

Chapter 2

Crystalline Materials: Surfaces of Solid Bodies

“It was not the same Jupiter he new on TV. He had expected Jupiter would be different, but not much”.

American writer Clifford D. Simak

“The idea that planets follow absolutely circular orbits is simple and elegant, but Brahe, Kepler and Newton proved that it was untrue”.

American physicist and writer Alan Lightman

We ask ourselves is sand different from stone? Or may be they are mainly pebbles? Or be Moon is a huge stone too? Then, if we understand what stones are, shall we understand the nature of sand and Moon?

American physicist Richard Phillips Feynman

Abstract The crystal structure of technical materials is considered, systematization of crystal structure defects is given. Special attention is devoted to dislocations, their interactions with crystal structure defects and influence thereof on mechanical properties of solids. The basic notions are reviewed about interfaces, surface layer of solids and principal surface phenomena (adhesion, adsorption, surface diffusion).

Material point, absolutely solid body, perfect gas, heat machine of Nicolas Carno, are physical models intended to help researchers study natural phenomena by simplifying the objects of material world. The perfect crystal treated in the first chapter belongs to the models. Solid materials are different because their crystalline space is distorted. That is why additional notions were needed in the near and far order to describe materials; the notion which were unnecessary before for perfect crystals. The near order is the substance condensed state in which the ordered arrangement of particles appears at distances comparable with atomic distances. The far order is the strict reproducibility of one and the same structural element in all directions throughout hundreds and thousands of periods of the crystalline lattice. The imperfect structure of engineering materials governs the values of effective cohesive forces.

2.1 Defects of Crystalline Structure

The structure of the majority of natural solid bodies is far from that of the perfect crystal because they contain a great number of defects. British physicist D. Griffiths believes that the “solid body is a collection of cracks” [1]. Unless the irregularities of the structure are taken into account, the modern theory of the solid body would be unable to assess adequately and quantitatively the physical properties of natural materials.

“Cracks”, “imperfections”, “deviations from perfect structure” called ‘defects’ appear when substances crystallize deforming the physical and chemical homogeneity of the lattice structure. There are three main types of defects of tribosystems: chemical composition inhomogeneity, dislocations, and voids [1–3].

The chemical composition inhomogeneity appears due to the foreign atoms and molecules in the crystallizing substances. They can occupy the nodes in the crystalline lattice under formation producing pinpointed defects which modify the crystal parameters. Such modifications occur because the extrinsic atom has the dimensions incompatible with those of the main atoms in crystals. These distortions of the crystalline lattice reduce the crystal full energy.

The changes in the crystal volume ΔV due to the intrusion of extrinsic atoms are calculated using formula [4]

$$\Delta V = 4\pi P_{cr}\delta, \quad (2.1)$$

where P_{cr} —the power of crystalline space expansion; $\delta = 3(1 - \nu)(1 + \nu)^{-1}$; ν —Poisson coefficient (S. Poisson—French mathematician, mechanic, physicist). It is $\delta \approx 1.5$ for most metals.

The atoms are displaced around the defect in the way that the crystal energy reduces to the minimum. Concurrently the energy of repulsion of ions in the defective crystal lattice diminishes compared with the perfect lattice. When an extrinsic atom is introduced, the crystal energy changes by the following value:

$$W_d = \Delta W_r + \Delta W_e, \quad (2.2)$$

where W_d —the full energy for point defect appearance; ΔW_r —the energy of repulsion of atoms in closed shells; ΔW_e —changes in the energy of electrons.

$$\Delta W_e = -\frac{4}{15} W_f \left(z - \frac{\Delta V_\infty}{\Omega} \right), \quad (2.3)$$

where z —the charge number; ΔV_∞ —the volume change around the defect in the infinite crystal; Ω —atom volume.

The constant is $\delta = 1$ for the infinite crystal in (2.1), hence, according to (2.1):

$$\Delta V_\infty = 4\pi P, \quad (2.4)$$

The point defects imply both cases when the extrinsic atom is present and absent in the crystalline lattice node. This phenomenon acquired vacancy or the Schottky defect (W. Schottky—German physicist) [5]. It is probable that this lattice node is vacant in the thermal equilibrium state, when the energy is equal to

$$p_e = \exp\left(-\frac{W_v}{kT}\right), \quad (2.5)$$

where W_v —the energy needed to displace the atom from the crystalline lattice node of the surface crystal; k —the Boltzmann constant.

Another type is the Frenkel defect (Ya.I. Frenkel—soviet physicist-theoretician): it is the atom displaced into the internode position uncommon for the atom. The number of defects according to Frenkel is the following:

$$N_F = (NN')^{\frac{1}{2}} \exp\left(-\frac{W_y}{2kT}\right), \quad (2.6)$$

where N —the total number of nodes, N' —the number in internodal positions; W_y —the energy needed to displace the atom from the lattice into the internodal position.

The deformation of the crystalline lattice with the point defect (Fig. 2.1) leads to the mechanical stresses σ in the solid body [2]:

$$\sigma = \nabla C \left(\frac{\Delta d}{d} \right) E, \quad (2.7)$$

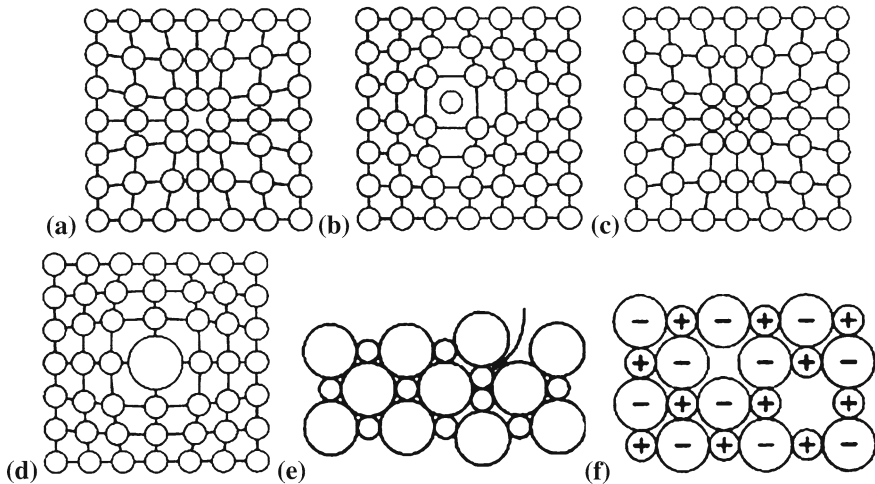


Fig. 2.1 Effect of point defects on crystalline space: **a** vacancy; **b** interstitial atom; **c** slight indentation defect; **d** slight displacement defect; **e** Frenkel defect; **f** Schottky defect (pair of vacancies in cation and anion sublattices)

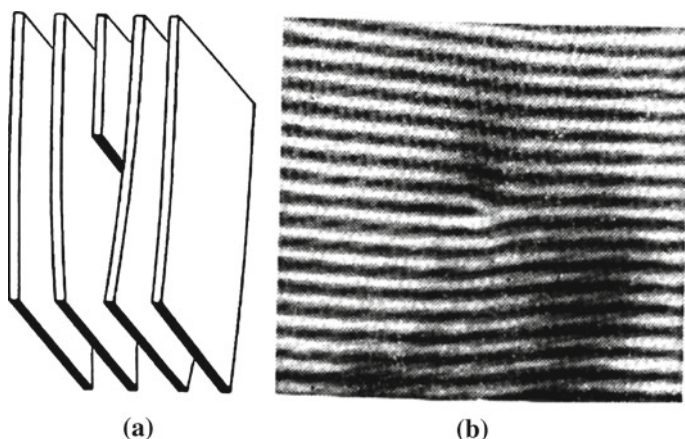


Fig. 2.2 Arrangement of atoms around boundary dislocation: **a** schematic image; **b** electron microscope image of dislocations in crystal

where ∇C_v —the gradient of point vacancies; d —the lattice period of the main substance (the solvent); Δd —the difference between lattice periods of the solvent and the soluble component; E —the modulus of the solvent elasticity.

The solvent implies the substance in which crystallization takes place; the soluble component is the extrinsic substance. If the concentration of the extrinsic phase is high enough, the distribution of the extrinsic substance in the solvent solid phase is laminar, the isoconcentrates (the lines equal to the concentration of vacancies) being parallel to the crystallization front in the plane in which the interface surface moves. The process evolves more intensively of the interface surface is due to absorption of extrinsic elements.

Dislocations are another type of defects of the crystalline structure [2, 5–7]. The dislocations are the crystalline structure defects along some line. Three mechanisms determine mainly the dislocations appearing when crystals grow: thermal stresses due to the stresses induced by the fluctuations in the solid phase and the oversaturation of the lattice with vacancies. The simplest types are boundary and helical dislocations.

The simplest presentation of the boundary dislocation is the line along which the crystallographic “semitplane” breaks (Fig. 2.2). The electron microscopes with high resolution power enable to observe arrangement of atom rows specific for boundary dislocations in some crystals (Fig. 2.2b).

The helical type dislocations result when crystal portions displace parallel to the broken crystalline semiplane rather than perpendicularly (Fig. 2.3). These dislocations are called so because their contour on the plane perpendicular to the line of break (the line of dislocations) is a helix around the line of dislocations.

The dislocation of crystalline structure fragments in the break plane can occur at any angle to the line of dislocation rather than parallel or perpendicular. These mixed dislocations can be considered consisting two types of boundary and helical dislocations.

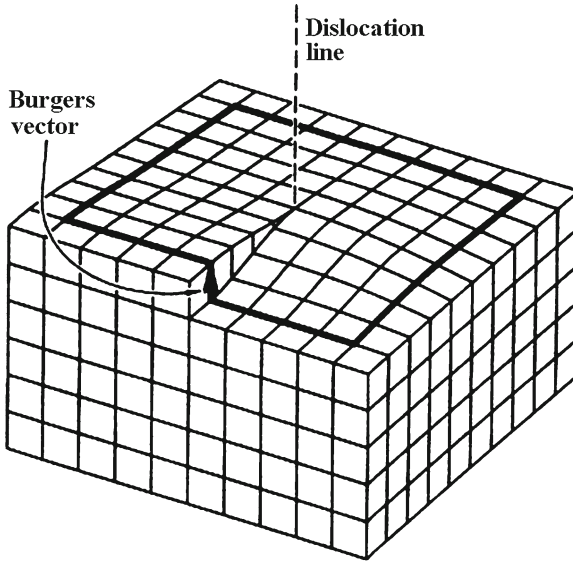


Fig. 2.3 Configuration of helical dislocations

The geometrical dislocations are characterized by the linear element $\vec{S}$ and the Burgers vector $\vec{b}$ (see Fig. 2.3) called after British physicist J. Burgers.

The linear element is the vector tangent to the line of dislocations. If the line is curved, the direction $\vec{S}$ is variable. The value and direction of the Burgers vector coincide with vector towards which the crystal portion above and beneath the plane of dislocations displace mutually. The modulus of the Burgers vector is usually equal to the least spacing between atoms in the lattice.

Since the linear element vector $\vec{S}$ can vary, while the vector $\vec{b}$ remains constant, the type of dislocations along its line can vary too. The boundary and helical components of the mixed dislocation characterized by the Burgers vectors $\vec{b}_\kappa$ and $\vec{b}_e$, respectively, depend on the orientation of the mixed dislocation Burgers vector $\vec{b}$ to $\vec{S}$. If the angle between them is equal to φ , then:

$$\begin{aligned}\vec{b}_\kappa &= \vec{S} (\vec{b} \cdot \vec{S}) = (|\vec{b}| \cos \varphi) \vec{S}, \\ \vec{b}_e &= \vec{S} \times [\vec{b} \vec{S}] = (|\vec{b}| \sin \varphi) \vec{n},\end{aligned}\tag{2.8}$$

where n —the normal to the line of dislocations.

The dislocation can be configured as a close loop staying under the surface. (Dislocation loops appear predominantly during material plastic flow it will be discussed further). It can be explained in the following way: the crystal becomes sectioned through the plane along some direction ABCD (Fig. 2.4); the lower part displaces in respect to the upper part on the Burgers vector $\vec{b}$. After two parts of the

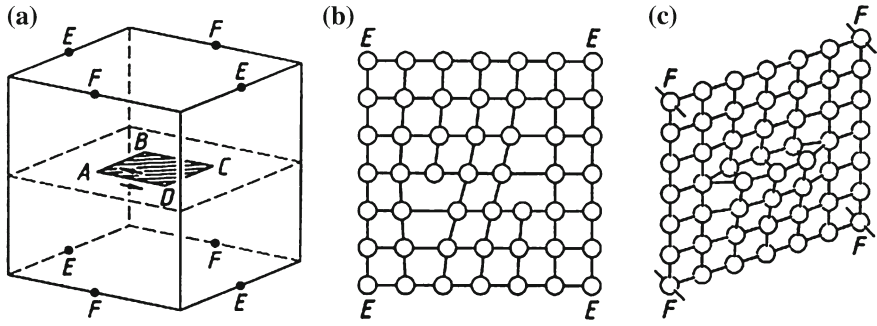


Fig. 2.4 Origination of dislocation loop: **a** view of *rectangular* closed dislocation loop (sectioned through AACD plane); **b** arrangement of atoms in upper plane; **c** arrangement of atoms in lower plane

crystal coincide, the ABCD boundary of this section represents the dislocation loop. It is characterized by identical value of the Burgers vector. The loop in Fig. 2.4. can be represented composed of two boundary AB and CD and two helical dislocations BC and DA. Both the boundary and helical components are antiparallel.

The closed dislocation loop changes direction at least in two points, but the vector $\vec{b}$ remains constant along all loop portions that is why it can consist only of helical dislocations. The closed loop can be plotted with only boundary dislocations if the Burgers vector is parallel to the loop plane. These dislocations were called prismatic or Frank–Reed dislocations (J. Frank—German physicist, W. Reed—American physicist). If the loop ends are fixed, the Frank–Reed dislocations can multiply under the effect of sufficiently strong stresses.

The expanding dislocation loop reaches the critical state when its radius becomes equal to the distance l between the points where the loop ends are fixed. The relevant displacement stress τ_{cr} can be calculated with the formula:

$$\tau_{cr} = \frac{G_s b}{l}, \quad (2.9)$$

where G_s —the shear modulus; b —the Burgers vector modulus.

The continuum physics apparatus is usually used to treat the effect of dislocations on elastic characteristics of solid bodies [8].

If the shear dislocations u_i are known in the Cartesian system of coordinates, the tensor component of the shear stresses τ_{jk} , appearing when dislocations move following the Hook law. The approximation of the isotropic crystal can be rerecorded as follows [3]:

$$\begin{aligned} \tau_{jj} &= \lambda \Delta + 2G_s e_{jj}, \\ \tau_{jk} &= G_s e_{jk}, \end{aligned} \quad (2.10)$$

$$e_{jk} = \frac{\partial u_j}{\partial k} + \frac{\partial u_k}{\partial j}; \quad e_{jj} = \frac{\partial u_j}{\partial j};$$

$$\Delta = \sum_j e_{jj}; \quad \lambda = 2G_s \nu (1 - 2\nu)^{-1},$$

where i, j, k —indexes of the tensor matrix components; ν —the Poisson coefficient; e_{ij}, e_{jk} —deformation components.

Each solution of this problem in the theory of elasticity should satisfy the conditions of equilibrium:

$$\tau_{jk} = \tau_{kj}; \quad \frac{\partial \tau_{jj}}{\partial j} + \frac{\partial \tau_{jk}}{\partial k} + \frac{\partial \tau_{ej}}{\partial e} + P_j = 0, \quad (2.11)$$

where P_j —the volume forces affecting the dislocation in the crystal.

The solution should obey the boundary conditions corresponding to this problem and the conditions of compatibility which are recorded as follows:

$$\frac{\partial^2 e_{jk}}{\partial j \partial k} = \frac{\partial^2 e_{jj}}{\partial k^2} + \frac{\partial^2 e_{kk}}{\partial j^2}, \quad (2.12)$$

$$2 \frac{\partial^2 e_{jj}}{\partial k \partial i} = \frac{\partial}{\partial j} \left(-\frac{\partial e_{ki}}{\partial j} + \frac{\partial e_{ji}}{\partial k} + \frac{\partial e_{jk}}{\partial i} \right).$$

The solutions for stresses and deformations relating to the helical dislocations can be obtained with the three stage routine:

1. Let us apply the Hook law (2.10) and determine the stresses which result from the deformation due to the appearing helical dislocations which can be recorded as follows:

$$u_x = u_y = 0; \quad u_z = \frac{b}{2\pi} \arctg \frac{y}{x}, \quad (2.13)$$

where x, y —the Cartesian coordinates of dislocations.

Hence, the only non-vanishing stress components are the following:

$$\tau_{xz} = \tau_{zx} = -\frac{G_s b y}{2\pi (x^2 + y^2)}, \quad (2.14)$$

$$\tau_{zy} = \tau_{yz} = \frac{G_s b x}{2\pi (x^2 + y^2)}.$$

Let us introduce the parameter Θ and $r = (x^2 + y^2)^{1/2}$, then:

$$\tau_{\Theta z} = \frac{G_s b}{2\pi r}; \quad \Theta = \arctg \frac{y}{x}. \quad (2.15)$$

2. Let us verify if solutions (2.14–2.15) satisfies the equation of equilibrium and the boundary conditions. The verification of the compatibility of the equation of

equilibrium can be made directly by substitution providing Eqs. (2.11) and (2.14) are fulfilled if [4]

$$\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} = 0. \quad (2.16)$$

Due to the stresses τ_{zx} and τ_{zy} , the dislocations can be twisted into the loop with the value equal to

$$M = \frac{1}{2} G_s b \left(R_{0disl}^2 - r_{0disl}^2 \right), \quad (2.17)$$

where R_{0disl} , r_{0disl} are internal and external radii of the helical dislocations.

3. Then the component of stresses $\tau_{\theta z}$ after correction for twisting becomes equal to

$$\tau_{\theta z} = \frac{G_s b}{\pi} \left(\frac{1}{2r_{0disl}} - \frac{1}{R_{0disl}^2 + r_{0disl}^2} \right). \quad (2.18)$$

To find the deformations following the method applied to the helical dislocations is impossible when applied to the boundary dislocations. Instead the so-called Airy function of stresses χ , is used which subordinates the following equation:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \left(\frac{\partial^2 \chi}{\partial x^2} + \frac{\partial^2 \chi}{\partial y^2} \right) = 0. \quad (2.19)$$

The Airy function corresponding to the boundary dislocations is the following:

$$\chi = -\frac{G_s b y}{2\pi (1 - \nu)} \ln \left(x^2 + y^2 \right)^{\frac{1}{2}}. \quad (2.20)$$

To calculate the stresses and displacements induced in the crystal the following expressions are used:

$$\begin{aligned} \tau_{xx} &= -\frac{G_s b y}{2\pi (1 - \nu)} \frac{3x^2 + y^2}{(x^2 + y^2)^2}, \\ \tau_{yy} &= \frac{G_s b y}{2\pi (1 - \nu)} \frac{x^2 - y^2}{(x^2 + y^2)^2}, \\ \tau_{zz} &= -\frac{G_s b y}{\pi (1 - \nu)} \frac{y}{x^2 + y^2}, \\ \tau_{xy} &= \frac{G_s b x}{2\pi (1 - \nu)} \frac{x^2 - y^2}{(x^2 + y^2)^2}, \end{aligned} \quad (2.21)$$

$$\begin{aligned}
u_x &= \frac{b}{2\pi} \left(\Theta - \frac{1}{2\pi} \right) + \frac{b \cdot x \cdot y}{4\pi (1-\nu) (x^2 + y^2)}, \\
u_y &= -\frac{b (1-2\nu)}{8\pi (1-\nu)} \ln \left(\frac{x^2 + y^2}{r_0^2} \right) - \frac{b}{4\pi (1-\nu)} \frac{x^2}{x^2 + y^2}.
\end{aligned} \tag{2.22}$$

No matter what mechanism causes stresses in the crystal, it results in the deformation which would be partly elastic, in the general case, and partly plastic. The relative value of each of these components depends on the material yield strength σ_Y . The plastic deformation ε_p resulting in generation of dislocations is determined by he relation:

$$\varepsilon_p = \frac{\sigma - \sigma_Y}{E}, \tag{2.23}$$

where E —the elasticity modulus.

The number of dislocations ρ_d per unit of the crystal volume is determined with the following formula:

$$\rho_d = a_e \frac{\varepsilon_p}{b}, \tag{2.24}$$

where a_e —the experimental coefficient.

Usually ρ_d is inversely proportional to the distance between dislocations.

The energy of the field of elastic stresses around dislocations can be found by integrating the elastic energy density through the crystal volume. Incase of the helical dislocations located in the hollow cylinder L long with the radii R_{0disl} and r_{0disl} , this energy is

$$U_v = \frac{G_s b^2 L}{4\pi} \ln \frac{R_{0disl}}{r_{0disl}}. \tag{2.25}$$

In respect to the boundary dislocations, the elastic energy is:

$$U_c = \frac{G_s b^2 L}{4\pi (1-\nu)} \ln \frac{R_{0disl}}{r_{0disl}}. \tag{2.26}$$

The elastic energy of the mixed dislocation is the superposition of boundary and helical dislocations is found in the following way:

$$U_c = \frac{G_s b^2 L}{4\pi (1-\nu)} \ln \left(\frac{R_{0disl}}{r_{0disl}} \right) (1 - \nu \cos^2 \varphi), \tag{2.27}$$

where φ —the angle between the Burgers vector and the axis of dislocations.

Thus, the dislocations possess a certain energy activity. Their interaction with point defects in the crystal concentrates them close to the axes of dislocations.

concentrating around dislocations the point defects form “cloud” or the Kottrell “atmosphere” (A. Kottrell—British metallurgist) [7, 9]. The concentration of impurities in the Kottrell atmosphere around the mixed dislocation is calculated from the following relation [3]:

$$C_{imp} = C_0 \exp \left\{ -\frac{4(1+\nu)}{3(1-\nu)} \left(G_s \cdot b \cdot \sin \varphi \cdot R_{at}^2 (R_{at} - R_{imp}) \sin \Theta \right) (rkT)^{-1} \right\}, \quad (2.28)$$

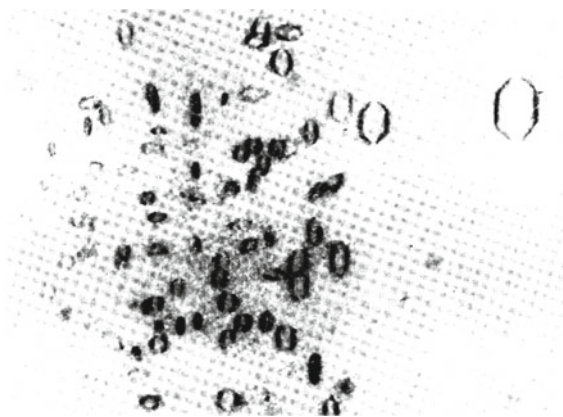
where C_0 —pre-exponential multiplier; R_{am} —the atom radius of the main substance; R_{imp} —the atom radius of the impurity; Θ_p —the angle of disagreement; r —the dislocation nucleus radius.

The concretion of the Kottrell atmosphere in transparent crystals results in “decoration” of dislocations making them visually perceptible. The defect of the Kottrell atmosphere can coagulate in the oversaturated solid solutions. They are likely to condense into single-, double-, or triple-layered loops parallel to the densest packed planes (Fig. 2.5). After the loop diameter exceeds some critical size, the loop sides flatten and join together. Exactly this defect is called the Frank–Reed dislocation. If the flattening does not result in the joining of the boundary loops, the dislocation originated in the Kottrell atmosphere is the boundary dislocation. If the flattening of disk is accompanied by the tangential dislocation, then the dislocation loop is of the partly mixed and partly boundary type.

Dislocations can move and interact fortifying or annihilating themselves. Concurrently the crystal full energy changes. The regularities of motions and interactions of dislocations are considered below.

The following group of defects in the structure and in the solid bodies confirms the Griffiths thesis that the natural crystal is most often a collection cracks or the defects of the type of voids. These defects cover the microcracks or Smekal voids (A. Smekal—chceck physicist) and extrinsic inclusions [1].

Fig. 2.5 Loop dislocation in Kottrell atmosphere in alloy Al+5 % Mg. Amplification is 4×10^4



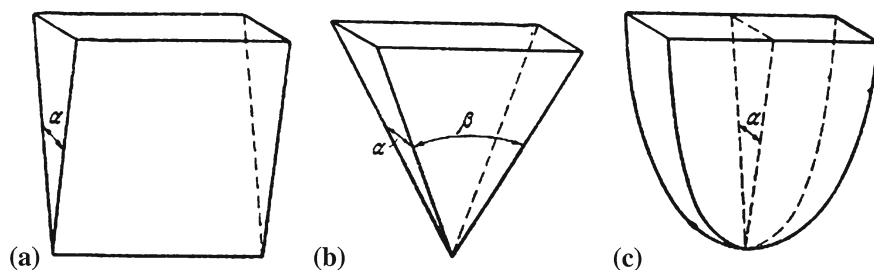


Fig. 2.6 Shapes of microcracks: **a** planar wedge-like; **b** wedge-like double sharpened; **c** elliptic section

The microcrack is the defect in the solid body which can be characterize as a rupture in the form of slot of micro- and submicrosize. These defects appear when wet crystals dry under thermal or mechanical effect on the structure, disorders of growth of crystals, foreign inclusion in the mother medium, etc.

The geometrical shape of cracks in crystalline bodies is different. Two shapes prevail: wedge-like and elliptical (Fig. 2.6).

A high concentration of mechanical stresses endangering the solid body strength appears at the top of microcracks. Any variable external deforming stresses promote the crack propagation encumbered with fatigue fracture of the solid body [10]. The Griffiths theory stipulates that the mechanical stress σ needed for the crack to develop is

$$\sigma = \sqrt{\frac{2E\varpi_d}{\pi \cdot l_{0.5}}}, \quad (2.29)$$

where ϖ_d —surface energy density; $l_{0.5}$ —crack semilength; E —modulus of material elasticity.

The microcracks may have multiple lateral branches producing intricate geometrical systems. It is believed that the integrity of communicating cracks propagates in many cases throughout the entire solid body volume forming a single capillary system. The latter possesses a large total surface and plays an essential role in interactions of materials with environment. The microcapillary system changes into the bonds following the thermal and mechanical solid body evolution. These changes have usually the progressing nature gradually making the microdefects grow and ramify into the net. Opposite changes are possible in particular cases, such as the thermoplastic irreversible collapse of surface microcracks discovered by A.S. Akhmatov.

The engineering materials have a special type of defects of the crystalline structures in the form of voids in the lattice. They appear due to the lack of whole group of atoms (or ions) in the spots where they should be according to the structural symmetry of the crystalline space. Thus, the crystal acquires a number of free microvolumes showing the known regularity in their spatial distribution. This type of defects acquired the name of Smekal voids. The latter are not geometrically closed voids,

hence, foreign substances can penetrate into them and strongly affect the physical and chemical characteristics of the solid body.

The foreign substances in the crystalline lattice resulting from the release of microscopic and ultramicroscopic particles in the crystal are a special type of defects. They appear due to a broad variety of mechanisms. They can appear as the crystal grows at the initial stages of crystallization, or due to a variety of secondary processes like artificial introduction of foreign substances into the crystal.

Thus, the structure of crystalline materials differs from its perfect model by the existing structural defects. They can have a decisive effect on the physical, chemical and mechanical characteristics of materials. The engineering materials are more active chemically than perfect crystals but their strength is many times more inferior.

2.2 Polycrystals

Polycrystalline materials together with monocrystalline materials are widely spread in nature, metals are among them [5, 6]. Their structure and composition are inhomogeneous because metals consist of numerous grains of adjacent grains of crystals called crystallites. The latter are fine monocrystals without distinctly pronounced facets. Most often they are of micron size that is the attendant crystalline structures are called microstructures. The microstructures can differ by size, shape and grain orientation. Each polycrystalline material has internal boundaries separating the adjacent grains of crystallites. The internal boundaries can be the boundaries of grains of one and the same phase or interphase boundaries. Boundaries in any case are parts of substances with a higher energy than that of grains, so there is a motive force striving to reduce the surface boundaries and to induce their dislocation correspondingly.

So, the intergrain boundary is a two dimensional defect of the crystalline lattice separating polycrystal regions with same but differently oriented crystalline structure. The lack of insight into the microstructure of intergrain boundaries is apparent. If the adjacent grains are disoriented slightly, the boundary looks like a periodic sequence of dislocations; it is a small-angle boundary. The large-angle boundary separates the grains of the stronger (over 15°) disoriented crystalline structure. The spacing between the spots where the dislocations reach the examined surface of the large-angle boundaries changes leapwise in steps at least one interatomic spacing. Figure 2.7 shows the photo of the boundaries of both types made with the electron microscope.

The symmetric small-angle boundaries consist of the same set of boundary dislocations with the Burgers vector b and the spacing between the dislocations D , which reduces as the “angle of disagreement Θ_d ” grows [6] Fig. 2.8.

$$\frac{b}{D} \approx \Theta_d, \quad (2.30)$$

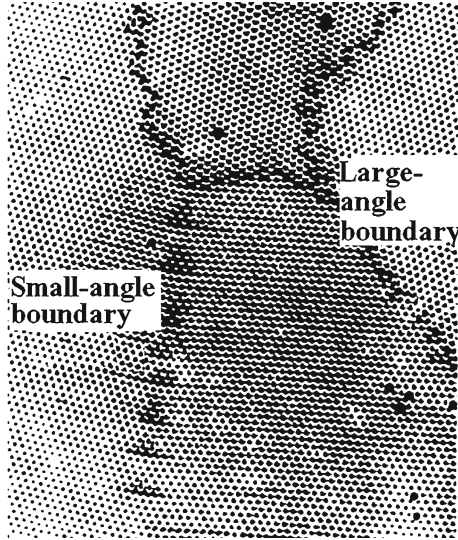


Fig. 2.7 Large- and small-angle boundaries [6]

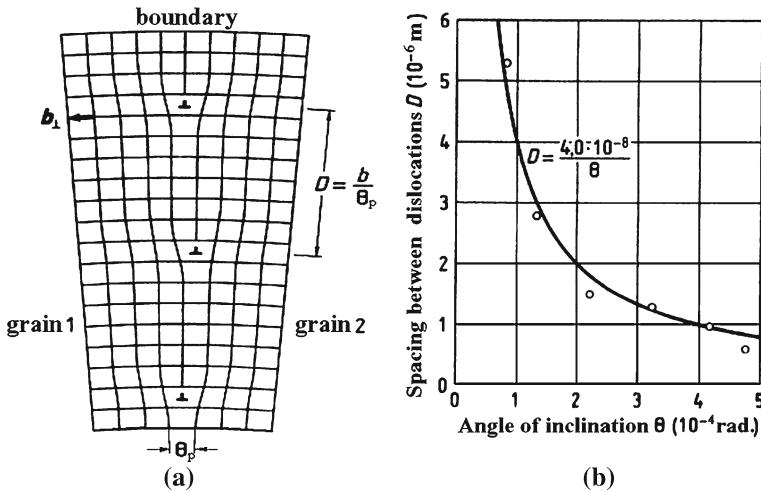
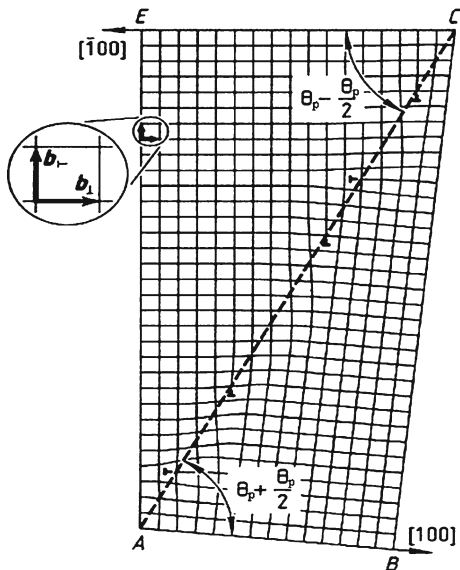


Fig. 2.8 Arrangement **a** and spacing between dislocations **b** for symmetric (100) small-angle boundaries

It is necessary to have at least two sets of dislocations with the orthogonal Burgers vectors for two asymmetric small-angle boundaries (Fig. 2.9). The effect of dislocations on the structure of crystals intensifies as the angle θ_d grows (Fig. 2.9). The boundaries this type of dislocations produce relate to the small-angle boundaries.

In addition to the mentioned small-angle intergrain boundaries, the solid bodies manifest the small-angle twisting boundaries which contain also at least two sets

Fig. 2.9 Arrangement of dislocations over small-angle asymmetric boundaries with angle of inclination Θ_d



helical dislocations. The mixed boundaries comprise the dislocation grids with three Burgers vectors.

Some crystallographic planes pass through the intergrain boundary and continue to adjacent grains. It means that some atoms in these planes are in perfect position in respect to the atoms in adjacent crystallites even on the intergrain boundaries. These nodes of lattices are called the nodes of coincidence; they form the lattice of coincidence positions. The parameter Σ is introduced as the measure of density of coincidence positions in the polycrystal:

$$\Sigma = \frac{V_{c.p.}}{V_c}, \quad (2.31)$$

where $V_{c.p.}$ —the volume of the lattice elementary cell with coincidence positions; V_c —the volume of the crystal elementary cell.

The small-angle boundaries can be characterized by the value of the parameter Σ close to 1. For instance, for the large-angle boundaries, it is $\Sigma > 1$; it is $\Sigma = 5$ when the angle of rotation is 37° .

The energy of intergrain boundaries γ is the sum of energies of separate dislocations; the sum depends on the orientation of adjacent grains.

The zero on the graph abscissa axis (Fig. 2.10) corresponds to the absence of boundaries. Even slight disorientation of two adjacent grains (10°) induces the energy leap almost to the maximum. Then the energy reduces somewhat just up to the angle range about 70° and remains constant afterwards [2].

It is noted above that the excessive energy of the intergrain boundaries pre-determines the crystal “drive” to minimize the dimensions and the energy as a result.

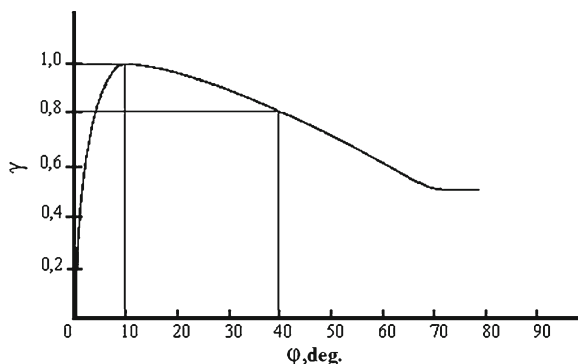


Fig. 2.10 Dependence of energy γ of boundaries between grains of silicon iron on angle of disorientation of grains ϕ

The motion of boundaries is affected by the geometrical dimensions of grains, the temperature, and insoluble impurities in the crystal. Most Polycrystals possess the property of anisotropy likely due to the anisotropy of grains and presence of impurities. It should be noted that anisotropy can be observed in one crystal and not observed in others. For instance, the common salt possesses the anisotropic crystal mechanical properties (the elasticity differs along the ribs and along the diagonal of the crystalline lattice), while its thermal and optical characteristics are isotropic with a high degree of certainty.

2.3 Solid Body Surface

J. Gibbs, the outstanding American physicist, one of the founders of thermodynamics and statistical mechanics, is honored as the forefather of the solid body surface theory. He was the first to treat the surface as the individual system in his fundamental work “The equilibrium of heterogeneous substances” in which he considered the surface different from the thermodynamic phases it shares [1, 2, 11, 12]. The surface layer, though being insignificantly thick, is a specific substance state with its intrinsic energy, entropy and other thermodynamic parameters. This approach permitted Gibbs to develop a macroscopic surface and surface phenomena theory. Further study of the properties of surface layers led to realization of huge difficulties which their existence introduced into the strict mathematical apparatus of crystallography. It was not without reason that great physicist-theoretician W. Pauli said vividly that devil in person created the surface [13].

The apparatus of quantum mechanics genuinely revolutionized the surface theory evolution. It enabled the development of the electron theory of surface layers and explain most of the effects relating to the specific structure of the solid body surface. The surface is one of the basic defects of the crystal three dimensional structures [13].

The broken surface chemical bonds alter the coordination of the sphere of surface atoms and re-hybridize their valence orbitals. It results in new surface electron states, the effective charges of surface atoms, the order of their arrangement and the inter-atomic distances change. The latter results in the crystal without extra deformation or distortion of its phonon spectrum. That is why the surface is rarely treated as the geometrical plane. The substance layer adjacent to the surface (the surface layer) is three-dimensional phase which has a number of physical properties different the volumetric characteristics of the condensed body.

Nevertheless, to make further calculations easier, let us apply the model homogeneous surface. It may look simple but it yields often good correlation with the experiment. Let us imagine the physical properties, the arrangement of atoms, and the distribution of their effective charges over the homogeneous surface change only normal to the surface. Thus, problem from three-dimensional turns into the one-dimensional.

The atoms of the surface layer even in perfect crystals are in principally new conditions from the solid body atoms. While the atom within the crystalline lattice is surrounded regularly by adjacent atoms from all sides, the surface atom has the relevant surrounding only from one side. It generates the force which affects the surface atom in the direction of the crystalline lattice interior (Fig. 2.11a). The combination of these forces causes surface tensioning particularly vividly manifested by fluids. It is exactly due to the surface tensioning the free falling drop becomes a ball having the least surface area.

The surface tensioning of solid bodies causes the deformation of surface layers. It reduces the crystalline lattice period versus the period in the crystalline space deeper regions (Fig. 2.11).

Figure 2.11a, b, leads to the conclusion that atoms in surface layers have free (uncompensated) chemical bonds. The electrons of these atoms possess a natural tendency to produce new links. While there are no foreign atoms on the surface, the surface electrons have only one opportunity to couple, it is to bond to adjacent surface atoms. It leads, in the simplest case, to pairing of the atoms and the resulting pairs were called dimers. The atoms of each dimer approach mutually and concurrently

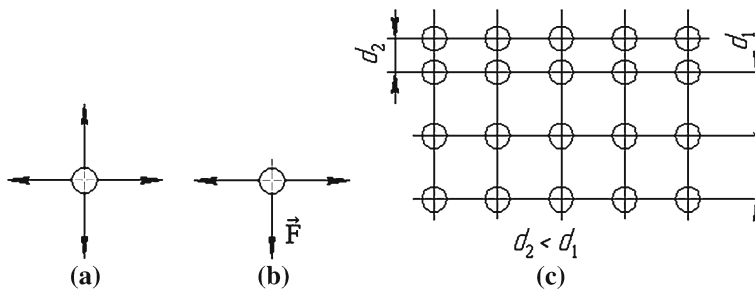


Fig. 2.11 Forces affecting atom within (a) and on surface of crystal (b), deformation of crystal surface layers (c)

move away from the adjacent surface atoms, the latter, in their turn, form mutually their own dimers. This process is accompanied by changes in the original crystalline lattice.

The crystalline lattice of surface layers (even that of the perfect crystal) is strongly distorted and it corresponds to a high concentration of dislocations accumulating on the surface. The solid body surface has in fact the excessive energy compared with deeper layers of the crystal. His energy is proportional to the surface area. Among the works dealing with the surface energy calculation, the results of Gilman are noteworthy (J. Gilman—American physicist and chemist) [14] because the calculation is relatively simple and the results feature good correlation with the experimental results. The Gilman equation for the crystal surface energy is the following:

$$U_{sur} = \frac{Ea_0^2}{\pi^2 y_0}, \quad (2.32)$$

where y_0 —the spacing between adjacent atomic planes; a_0 —the radius of action of cohesive forces; E —the elasticity modulus.

The difference between the surface crystalline structure and the volumetric crystal structure corresponds to the same large difference in the electron structure.

Due to the crystalline lattice periodic structure, the electron density follows the Fourier harmonic law (J. Fourier—French mathematician and physicist):

$$\rho_e = \frac{1}{\Omega} \sum_{h,k,l} F_{hkl} \exp[-2\pi i (h'x + k'y + l'z)], \quad (2.33)$$

where x, y, z —elementary cell coordinates; Ω —elementary cell volume; F_{hkl} —structural amplitude [15].

Figure 2.12 shows the diagrams of distribution of the crystalline lattice energy and the field.

A simple relation combines the electron density and the wave function of the perfect crystal in the quantum theory of solid bodies:

$$\rho_e = |\psi|^2 \sim \cos^2 \frac{\pi x}{d}, \quad (2.34)$$

where d —the spacing between lattice nodes.

When considering the surface electron states on the solid body surface, substantial deviations from the periodic structural order should be taken into account. Namely the discrete periodic fields of the lattice ion carcasses in Fig. 2.12a, are replaced with the evenly positively charged ground creating a homogeneous field averaged over the space. This approach is vividly called the “gel model” [16]. According to the gel model, the electrostatic potential created by the surface electric field is the following:

$$\varphi = -Ze^2 \sum_R \frac{1}{|r - R|} + \int \frac{\rho_e(r')}{|r - r'|} dr + \varphi_{ex}, \quad (2.35)$$

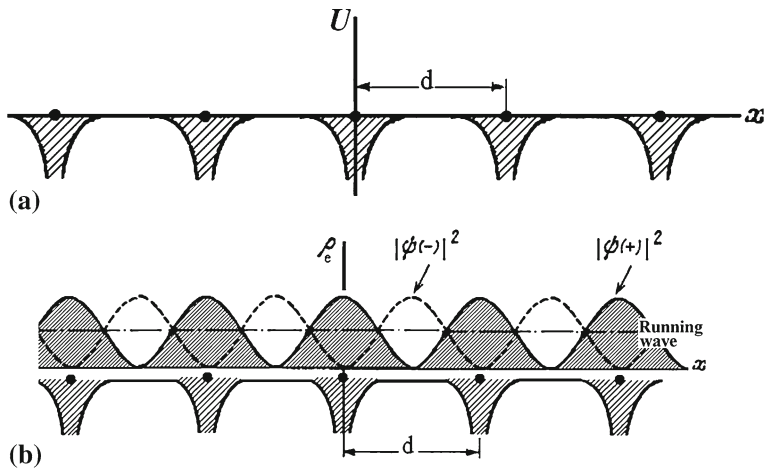


Fig. 2.12 Perfect crystal energy “picture”: **a** potential electron energy change; **b** wave function describing electron state

where Z —ion charge; R —radius-vector characterizing the atom position in the crystalline space; φ_{ex} —exchange potential.

The exchange potential is the characteristic of the quantum nature of exchange interactions fortifying the interatomic and intermolecular bonds by increasing the electron density between positively charged nuclei. The exchange interactions have the non-Coulomb nature and depend on the type of wave functions describing how the electrons behave in quantum systems.

The electron density profile for the mail state in the gel model possesses the planar translation invariance, see Fig. 2.13, but the density $\rho_e(z)$ variance has two particular features: first, electrons “spill out” into the region $z > 0$ (vacuum) and produce a surface electrostatic dipole; second, the function $\rho_e(z)$ oscillates when its value approaches the value compensating the volumetric charge. These are called Friedel oscillations after their discoverer French mineralogist Ch. Friedel. The wavelength of these oscillations is the following:

$$\lambda_{Fr} = \frac{\pi}{\kappa_{Fr}}, \quad \kappa_{Fr} = \left(3\pi^2\rho_e\right)^{\frac{1}{3}}, \quad (2.36)$$

The Friedel oscillations originate because electrons in metals can move freely when their energy is close to the Fermi energy producing almost monochromatic waves; here interference over the metal boundary causes oscillations. The electrons having the constant wave vector with the value between 0 and κ_{Fr} “try” to screen off the distribution of the positive ground charge which contains a step at $z = 0$. The Friedel oscillations contribute significantly to formation of the surface dipole layer playing a sizeable role in surface processes [17].

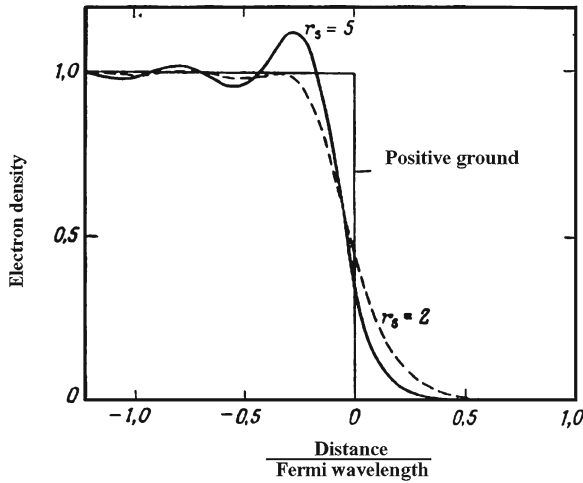


Fig. 2.13 Electron density profiles in gel model

The processes governed by surface phenomena are adhesion, adsorption, and surface diffusion.

Adhesion is the binding of surfaces of unlike bodies in contact [2, 14]. Adhesion, in narrow sense, is the ability of interfaced materials to produce strong compounds. The atomic molecular origin of adhesive forces is the same as solid body cohesion.

Adhesion depends on the nature contacting condensed bodies, the surface property and the contact area. The adhesion amplifies if the bodies are electrically charged, if donor-acceptor bonds form in the contact, if there is capillary condensation from the surface of one body on the other resulting in the contact chemical bonds.

The adhesive forces of interaction strongly affect the structure of crystalline bodies. For instance, when two copper specimens with the face-centered cubic structure are brought into contact, strong enough adhesive forces appear. The densely packed hexagonal crystals interact considerably weaker. If two specimens of unlike metals are brought into contact, their adhesive interaction is much weaker than that between two like metals.

The interface between the solid body and the fluid induces the wetting effect. The double electrically charged layer and donor-acceptor bonds play a special role in the interface near contacting surfaces. The “force” of adhesion is determined by the free surface energy loss by the interfaced bodies which are equal to the equilibrium adhesion function W_A :

$$W_A = (\gamma_{13} + \gamma_{23}) - \gamma_{12}, \quad (2.37)$$

where γ_{13} , γ_{23} , γ_{12} —the surface tensioning coefficients between interfaced bodies (1 and 2) and environment (3).

The problems of determination of adhesive forces in metal-polymer interfaces are due to the fact that they are strongly affected by the state of interfaced surfaces. The adhesive forces are large during adhesive interaction between polytetrafluorine ethylene (PTFE) and purified tungsten specimen surface in the vacuum. The electron and ion microscopy reveals that fragments of PTFE molecules on the metallic specimen surface form groups of tightly bonded particles or clusters. The Auger spectroscopy revealed that the fluorine atom at the polymeric chain end forms the physical and chemical bonds with the specimen surface. The adhesive interaction between the PTFE compounds and tungsten is much weaker in the air.

The combination of experimental methods of adhesion study has obtained the title of adhesionometry and the instruments to implement it are adhesionometers. As a rule, the methods of adhesionometry serve to measure the forces of fracture of adhesive compounds.

The researchers have at their disposal the nondestructive methods which enable to judge the forces of adhesion by variations of physical and chemical characteristics of contact interactions. For instance, the energy of adhesion is rated by the boundary wetting angle ζ with the help of the Dupret-Young law (J. Dupret—French physicist and chemist):

$$W_A = \gamma_{12} (1 + \cos \zeta). \quad (2.38)$$

Adsorption means the absorption of the condensed body (adsorbent) by the surface layer from the substances in the gaseous or fluid phase. The desorption or reverse adsorption is possible when the adsorbents are regenerated by eliminating the absorbed substances (adsorbates). The volumetric adsorbate can be calculated using the Freundlich formula (H. Freundlich—German physicist and chemist):

$$V_{ad} = \kappa_{ad} P_{ad}^n, \quad (2.39)$$

where V_{ad} —the volumetric adsorbate; κ_{ad} —the constant depending on the nature of adsorbate and adsorbent; P_{ad} —the adsorbate pressure; n varies from 0.1 to 0.9 (it tends to increase as the temperature grows).

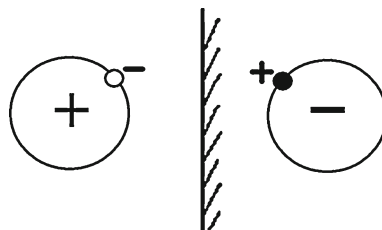
The main thermodynamic equation describing adsorption is the Gibbs equation:

$$G_{Gb} = - \left(\frac{\partial \gamma}{\partial \mu_{chem}} \right)_T, \quad (2.40)$$

where γ —the tensioning coefficient at the phase interface; μ_{chem} —the adsorbate chemical potential.

The Gibbs equation serves as the original to derive particular equations of adsorption. Usually the adsorbent surface is always coated by adsorbate particles; the longer the particles stay on the surface, the thicker becomes the coat. It is due to the forces of interactions between the adsorbent surface and the adsorbate particles. The surface energy reduces in the process of adsorption. It proves that adsorption is an energy gainful process with the ensuing consequences.

Fig. 2.14 Hydrogen atom and its antipode reflected in metal



There are physical or simple adsorption and chemisorption when chemical bonds appear between molecules of substances and the sorbent. The force of attraction should accompany the physical adsorption to bond particles to the solid body surface. Van der Waals forces play this role (see para 1.1), their mechanism is the polarization effect.

Electrons in the solid body are kept spaced due to the Coulomb and quantum exchange interaction based on the Pauli principle. These forces and polarization effect in the positively charged region around the electron called the hole with exactly the same charge as the electron but with the opposite sign. Moving through the crystal, the electron “trails” the tail of holes. When the electron quits the solid body, it leaves a hole on the solid body surface as the polarization charge. Similar processes evolve when atoms approach to the solid body surface. The example of interactions between hydrogen atoms and the metal surface (Fig. 2.14) gives the idea how the symmetric “antihydrogen” appears in the metal. In case of the multielectron atom the pattern of interactions is more complicated: quantum mechanical ion exchange interaction adds to the “purely Van-der-Waals” mechanism of adsorption.

The electrons are kept spaced due to the exchange components of the surface forces. At the qualitative level, the electron to create its own exchange correlation hole [16] with a single unaffected by other electrons. The electron moves through the crystalline space and rails the shell of holes called figuratively the “polarization coat” in [16]. The graphic presentation serves to describe vividly how the atom interacts with the solid body surface representing it as the line of constant charge density reflecting objectively the polarization processes.

The electron density configuration in Fig. 2.15a, corresponds to the case when a single atom is on the “electron gel” surface. The electron densities in the atom and on the solid body displace. The contour map is more demonstrative showing the difference between charge planes in the atom-surface system and the superposition of charge planes of the free atom and the pure surface (Fig. 2.15b). The surface region with the deficit of electrons is well seen which can be represented as the corresponding “mirrored antiatom”.

The localization of valent electrons of the atom adsorbate on the atom “side” facing the adsorbent surface does not mean that bonds appear in the chemical sense. Bonds appear due to the same cause why the energy of valent electrons reduces because their own holes surround them. The energy of this interaction keeps atoms

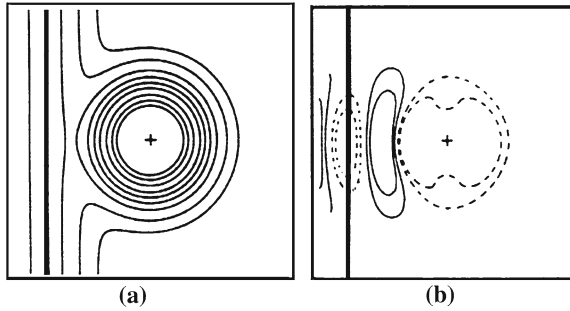
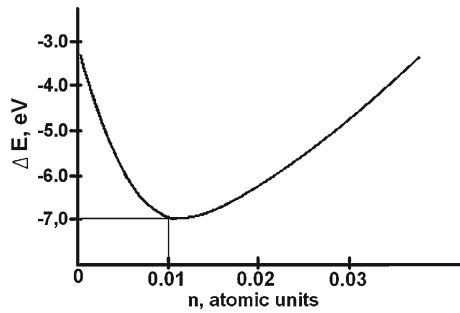


Fig. 2.15 Constant charge density line calculated for xenon adsorption on gel, **a** full charge density; **b** changes in charge density induced by adsorption. *Full line* corresponds to excess of electrons, *dotted lines* correspond the deficit of electrons

Fig. 2.16 Dependence of energy of submersion of atoms into “gel” on density of gas of electrons



on the surface with the help of the mechanism of physical adsorption. This energy amounts to

$$W_{ad} = - \int \frac{\rho_e(r') \rho_{ex}(r)}{|r - r'|} dr dr', \quad (2.41)$$

where $\rho_e(r')$, $\rho_{ex}(r)$ —the distribution of electrons and holes in the adsorbent.

The “true” chemical bonds between the surface and external atoms appear as a result of chemisorption when atoms of adsorbate and adsorbent particles “blend” directly. This process is called “immersion of atoms in gel”. The graphic image of the dependence of energy of interactions between free atoms in the “gel” of the adsorbent surface layer has the minimum corresponding to the “potential hole” (Fig. 2.16). To obtain this dependence, the electron density was assumed identical to the charge density change in the adsorbent close to the surface. The constant charge density line is shown in Fig. 2.17.

Figure 2.17 shows the constant charge density line (Fig. 2.17a) and the electron density contour map (Fig. 2.17b) for the “Cl—copper surface (gel)” system [16]. Figure 2.17b, shows clearly the surface region of fusion of electron densities of these elements evidencing the processes of chemisorption and (“atom submersion

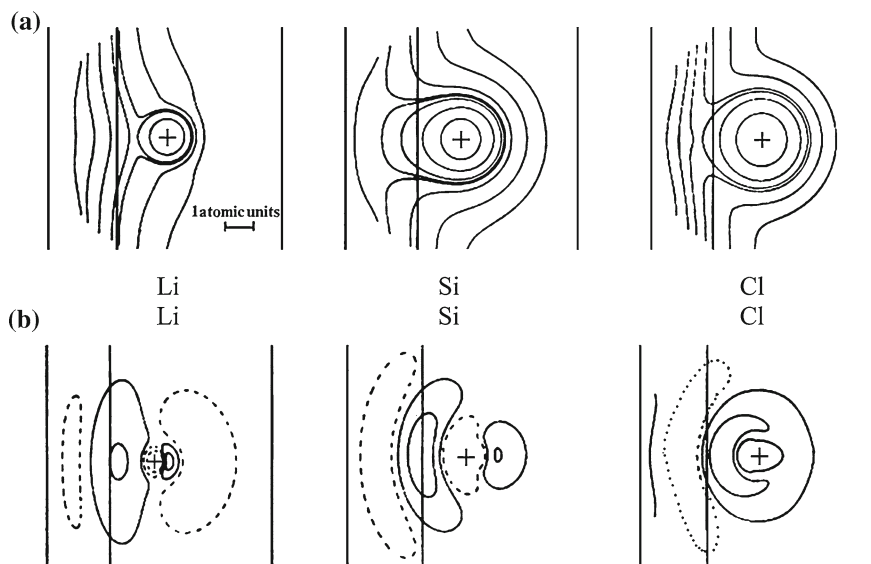


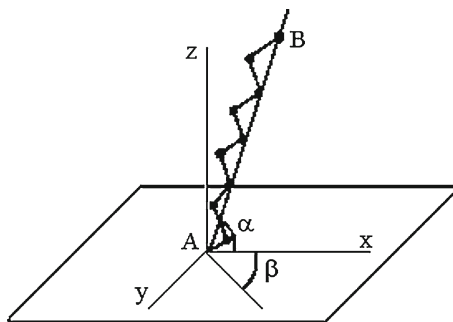
Fig. 2.17 Constant charge density line during adsorption of atoms Li, Si, Cl on gel, **a** full charge; **b** targeted charge. Lines: designations see Fig. 2.15

in gel”) and the regions of the minimal electron densities they induce when forming the “polarization coat”.

The difference of electron densities appearing during chemisorption permits to introduce the notion of the binder (the maximum electron density) and the antibinder (the minimum density) levels which represent the system of sorbed atoms or molecules called the surface cluster or “surface molecule” [16].

To describe molecular adsorption, the orientation of adsorbate particles should be known in respect to the substrate. The matter of their spatial arrangement during adsorption is omitted just because of the symmetric molecules. But these molecular structures are capable to polarize and often acquire the charge density asymmetric distribution. The macromolecules and molecules of lubricating materials have the dominating chain structures. The chain structure position on the solid body surface is characterized by two coordinates x , y and two angles α , β (Fig. 2.18).

Fig. 2.18 Chain molecule orientation on plane



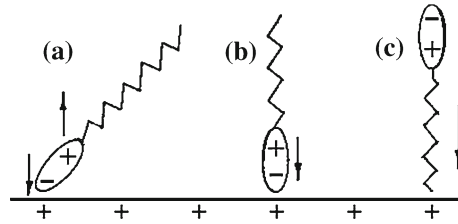


Fig. 2.19 Orientation of chain molecules with active center on metallic specimen surface: **a** molecule experiences torque; **b** nonelastic collision occurs; **c** absolutely elastic impact

The adsorbed molecule orientation in respect to the adsorbent surface is determined by the interaction between the surface adsorption centers and the molecule active centers. In the simplest case, molecules are devoid of active centers at all or have one–two centers at the molecular chain ends or through its length.

The adsorption orientation of polar chain molecules with a single adsorption center most worthwhile to discuss from the tribological viewpoint because they orient in respect to the tribosurface of molecules of the lubricating material (Fig. 2.19).

When the solid body surface interacts with electrical fields, the charge redistributes in the polar molecules and dipole group appear. Depending on the polar molecule orientation in the surface force field, their interaction resembles different impact during collision (Fig. 2.19). The mobility of adsorbed molecules is as high as the temperature, and it is high the lower the level of saturation of the monomolecular adsorption layer and the fewer the obstacles to molecule motion over the surface. The multimolecular structure resulting from chemical reactions has the most freedom to move. The appearance of the primary molecular monolayer is accompanied by desorption and evolves with the dynamic adsorption being in equilibrium. The occupation of free spots with adsorbed particles on the adsorbent surface depends on the length of chains and the position of active centers “a” along the chains (Fig. 2.20). Then follow the next rows of the multimolecular layer.

Diffusion is the motion of the medium particles resulting in the transfer of substances and leveling of concentrations or the equilibrium distribution if concentrations of particles of the given type in the medium [2, 17, 18]. The process of diffusion is treated farther in more detail; now one of the features of this phenomenon is considered, it is the surface diffusion. The surface diffusion implies the displacement of particles by random thermal fluctuations over the solid body surface within the first layer of atoms. The energy barriers the particles overcome on the diffusing surface

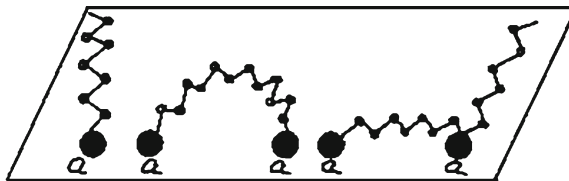


Fig. 2.20 Formation of multimolecular adsorption layer of polar molecules

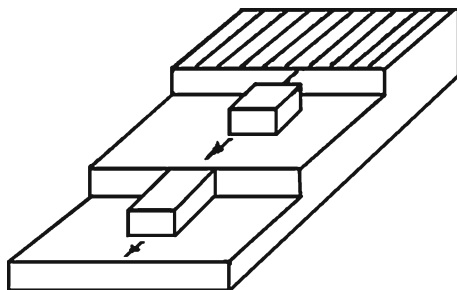


Fig. 2.21 Schematic image of surface diffusion

are much lower than their volumetric values. Hence, the energy of activation of the surface diffusion makes up just a part of the energy of activation of the volumetric diffusion. The surface diffusion process proper is usually considered as the sequence of elementary acts shown schematically in Fig. 2.21. When substances under the effect of thermodynamic forces, the atoms detach from the second atomic plane, move along smooth terraces, slide off the lattice step and get trapped in the vacancies.

Groups of bonded atoms or some regions of the surface layer as a whole can move during surface diffusion. Usually the surface diffusion is considered as the process altering the adsorbate concentration from the non-equilibrium to the equilibrium distribution when there are corresponding concentration gradients.

In the general case, the solid body surface has a laminar structure (Fig. 2.22). The topmost are the films consisting of the atoms and molecules adsorbed from the environment. This film is differently thick: it is thicker where the defects of the crystalline structure accumulate (the adsorption centers). The mechanical working of the engineering materials (forging, extrusion, etc.) activates the surface layers additionally.

The solid body surface is not absolutely smooth, at least due to the dislocations creating dislocation steps. This type of surface deviations from the perfect state are

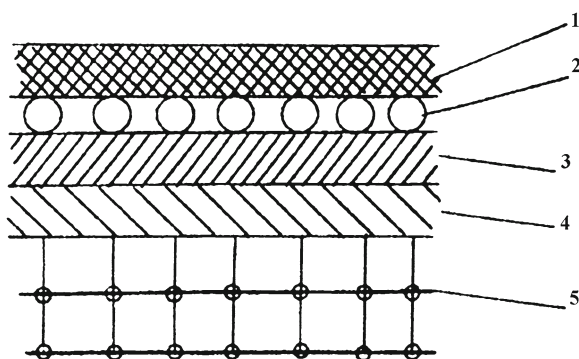


Fig. 2.22 Scheme of solid body surface: 1 films of adsorbed molecules, 2 surface layer proper, 3, 4 layers modified by mechanical treatment of structure, 5 solid body crystalline structure proper

called the submicroroughness. Its parameters vary from fractions of a micron to hundreds angstroms; they are essential nanotopology characteristic of the surfaces of solid bodies. The problem of submicroroughness effect on contact interaction between solid bodies is currently the object of thorough research.

Other surface deviations from the perfect relate to the machining of materials. They are subdivided into waviness and roughness and are treated in many publications [19].

2.4 Phase Boundaries

The surface of condensed bodies predetermines a specific type of phase boundaries [1, 6]. The contacting phases of one substance having incompatible lattice parameters or an entire different nature, make up a distinct interface boundary (Fig. 2.23a).

If the crystalline structure is not disoriented, the phases coalesce; all crystallographic planes continue through the phase boundary (Fig. 2.23b). The coherent boundary phase forms when the phases possess identical structures, but they have twin mutual orientation. In his case, all lattice nodes of one crystal are lattice nodes of the other crystal.

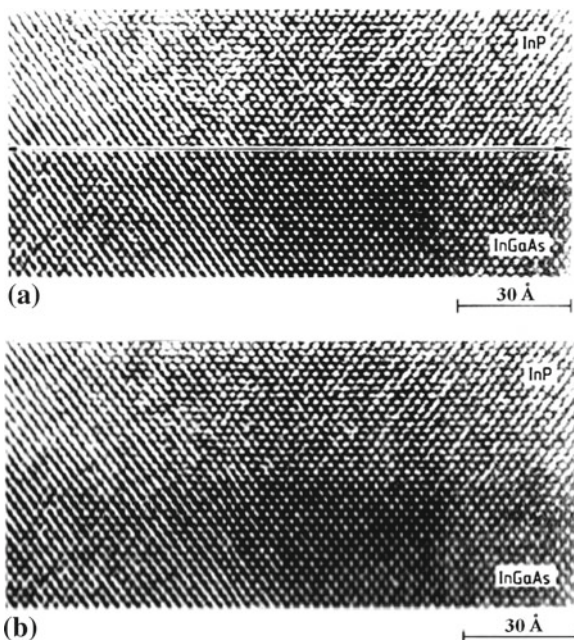


Fig. 2.23 Arrangement of atoms of one same substance at phase boundary: **a** disagreement between lattice parameters; **b** latent boundary

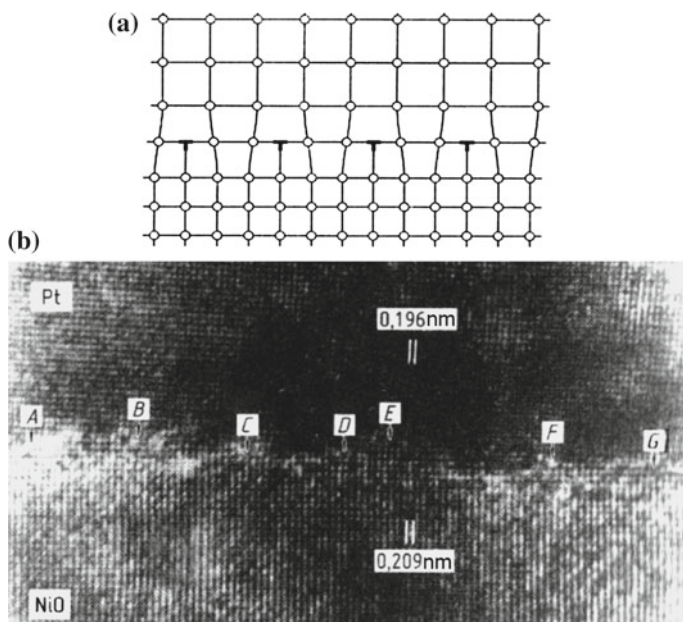


Fig. 2.24 Semicohherent boundary (nm): **a** scheme, **b** microscopic photograph of boundary between Pt and NiO (letters indicate ruptures of crystallographic planes) [6]

As crystals grow, the disagreement between the structure parameters over phase boundary augments and the elastic energy increases at the phase boundary. The energy is gainful to compensate the disagreement by producing boundary dislocations which relieve mechanical stresses. This type of boundaries is termed partially coherent type (Fig. 2.24).

If both phases possess absolutely different structures, the coherence is fully lost and the incoherent phase boundary (Fig. 2.25). Like in the case of the intergrain boundaries, some energy can appear at the phase boundary and preferable lattice configurations. The phase boundaries in composites are, as a rule, in the nonequilibrium state (Fig. 2.25).

The insufficient knowledge of the structure phase boundaries inhibits the description of their properties at the atomic level [6]. The phenomenological description is usually used combining the interface properties with the physical parameters of interactions between phases which can be determined experimentally. One of them is the surface tensioning γ which is associated with excessive surface free energy and determines the equilibrium type of the interface surfaces in mixed phases.

Let us consider the fluid drop shape in equilibrium on the solid body surface (Fig. 2.26). The surface tensioning act along the contact line as the forces conditioning the drop configuration based on the criterion of the minimum energy. The equilibrium in vertical direction takes place if

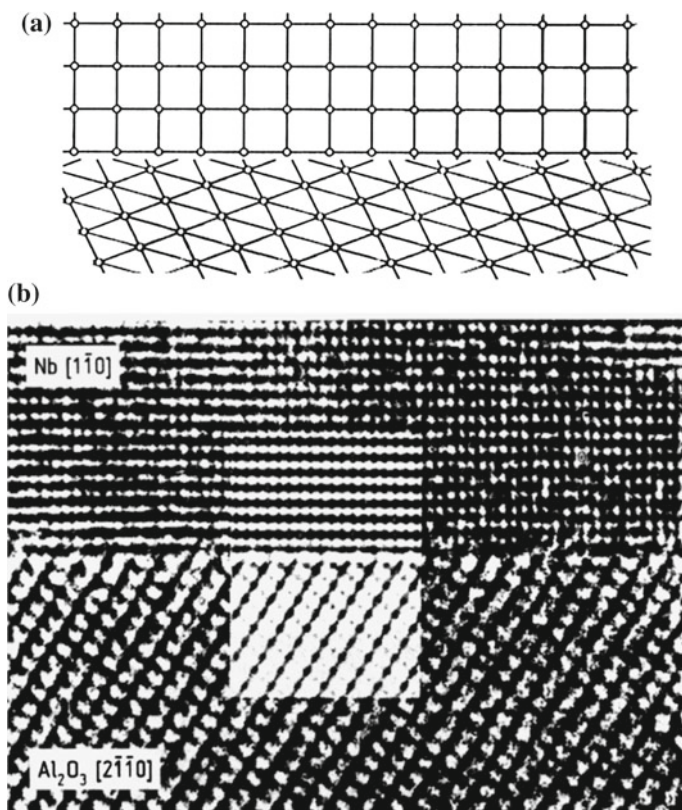


Fig. 2.25 Incoherent boundary: **a** schematic view; **b** high resolution electronic microscope image

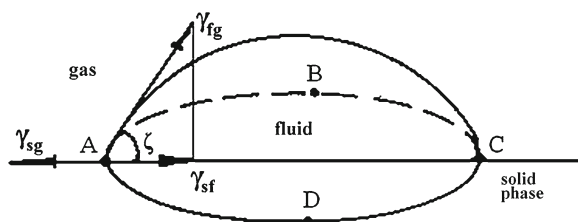


Fig. 2.26 Scheme of fluid drop in equilibrium on solid body surface

$$\gamma_{sg} = \gamma_{sf} + \gamma_{fg} \cos \zeta. \quad (2.42)$$

This equation (the Dupret equation) enables to estimate the wetting angle ζ .

The drop spread over the solid body surface (2.42) is a particular case of the equilibrium of three phases (Fig. 2.27). In the general case, the Herring equation is true (C. Herring—American physicist theoretician):

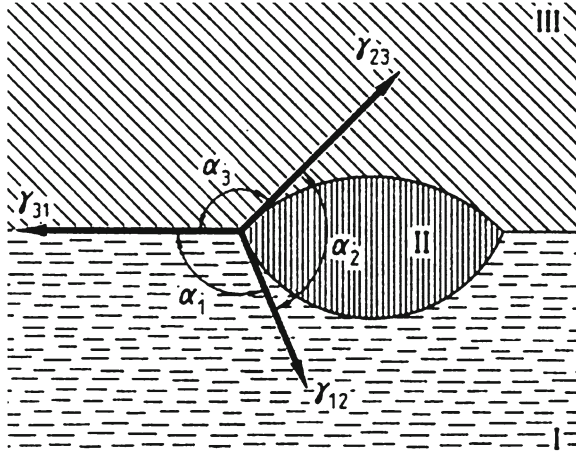


Fig. 2.27 Three phase system equilibrium. I and II—fluids, III—gas

$$\frac{\gamma_{23}}{(1 + \varepsilon_2 \varepsilon_3) \sin \alpha_1 + (\varepsilon_3 - \varepsilon_1) \cos \alpha_1} = \frac{\gamma_{13}}{(1 + \varepsilon_1 \varepsilon_3) \sin \alpha_2 + (\varepsilon_1 - \varepsilon_2) \cos \alpha_2} = \frac{\gamma_{12}}{(1 + \varepsilon_1 \varepsilon_2) \sin \alpha_3 + (\varepsilon_1 - \varepsilon_3) \cos \alpha_3}, \quad (2.43)$$

where $\varepsilon_i = \frac{\partial}{\partial \zeta_i} (\ln \gamma_{hkl})$ determines the dependence of the interphase energy on the adsorbate phase orientation in respect to the selected crystallographic directions of the adsorbent crystalline lattice. The subline indexes correspond to Fig. 2.27.

The surface energy of boundaries of some crystallographic phases turns out very low, for instance, that of the coherent twin boundaries. If the energy of all three boundaries is independent of their orientation in space, the Herring equation is simplified to the Young equation:

$$\frac{\gamma_{12}}{\sin \alpha_3} = \frac{\gamma_{23}}{\sin \alpha_1} = \frac{\gamma_{31}}{\sin \alpha_2}. \quad (2.44)$$

References

1. A.S. Akhmatov, *Molecular Physics of Boundary Friction* (Physical-Mathematical Literature, Moscow, 1963), p. 472
2. D.N. Lyubimov, V.A. Ryzhikov, *Phys. Chem. Processes in Friction: Manual*. Novocherkassk: South Russ. State Eng. Univ. 147 (2006)
3. R. Kana (ed.), *Physical Science of Metals*, vol. 3 (Mir, Moscow, 1968), p. 483
4. Y.D. Eshelby, *Appl. Phys.* **25**, 255 (1954)
5. Ch. Kittel, *Introduction into Solid Body Physics* (Mir, Moscow, 1978), p. 791

6. G. Gottstein, *Physical and Chemical Principles of Science of Materials* (Binom, Moscow, 2009), p. 375
7. L.S. Pinchouk, V.A. Strouk, N.K. Myshkin, A.I. Sviridyonok, *Science of Materials and Structural Materials* (Vysshaya Shkola, Minsk, 1989), p. 459
8. L.D. Landau, E.M. Livshits, *Continuum Physics*, vol. 8 (Fizmatlit, Moscow, 2005), p. 656
9. A.M. Prokhorov (ed.), *Physical Encyclopedia*, vol. 1 (Sov. Encyclopedia, Moscow, 1988), p. 638
10. G.S. Pisarenko (ed.), *Strength of Materials*, (Vyshcha Shkola, Kiev, 1986), p. 775
11. S. Morrison, *Chemical Physics of Solid Body Surface* (Mir, Moscow, 1980), p. 367
12. Kh. X. Chikhos, *System Analysis in Tribonics* (Mir, Moscow, 1982), p. 348
13. V.F. Kiselev, S.N. Kozlov, A.V. Zoteyev, *Fundamentals of Solid Body Surface Physics* (INBU, Moscow, 1999), p. 284
14. D. Bakley, *Surface Phenomena During Adhesion and Friction Interaction* (Mashinostroyenie, Moscow, 1986), p. 360
15. A.M. Prokhorov (ed.), *Physical Encyclopedia*, vol. 2 (Sov. Encyclopedia, Moscow, 1990), p. 703c
16. E. Zenguil, *Surface Physics* (Mir, Moscow, 1990), p. 536
17. V. Jayavaya, R. Vanselova (ed.), *New in Solid Body Surface Research* (Mir, Moscow, 1977), p. 314
18. D.N. Lyubimov, K.N. Dolgoplov, *Difusive Processes in Friction* (IP Bouryhin V.M., Shakhty 2010), p. 148
19. A.V. Chichinadze (ed.), *Fundamentals of Tribology* (Science and Technology, Moscow, 1995), p. 778

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