stress for plastic deformation due to surface dislocation source locking by adsorbed environment
σ_{si}	: excess stress for plastic deformation due to the blocking of internal dislocation escape

form the surface by desorption of environments.

$\frac{d\sigma_E}{d\epsilon}$: contribution on strain hardening rate for plastic deformation due to environments

$\frac{d\sigma_s}{d\epsilon}$: contribution on strain hardening rate for plastic deformation due to surface dislocation source locking by adsorbed environment

$\frac{d\sigma_{si}}{d\epsilon}$: contribution on strain hardening rate for plastic deformation due to the blocking of internal dislocation escape from the surface by desorption of environments

θ : liquid contact angle

F^I : interfacial free energy between solid and environment

F^T : total free energy of system

F^V : volume free energy of solid

F^B : grain boundary free energy

F^E : free energy of the external environment surrounding the solid

W : maximum work

r : radius

L : length

A : area

Subscripts used

o : initial or strain free state

ϵ : strained state

E, e : environment phase

S : solid phase

Arabic Numerals: liquid phase

G : gaseous phase

II. The Work of Surface Creation

For two phases in equilibrium i.e. solid metal either with liquid or gas environment—the free energy of the system can be expressed as follows:

$$F^T = F^V + F^B + F^E + F^I \dots\dots\dots (1)$$

When the metal specimens are prepared metallurgically in the same way, the values for F^V and F^B for different specimens would be same. However, if the environments are different from one test to another, F^E and F^I would have different values. Therefore, the difference in

total free energy of the system due to change in environment from 1 to 2 would be

$$F^{T_2} - F^{T_1} = E^{E_2} + F^{I_2} - (F^{E_1} + F^{I_1}) \dots\dots (2)$$

If the system is deformed by applying a load to the solid, the change in free energy of the surrounding environment would be negligible. That is,

$$F^{E_{1\epsilon}} - F^{E_{10}} = 0 \text{ and } F^{E_{2\epsilon}} - F^{E_{20}} = 0, \dots\dots (3)$$

where ϵ and 0 subscripts refer to the strained and unstrained conditions respectively.

However, the interfacial free energy would be changed as the solid is deformed. Therefore, the contribution to the total free energy change of the system due to different environment as the solid is deformed comes solely from interfacial free energy term.

Therefore,

$$(F^{T_{2\epsilon}} - F^{T_{20}}) - (F^{T_{1\epsilon}} - F^{T_{10}}) = (F^{I_{2\epsilon}} - F^{I_{20}}) - (F^{I_{1\epsilon}} - F^{I_{10}}), \dots\dots (4a)$$

$$\frac{\partial F^{T_2}}{\partial \epsilon} - \frac{\partial F^{T_1}}{\partial \epsilon} = \frac{\partial F^{I_2}}{\partial \epsilon} - \frac{\partial F^{I_1}}{\partial \epsilon} \dots\dots (4b)$$

From the definition of the interfacial tension and equation (4), the differences in ideal work of surface creation between environment 1 and 2 would be expressible under constant temperature, pressure, volume and composition.

$$\Delta F^I_1 - \Delta F^I_2 = \Delta A_1 \gamma_{s1} - \Delta A_2 \gamma_{s2} = W_1 - W_2 \quad (5)$$

The actual work to be put into solid so as to create interface of A would be proportional to the interfacial tension. The difference in actual work because of the difference in environment 1 and 2 would be proportional to $\Delta F^I_1 - \Delta F^I_2$, $W_1 - W_2$, and $\gamma_{s1} - \gamma_{s2}$.

III. Surface Generation as Function of Strain

As the solid is strained, the interface between solid and external environment would be increased. To the first order approximation, the volume constancy condition can be used for the calculation of surface area generation in terms of strain as cylinder of volume V is strained.

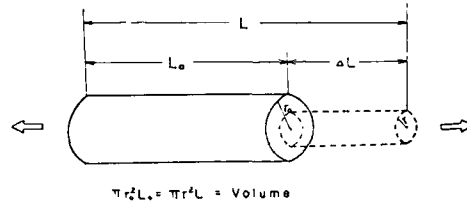


Fig. 3 Volume constancy of cylinder specimen.

From Fig. 3,

$$V = \pi r_0^2 L_0 = \pi r^2 L_0 (1 + \text{Strain}) \dots\dots (6)$$

Therefore,

$$r = \frac{r_0}{(1 + \text{Strain})^{1/2}} \dots\dots (7)$$

Similarly, the surface area A of cylinder which would come into contact with an external environment is

$$A = A_0 (1 + \text{Strain})^{1/2} \dots\dots (8)$$

Since true strain $\epsilon = \ln(1 + \text{Strain})$,

$$(1 + \text{Strain}) = e^\epsilon \dots\dots (9)$$

$$A = A_0 e^{\epsilon/2} \dots\dots (10)$$

The equation (10) hold regardless of the geometry of the specimen as long as it has a uniform cross section along tensile strain direction.

However, this cannot account for the surface area increase due to slip lines and steps at solid surface as it is deformed. In actual picture, the mode of the increase in new interface area would be rather parabolic owing to the concentrated formation of slip bands in the early stage of plastic deformation of metal. Internal defects and voids nucleation and growth during plastic deformation would make real solid deviate from volume constancy of continuum mechanics.

IV. Interfacial Tension and It's Physical Interpretation

From equations (4), (5) and Young's equ-

ation³ on three phase equilibrium, the change in total free energy of the system due to different environment as the solid is deformed to create ΔA becomes

$$F^{T_{2t}} - F^{T_{20}} - (F^{T_{1t}} - F^{T_{10}}) = \Delta F'_2 - \Delta F'_1 = \Delta A (\gamma_{1G} \cos \theta_1 - \gamma_{2G} \cos \theta_2) \dots (11)$$

Suppose that $\gamma_{1G} < \gamma_{2G}$. Then, $\theta_1 < \theta_2$ ³. From Young's equation

$$\gamma_{1G} - \gamma_{2G} = \frac{\gamma_{SG} - \gamma_{S1}}{\cos \theta_1} - \frac{\gamma_{SG} - \gamma_{S2}}{\cos \theta_2} < 0 \dots (12)$$

Therefore,

$$\frac{\gamma_{SG} - \gamma_{S1}}{\cos \theta_1} < \frac{\gamma_{SG} - \gamma_{S2}}{\cos \theta_2} \dots (13)$$

Inequality in equation (13) is valid even if

$$\gamma_{SG} - \gamma_{S1} = \gamma_{SG} - \gamma_{S2} \dots (14)$$

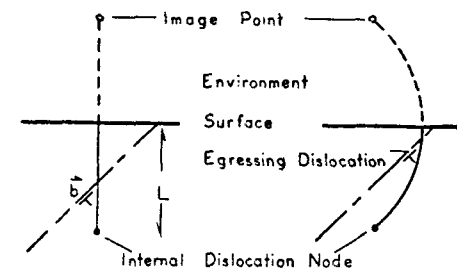
However, $\gamma_{SG} - \gamma_{S1} \neq \gamma_{SG} - \gamma_{S2}$, if $\gamma_{1G} \neq \gamma_{2G}$. Therefore, another condition which satisfy the inequality in (13) has to be

$$\gamma_{SG} - \gamma_{S1} < \gamma_{SG} - \gamma_{S2}$$

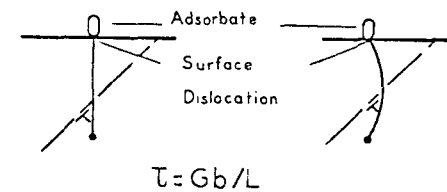
Therefore,

$$\gamma_{S1} > \gamma_{S2} \dots (15)$$

This is to say that the lower the surface



(A) no adsorption



(B) adsorption on surface dislocation

Fig. 4 Adsorption Locked Surface Dislocation Strengthening

tension of liquid, the higher the interfacial tension between solid and liquid. In physical analogy, the liquid of lower surface tension adsorbs better on solid surface. Consequently, there would be more interaction across the interface between solid and liquid. Therefore, the amount of work required to create interface, i.e. interfacial tension, as well as the surface dislocation locking due to adsorption would be greater for the liquid of lower surface tension. This difference in interfacial tension would attribute to the difference in strain hardening due to variation in environments.

V. Adsorption Locked Surface Dislocation Strengthening

Environmental contributions on strengthen-

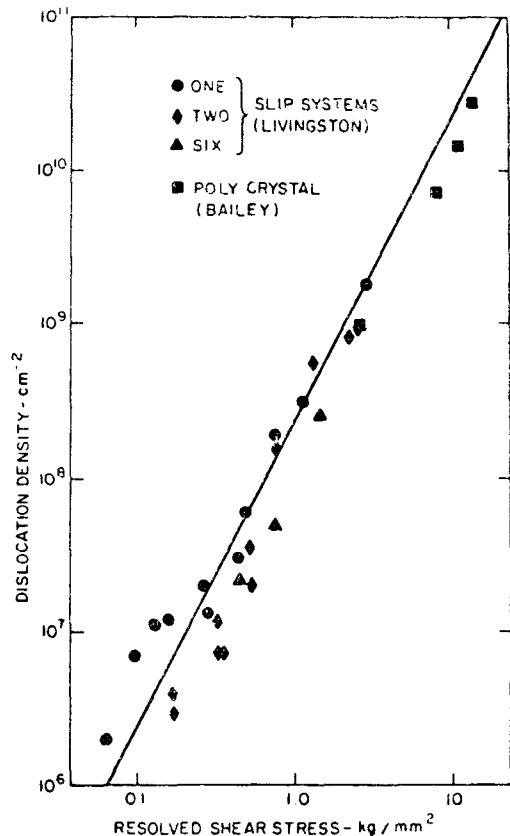


Fig. 5 Average dislocation density as a function of resolved shear stress for copper (after Livingston and Bailey)⁶⁻⁷⁾

ing probably come from the work of surface creation and the interaction energy of egressing internal dislocation with the adsorption locked surface dislocations as shown in Fig. 4. The work of surface creation per unit cross sectional area would be proportional to

$$\frac{\gamma_{se}A}{A_x} = \frac{\gamma_{se}A_o}{A_{xo}} e^{1.5\epsilon} \dots\dots\dots(16)$$

since

$$A_x = \frac{A_{xo}}{(1+\text{Strain})} = \frac{A_{xo}}{e^\epsilon} \dots\dots\dots(17)$$

The interactions would be a function of surface dislocation locking strength and the density (ρ_s) of the surface dislocations which are locked by the adsorbate. For cubic metals, the stress is known to be proportional to the square root of the dislocation density⁶⁾. (cf. Fig. 5) Therefore, the interactions can be assumed to be proportional to $\rho_s^{0.5}$.

The higher the value of γ_{se} , the more interaction across the interface between adsorbates and solid surface; the stronger locking of the surface dislocations would be expected. Since

the surface dislocation locking strength would be proportional to γ_{se} ; the interactions would be related to not only $\rho_s^{0.5}$, but γ_{se} also. Therefore, the excess stress due to adsorption locked surface dislocation (σ_s) would be a function of $\frac{A_o}{A_{xo}} e^{1.5\epsilon}$, $\rho_s^{0.5}$, and γ_{se} ; and these variables are interdependent. Therefore, the following formulation on ρ_s is proposed in order to include the effects of the above mentioned variables.

$$\sigma_s = \alpha \frac{A_o}{A_{xo}} e^{1.5\epsilon} \gamma_{se} \rho_s^{0.5} \dots\dots\dots(18)$$

VI. Adsorption Induced Reduction of Surface Energy Weakening

When the adsorbates adsorb preferentially on surface dislocations and defects, the strengthening effects would be resulted due to adsorption locking of those defects. However, when the adsorbates spread beyond those surface defects and adsorb on defect free surface, the reduction of surface tension of metal would take place and, in turn, aid the egress of internal dislocations toward surface as shown in Fig. 6. Therefore, the weakening would probably depend on the interaction energy of egressing internal dislocations with metal surface and the surface area. The interaction would be a function of the internal dislocation density (ρ_i) and the surface tension of metal. The surface tension of metal can be approximated as a product of surface site uncoverage (f) and the surface tension of metal under vacuum (γ_s). The higher the degree of adsorption—i.e. lower value of f , the lower the metal surface tension; the less the resistance from surface layer of solid for the egress of internal dislocations. For cubic metals, even when Peierls-Nabarro's mechanism is contributing to the thermal component of flow stress, the total flow stress is known to be proportional to the square root of dislocation density⁷⁾.

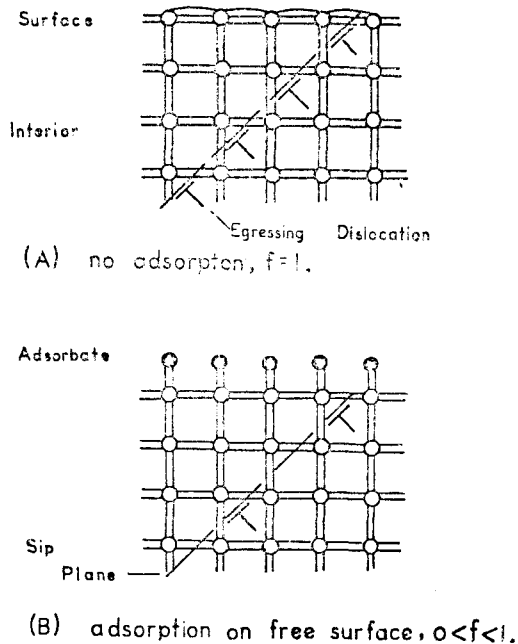


Fig. 6 Adsorption Induced Reduction of Surface Energy Weakening

Therefore, the stress (σ_{si}) due to blocking the egress of internal dislocations toward surface can be expressible in terms of $\rho_i^{0.5}$, $f\gamma_s$ and $\frac{A_o}{A_{x0}} e^{1.5\epsilon}$. With the same token as the derivation of equation (18), σ_{si} can be expressed

$$\sigma_{si} = \alpha \frac{A_o}{A_{x0}} e^{1.5\epsilon} f \gamma_s \rho_i^{0.5} \dots \dots \dots (19)$$

Equations (18) and (19) are both counteracted each other by the fraction of surface uncoverage (f). If $f \rightarrow 0$, the environment softening and if $f \rightarrow 1$, the environment-hardening would be resulted. The former could be accounted as Rebinde effect. Depending on whether mode of adsorption is primarily on the surface dislocation sites or rest of the surface, the environment-hardening or softening would occur.

VII. Environmental Contributions on Stress-Strain Curves, Strain Hardening, and Energy of Plastic Deformations

For hypothetical case where no environments are present such as high vacuum or completely inert environments, the flow stress of the metal becomes

$$\sigma = \sigma_B + \sigma_{si}$$

with $f=1$.

And on the other hand, when the adsorption of environments are such that all the surface sites of solid is taken up, the flow stress of the metal becomes

$$\sigma = \sigma_B + \sigma_s$$

with $f=0$.

In ordinary condition, the flow stress of the metal becomes

$$\begin{aligned} \sigma &= \sigma_B + \sigma_E \\ &= \sigma_B + \sigma_s + \sigma_{si} \\ &= \sigma_B + \alpha \frac{A_o}{A_{x0}} e^{1.5\epsilon} (\gamma_{se} \rho_s^{0.5} + f \gamma_s \rho_i^{0.5}) \dots \dots \dots (20) \end{aligned}$$

with $0 < f < 1$.

In fig. 7, there are three curves. Ones with $\sigma = \sigma_B + \sigma_{si}$ and $\sigma = \sigma_B + \sigma_s$; and other with $\sigma =$

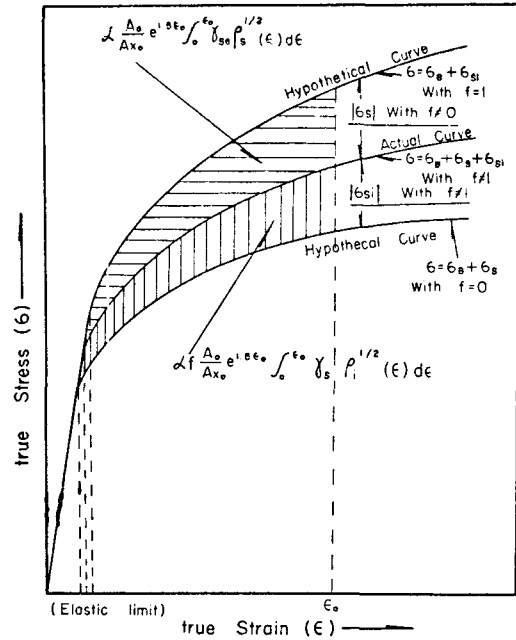


Fig. 7 Schematics showing hypothetical and actual stress strain curves.

$\sigma_B + \sigma_s + \sigma_{si}$. The former curve is one which the metal with no external environmental adsorption would behave and the other which the metal with complete coverage by adsorption of environments. The latter is the one which the metal under ordinary external environment would behave. σ_s and σ_{si} represent the contribution on flow stress due to environment hardening or softening by interfacial interaction of external environment via adsorption.

From equation (18), the strain hardening rate of metal due to locking of surface dislocations or point defects by adsorbed environments would be

$$\begin{aligned} \frac{d\sigma_s}{d\epsilon} &= \alpha \frac{A_o}{A_{x0}} e^{1.5\epsilon} \\ & (1.5 \gamma_{se} \rho_s^{0.5} + \rho_s^{0.5} \frac{d\gamma_{se}}{d\epsilon} + 0.5 \gamma_{se} \rho_s^{-0.5} \frac{d\rho_s}{d\epsilon}) \dots \dots \dots (21) \end{aligned}$$

From equation (19), the strain hardening rate of metal due to blocking the escape of internal dislocations at the surface as a results of ad-

sorbed environments would become

$$\frac{d\sigma_{si}}{d\epsilon} = \alpha \frac{A_o}{A_{x0}} e^{1.5\epsilon} f(1.5\gamma_s \rho_i^{0.5} + \rho_i^{0.5} \frac{d\gamma_s}{d\epsilon} + 0.5\gamma_s \rho_i^{-0.5} \frac{d\rho_i}{d\epsilon}) \dots\dots\dots (22)$$

The strain hardening rate of metal due to adsorbed environments would be

$$\frac{d\sigma_E}{d\epsilon} = \alpha \frac{A_o}{A_{x0}} e^{1.5\epsilon} [1.5\gamma_{se} \rho_s^{0.5} + \rho_s^{0.5} \frac{d\gamma_{se}}{d\epsilon} + 0.5\gamma_{se} \rho_s^{-0.5} \frac{d\rho_s}{d\epsilon} + f(1.5\gamma_s \rho_i^{0.5} + \rho_i^{0.5} \frac{d\gamma_s}{d\epsilon} + 0.5\gamma_s \rho_i^{-0.5} \frac{d\rho_i}{d\epsilon})] \dots\dots\dots (23)$$

From equation (18), the energy required for plastic deformation due to adsorption locked surface dislocation strengthening (E_s) would be

$$E_s = \int \sigma_s d\epsilon = \alpha \frac{A_o}{A_{x0}} \int e^{1.5\epsilon} \gamma_{se} \rho_s^{0.5} d\epsilon \dots\dots\dots (24)$$

From equation (19), the energy required for plastic deformation due to adsorption induced surface energy reduction weakening (E_{si}) would

$$E_{si} = \int \sigma_{si} d\epsilon = \alpha \frac{A_o}{A_{x0}} \int e^{1.5\epsilon} f \gamma_s \rho_i^{0.5} d\epsilon \dots\dots\dots (25)$$

Of course, above equation describes contribution of environment on the stress-strain behaviour of metal provided that the volume constancy of metal is kept during deformation and the deformation of metal is uniform throughout the total volume. However, in actual deformation of metal, the deformation mode is not uniform. Also, at the later stage of the plastic deformation, the surface crack or internal void would be formed. These factor would make the derived equations deviate from actual behaviour of metal.

VIII. Temperature Effects

The temperature at which the metal is strained would greatly affect the mode of adsorption at surface. Depending on different modes of adsorption, the surface or interfacial tension would be changed. This would, in turn alter the dislocation surface interactions.

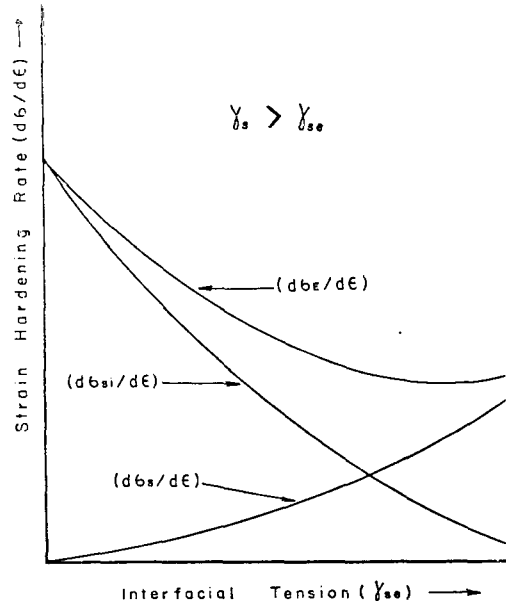


Fig. 8 Strain Hardening Rate vs. Interfacial Tension at Lower Temperature, where physical adsorption occurs.

At lower temperature, the adsorption by environments would be mostly physical adsorption. Consequently, f would have a value relatively closer to unity. Therefore, the net strain hardening rate of metal due to adsorbed environments would be mainly controlled by the blocking the escape of internal dislocations at the surface. In other words, $\frac{d\sigma_{si}}{d\epsilon} > \frac{d\sigma_s}{d\epsilon}$ and $\frac{d\sigma_E}{d\epsilon}$ would be governed by the magnitude of $\frac{d\sigma_{si}}{d\epsilon}$ as shown schematically in Fig. 8. The stress approaches $\sigma = \sigma_B + \sigma_{si}$ in Fig. 7. At higher temperature, the adsorption by environments tend to become chemisorption. Therefore, f would have a value closer to zero. Moreover, as the temperature is increased, γ_s would decrease while γ_{se} would increase as surface film formed. As a consequence, γ_{se} tend to become larger than γ_s . The net

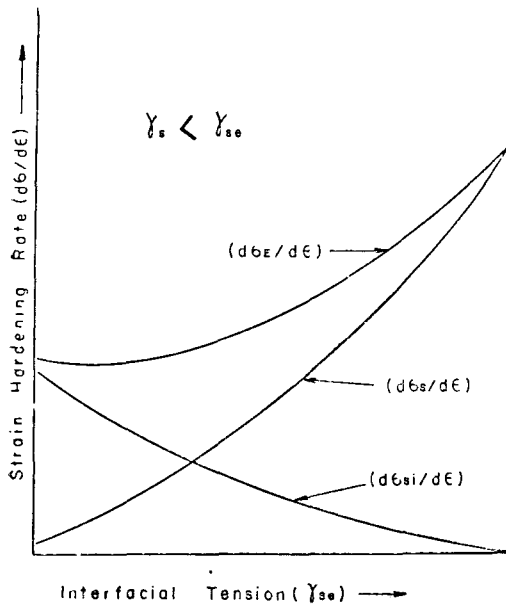


Fig. 9 Strain Hardening Rate vs. Interfacial Tension at Higher Temperature, where chemisorption take place.

strain hardening rate of metal due to adsorbed environments would be governed mostly by the locking of surface dislocations. Thus $\frac{d\sigma_{Si}}{d\epsilon} < \frac{d\sigma_S}{d\epsilon}$ and $\frac{d\sigma_E}{d\epsilon}$ would be mainly affected by the magnitude of $\frac{d\sigma_S}{d\epsilon}$ as shown schematically in Fig. 9. In this case, the stress approaches $\sigma = \sigma_B + \sigma_S$, as shown in Fig. 7. This interpretation also coincide with the effect of temperature on the flow stress in same environment; since the higher the temperature, the lower the flow stress of metal in general. At high temperature, due to thermally activated processes such as the climb of edge dislocation (movement of sessile dislocation), the considerable amount of recovery takes place on strained lattice in bulk. However, at surface, the mode of adsorption would become chemisorption. Once the chemisorbed layer is formed, the mobility of surface dislocations are greatly reduced as well as the egress of internal dislocation at the surface. Therefore, the greater effect of environ-

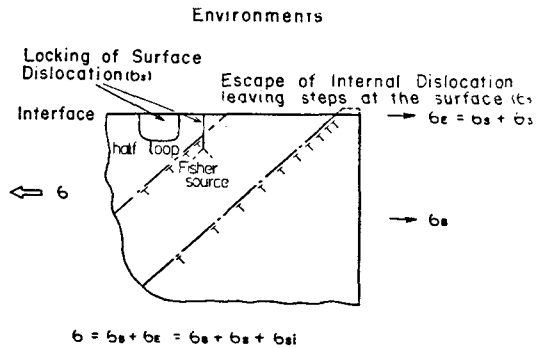


Fig. 10 Schematics of Dislocation Behaviour at Near Surface

ment could be observed. The pronounced effect could well be expected at high temperature creep test. In a steady-state creep, there exist an equilibrium between the rate of recovery and strain hardening rate and stable substructure would form. Consequently, the apparent dislocation density is constant and net dislocation multiplication rate would be zero.

IX. Summary

From theoretical considerations, the followings are expected.

- a) The lower the surface tension of environment, the higher the interfacial tension between solid and environment.
- b) At lower temperature, the higher the interfacial tension, the lower the net strain hardening rate ($\frac{d\sigma_E}{d\epsilon}$) due to the adsorbed environment. The flow stress approaches to $\sigma = \sigma_B + \sigma_{Si}$
- c) At higher temperature, the higher the interfacial tension, the higher the net strain hardening rate ($\frac{d\sigma_E}{d\epsilon}$) due to the adsorbed environment. The flow stress approaches to $\sigma = \sigma_B + \sigma_S$
- d) Since $\sigma = \sigma_B + \sigma_E$, if σ_B/σ is close to unity, σ_E becomes very insensitive to environment. The large value of σ_B overshadows the contribution of σ_E term.(cf. Fig. 10)
- e) The environment contribution to the

energy required for plastic deformation (E_E) can be expressed as follows:

$$E_E = E_s + E_{s_i} = \alpha \frac{A_o}{A_{x_0}} \int e^{1.5\epsilon} (\gamma_{se} \rho_s^{0.5} + f \gamma_s \rho_i^{0.5}) d\epsilon$$

The environment contribution to the stress (σ_E) can be expressible in following form:

$$\sigma_E = \sigma_s + \sigma_{s_i} = \alpha \frac{A_o}{A_{x_0}} e^{1.5\epsilon} (\gamma_{se} \rho_s^{0.5} + f \gamma_s \rho_i^{0.5})$$

The environment contribution on the strain hardening rate ($\frac{d\sigma_E}{d\epsilon}$) can be expressible in following form:

$$\begin{aligned} \frac{d\sigma_E}{d\epsilon} &= \frac{d\sigma_s}{d\epsilon} + \frac{d\sigma_{s_i}}{d\epsilon} = \alpha \frac{A_o}{A_{x_0}} e^{1.5\epsilon} [1.5 \gamma_{se} \rho_s^{0.5} \\ &+ \rho_s^{0.5} \frac{d\gamma_{se}}{d\epsilon} + f (1.5 \gamma_s \rho_i^{0.5} + \rho_i^{0.5} \frac{d\gamma_s}{d\epsilon} \\ &+ 0.5 \gamma_s \rho_i^{-0.5} \frac{d\rho_i}{d\epsilon}) + 0.5 \gamma_s \rho_s^{-0.5} \frac{d\rho_s}{d\epsilon} \end{aligned}$$

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