

## **STRENGTH OF MATERIALS AND DAMAGE ASSESSMENT**

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**Keywords:** deformation, stress, strength, fracture, crystal lattice, bond, dislocation, damage.

### **Contents**

1. Damage and mechanical behavior of materials
2. General ideas and definitions
3. Structures and bond types of solids
4. A physical view of defects
5. Dislocation mechanisms of origin and growth of cracks
6. Fractography of surfaces of extending cracks
7. Fundamental definitions of defects
8. Methods for evaluating the level of damage

Glossary

Bibliography

Biographical Sketch

### **Summary**

The physical interpretation of the service life of a material that is under load requires the direct study of evolution of its structure, analysis of connection between elementary phenomena of plastic deformation and damage, and establishing the damage accumulation relationships. The development of increasingly precise methods for studying the microstructure and identifying the defects is associated with the increase of severity of requirements on operation conditions and safety as well as the economic effectiveness of the mechanical structures. Therefore, the problem of determining a change of the damage level in solids becomes more and more urgent in the course of time.

### **1. Damage and Mechanical Behavior of Materials**

In general, by the level of damage in mechanics we mean a change of the mechanical properties which may have a different nature. However, this process is interpreted phenomenologically as the process of forming and growth of microvoids and cracks of various types because of breaking the interatomic bonds. For example: in metals this takes place by means of the motion and concentration of dislocations; in polymers – by breaking bonds between long molecular chains; in ceramics and composites – as a result of loss of cohesion between matrix and filler. The process of damage begins at the very early stages of deformation and is due to all sorts of shear mechanisms: a diffusion creep associated with the directed transport of atoms because of a stress state; accumulation of ruptures of the atomic bonds because of thermal fluctuations; and structural changes in the course of time. Various types of structural defects, which

determine accumulation of the damage, are schematically shown in Figure. 1.

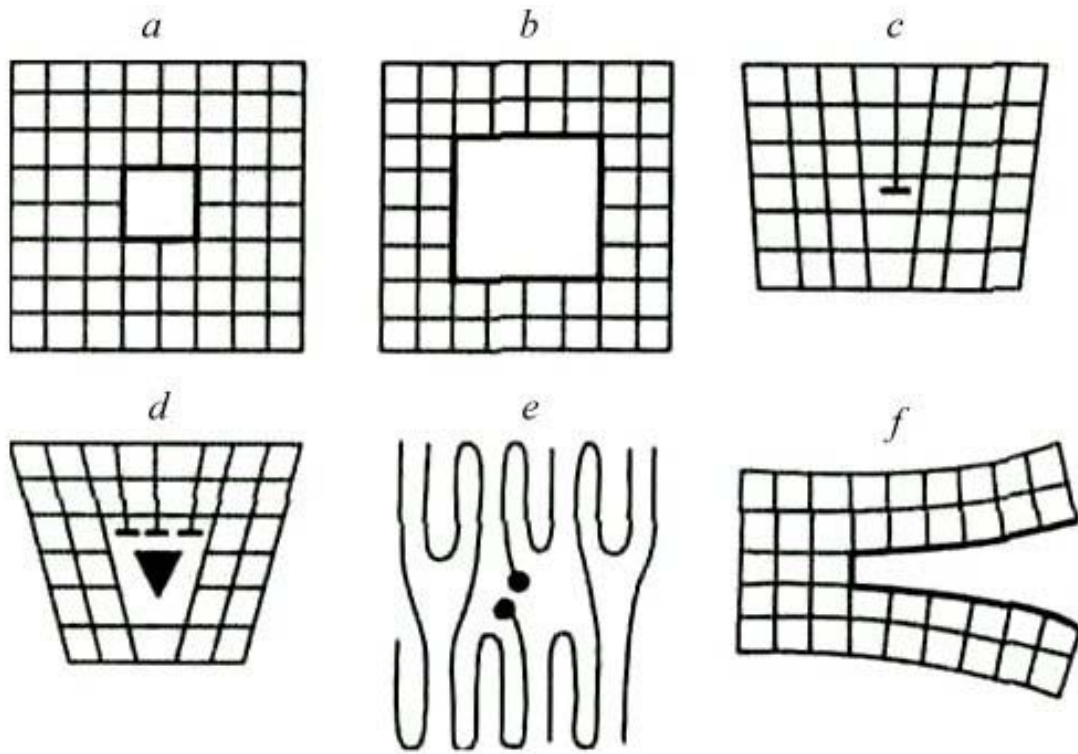


Figure 1: Types of the structure defects; a – elementary vacancy (Schottky defect); b – pore; c – dislocation; d – formation (forming) of a microcrack; e – rupture of the molecular chains; f – crack.

Numerous elementary processes of defect formation manifest themselves in the macroscopic characteristics of materials and the multi-stage nature of mechanical behavior. We can divide the damages into the scattered defects those are small in size and encountered in large numbers per unit volume, and those localized in the form of large cracks, which manifest themselves in the final stage of the failure process. In this connection, we introduce the following levels of examination: a microlevel - the level at which we analyze the deformation and damage mechanisms (these levels are atoms in the case of elasticity, dislocations in the case of plasticity, and inclusions or microcracks in the case of defect formation); a mesolevel is the level of characteristic element of volume  $V$  in the form of a mathematical point that is small enough to define the spatial partial derivative but large enough to describe the elementary discrete mechanisms of the change of the structure by means of continuous variables from the physical viewpoint,. The volume  $V$  must be small enough to avoid the smoothing out of the large gradients but, at the same time, large enough to reflect, on the average, the microprocesses those are taking place. For experimental purposes and numerical analysis, it is customary to examine the following orders of magnitude of the  $V$  values:  $(10^{-4} \text{ m})^3$  – for metals and ceramics;  $(10^{-3} \text{ m})^3$  – for polymers and composites;  $(10^{-2} \text{ m})^3$  – for wood;  $(10^{-1} \text{ m})^3$  – for concrete. Dimensions and the constitutive equations of a newly formed microcrack are established on this level; a macrolevel is the level of structural elements, on which we examine cracks of length ranging from a millimeter to

meters.

## 2. General Ideas and Definitions

In the mechanics of a solid deformable body, various elements of machines and structures (for example, cores, plates, and beams shoulder-blades of turbines and vessels of high pressure) are considered as solids of given configuration. It is thought that the given solid body has some complex of physical-mechanical properties reflecting the main properties of a real material and an element of design, on the whole.

A solid body, under the influence of external forces (efforts/loads) in greater or smaller degree changes its size and form, and thereby deformed. The deformations, arising in such cases, are elastic or plastic. A deformation that completely disappears upon removal of influences which caused its occurrence is referred to as elastic. A deformation that does not disappear after removal of specified loads, is referred as residual or plastic. A property of solid body to restore the initial form and sizes is called as elasticity, and to keep the deformations as plasticity.

If loads, acting on a body, are great enough, one going through some deformation stage collapses, that is, it loses the integrity - breaks up to separate parts. A property of a solid body representing resistance to deformation is its stiffness and to failure -is the strength. Due to them, character of physical interaction between particles (atoms, ions, molecules etc.), forming a solid body, appears depending on the distance change between these particles in the process of the body deformation. These and other properties of real solid bodies are determined by test of various samples made of the given material on the given kind of deformation, for example tension, twisting, bending, shearing. As a result of such experiment, the diagram (Figure. 2) reflecting the dependence between values of the acting load  $P$  and deformation of a sample  $\Delta l$  is constructed. Figure. 2 shows the stress-strain relationship of a standard cylindrical sample of steel in a tension test.

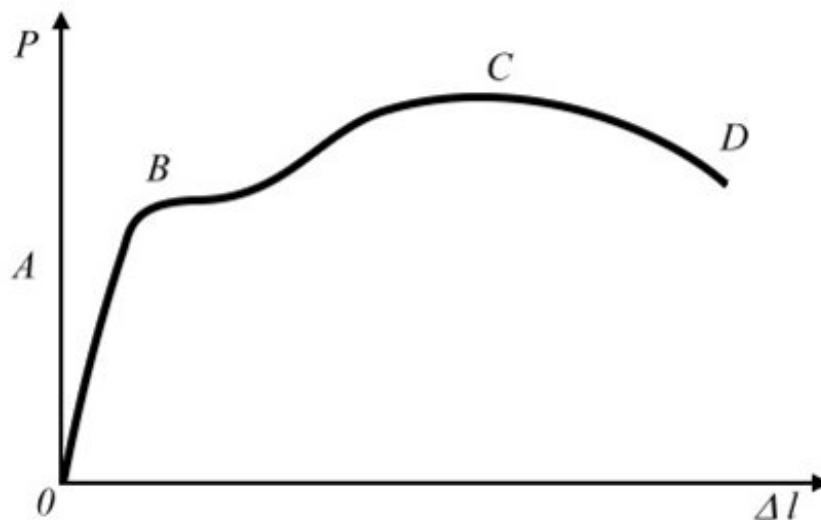


Figure 2: The tension diagram of a cylindrical sample from steel.

The maximal effort per unit of the sample cross section area, which it withstands before

failure, refers to as ultimate strength of a material. This strength value  $\sigma_b$  corresponds to a point C on the diagram shown in Figure. 2. Other characteristic points of the diagram also correspond to the important physical-mechanical properties of a material. Thus, the point A characterizes an elasticity limit  $\sigma_e$ , and the point B characterizes a limit of the yield stress  $\sigma_y$ ; at the point D, a body breaks down.

The limit of relative strength of a material  $\sigma_b$  differs from the theoretical value of  $\sigma_{th}$ , which is estimated by the intensity of interaction between atomic planes in an ideal crystal lattice of such material. The limit of theoretical strength is experimentally supported in the destructive testing of samples as very thin rods. The level of relative strength of the majority of materials is two or three orders of magnitude smaller (less) than the theoretical one due to various defects in the structure of a real solid. The defects of structure initiate material failure. Therefore, to determine the strength of any material it is necessary to have the data on the processes of deformation and failure in a material with defects.

### 3. Structures and Bond Types of Solids

The substances, existing in Nature, can be in one of four states of aggregation of matter: solid, liquid, gas or plasma. In contrast to other substances, the solids are capable of keeping the form and size (at a constant temperature), that is, they have strength and stiffness. Under the action of external forces, the internal forces in a solid body arise due to interactions between the particles caused by change of distance between them. At low temperatures, all substances are transformed (pass) into a solid state (condition). The equilibrium condition of a body with the given structure is defined from the minimum of the total thermodynamic potential:

$$F = U - TS + PV. \quad (1)$$

Here,  $U$  is internal energy;  $S$  is entropy;  $P$  is a pressure; and  $V$  is volume. Solids can be crystalline or amorphous. The presence of long order is characteristic for a crystal structure. For an amorphous body, the so-called near order is a specific. Despite identical composition of initial particles, solid bodies can have various crystal structures. Their ability - polymorphism - is caused by the presence of several relative minima of thermodynamic potential. A distinctive feature of monocrystal bodies is anisotropy that is their properties depend on direction. The polycrystals, consisting of a set of randomly oriented monocrystals, are also amorphous and isotropic bodies.

For the description of the internal structure of crystals, the concept of a crystal lattice is used. At its nodes the particles (atoms, ions or molecules) are placed. The elementary cell of a crystal lattice represents a parallelepiped. By its simple moving in three directions (translation) the spatial crystal lattice can be constructed. The lengths of parallelepiped, edges are  $a, b, c$  and the values of angles between its sides are  $\alpha_0, \beta_0, \gamma_0$ . Figure. 3 shows a crystal lattice. In 1948, the French crystallographer O. Bravais had shown, that, depending on the size and mutual orientations of elementary cell edges, the existence of 14 types of crystal lattices (Bravais lattice) was possible.

Some typical forms are: base-centered, body-centered and face-centered lattices of crystals. If the nodes of a crystal lattice are only on the top of the parallelepiped, the lattice refers to a primitive or elementary type (lattice). If the nodes are also at the center of the parallelepiped bases, it refers to the base-centered type. If a node is placed at the center of a cell, the lattice refers to the body-centered type, and if there are nodes at the center of each side, it is considered as the face-centered type.

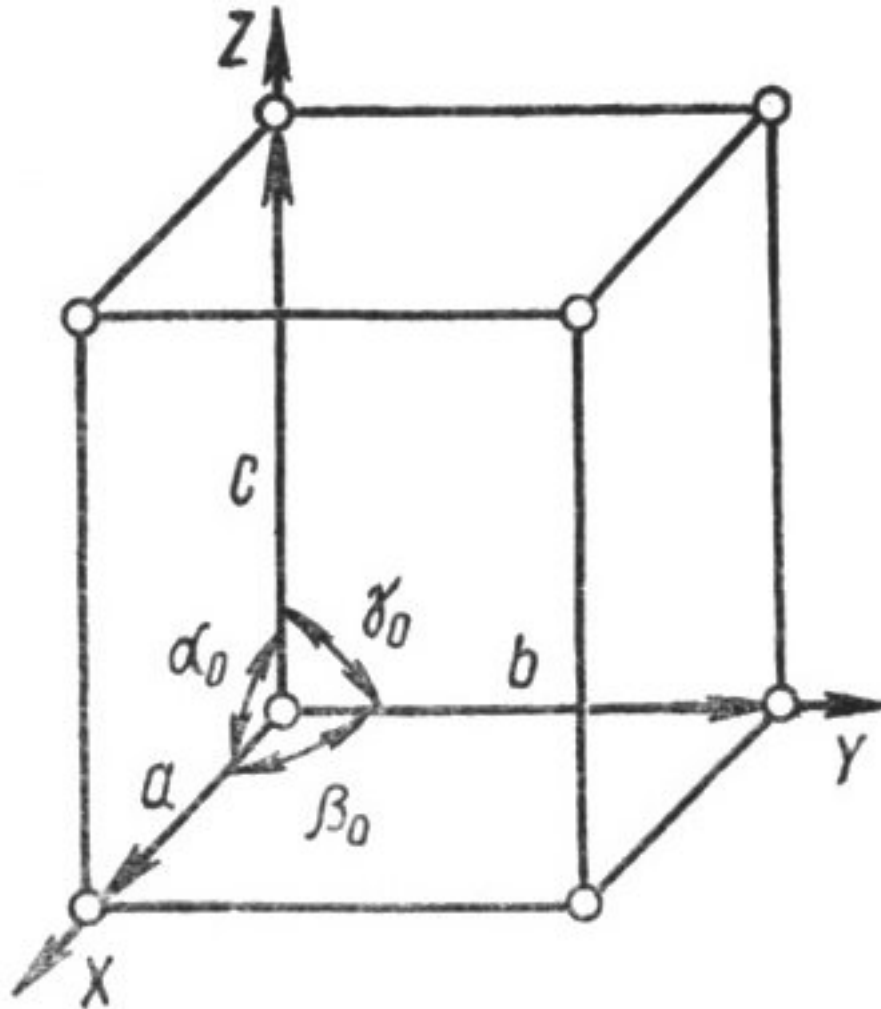


Figure 3: Schematic image of a crystal lattice.

Depending on the angles  $\alpha_0, \beta_0, \gamma_0$  between sides of a cell and the ratio between lengths of its edges, there are seven crystal systems (syngonies): 1) cubic; 2) hexagonal; 3) tetragonal; 4) rhombohedral; 5) rhombic; 6) monoclinic; 7) triclinic.

For cubic syngony  $\alpha_0 = \beta_0 = \gamma_0 = 90^\circ, a = b = c$  (Figure. 4). Thus, three versions of a cubic lattice are possible: simple, body and face-centered (BCC and FCC). For hexagonal syngony ( $\alpha_0 = \gamma_0 = 90^\circ, \beta_0 = 120^\circ, a = c \neq b$ ), the elementary cell represents a six-faced prism (Figure. 4). An elementary cell of tetragonal syngony ( $\alpha_0 = \beta_0 = \gamma_0 = 90^\circ, a = b \neq c$ ) is the rectangular parallelepiped with a square on the

basis (Figure. 4). In this system, the simple and the body-centered lattices can be present. In rhombohedral syngony ( $\alpha_0 = \beta_0 = \gamma_0 \neq 90^\circ, a = b = c$ ), an elementary cell is rhombohedron (Figure. 4; in rhombic ( $\alpha_0 = \beta_0 = \gamma_0 = 90^\circ, a \neq b \neq c$ ) it is rectangular parallelepiped with various lengths of edges (Figure. 4). In this syngony, four spatial lattices are observed: simple, base-, body- and face-centered.

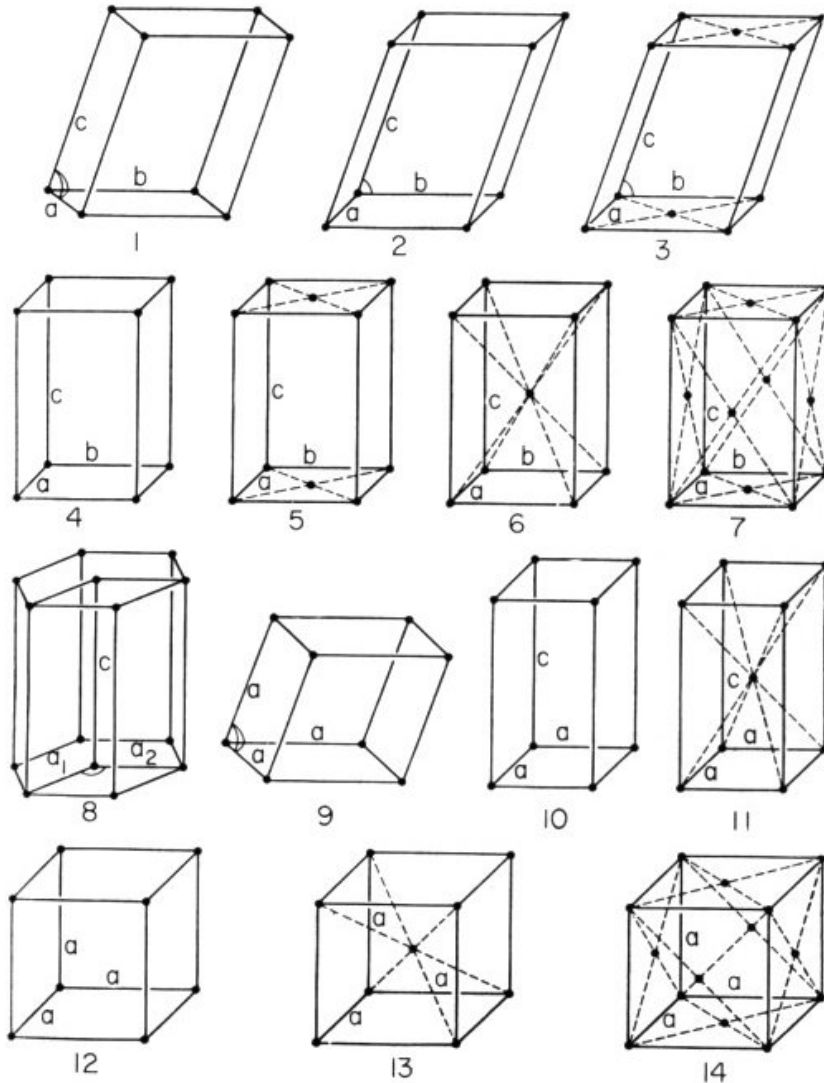


Figure 4: The 14 Bravais lattice: 1 – triclinic; 2 – monoclinic; 3 – base-centered monoclinic; 4 – orthorhombic; 5 - base-centered orthorhombic; 6 - body-centered orthorhombic; 7 - face-centered orthorhombic; 8 – hexagonal; 9 - rhombohedral; 10 – tetragonal; 11 - body-centered tetragonal; 12 – cubic; 13 - body-centered cubic; 14 - face-centered cubic.

In monoclinic syngony ( $\alpha_0 = \beta_0 = 90^\circ, \gamma_0 \neq 90^\circ, a \neq b \neq c$ ) with the elementary cell, which represents the inclined parallelepiped (Figure. 4), there are two spatial lattices: simple and base-centered. The spatial lattice of a triclinic syngony

( $\alpha_0 \neq \beta_0 \neq \gamma_0 \neq 90^\circ, a \neq b = c$ ) has the elementary cell as a parallelepiped (Figure. 4), in which all edges and angles (between them) are not equal one to another.

Because of anisotropy in crystals, it is necessary to systematize designations of the coordinate planes and directions in a crystal. For this purpose, the system of coordinates is chosen, where the axes coincide with three edges of an elementary cell, and the origin of coordinates is placed at one of the lattice corners. It is accepted, that axial units of length correspond to the lengths of edges of the cell. It means that a unit of length on the axis X will be  $a$ , on the axis Y,  $b$ , and on the axis Z,  $c$ . Location of any plane in a space is determined by three points. It is convenient to take the intersection points of a plane with coordinate axes.

Let the plane S cross the coordinates axes at points A, B, C (Figure. 5) and cut on the axes segments (pieces)  $m = OA/a$ ;  $n = OB/b$ ,  $p = OC/c$ . For the case, represented in Figure. 5 it follows:  $m = 4$ ,  $n = 3$ ,  $p = 2$ . The ratio of the reciprocal of axial segments (pieces)  $\frac{1}{m} : \frac{1}{n} : \frac{1}{p}$ , expressed through ratio of three least integers  $h, k, l$ , known as the Miller indexes, is written as:

$$h:k:l = \frac{1}{m} : \frac{1}{n} : \frac{1}{p} . \tag{2}$$

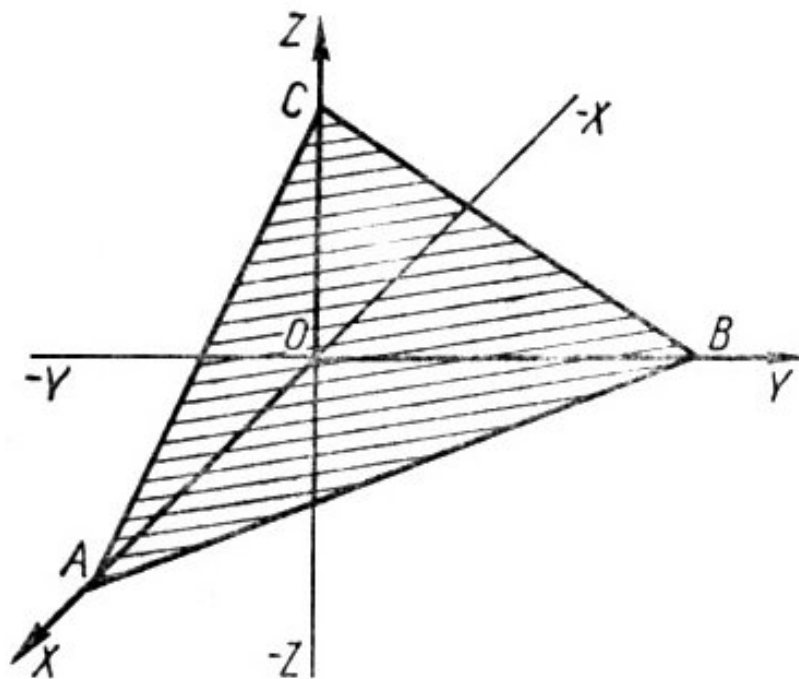


Figure 5: A schematic sketch of section of the coordinate corner by a plane.

The Miller indexes are put in parentheses ( $h, k, l$ ), and the sign of the ratio between

them is not put. For plane S (Figure. 5):

$$\frac{1}{m} : \frac{1}{n} : \frac{1}{p} = \frac{1}{4} : \frac{1}{3} : \frac{1}{2} = \frac{3}{12} : \frac{4}{12} : \frac{6}{12} = 3 : 4 : 6. \quad (3)$$

That is, the Miller indexes are  $h = 3, k = 4; l = 6$  or (3, 4, 6). If the plane is parallel to any of the axes, the Miller index, corresponding to this axis, is equal to zero ( $0 = \frac{1}{\infty}$ ). For the negative meaning of a segment (piece), cut by a plane, the corresponding Miller index has negative sign. This sign is put above an index, for example ( $\bar{1}02$ ). With known Miller indexes, it is easy to determine the segments (pieces) cut by a plane on the coordinate axes.

A family of equivalent planes is designated by the curly brackets. For example, the symbol {100} designates all family faces of a cube (100), (010), (001), and so on.

Indexes of directions in a crystal represent a set of the least numbers  $n_1, n_2, n_3$ . Its ratio to each other is equal to the ratio of projections of the vector, parallel to the given direction on a coordinate axis (the value of vector projections on axis of coordinates should be expressed in the appropriate scales  $a, b, c$ ). These indexes are shown in square brackets:  $[n_1, n_2, n_3]$ . The family of equivalent directions is designated as :  $\langle n_1, n_2, n_3 \rangle$ .

Crystals of a hexagonal system (Figure. 4) are described by four coordinate axes:  $x_1, x_2, x_3$ , and  $z$ . The axes  $x_1, x_2, x_3$  have an identical scale, lie in one plane and emerge from the origin of coordinates under a corner of  $120^\circ$ . The axis  $z$  is perpendicular to the coordinate plane. In hexagonal syngony the Miller-Bravais indexes are applied. The principle of finding these indexes is the same, as for the Miller indexes:

$$\frac{1}{m} : \frac{1}{n} : \frac{1}{p} : \frac{1}{g} = h : k : l : i. \quad (4)$$

The particles, making up a solid body, are positioned at the nodes of a crystal lattice. Depending on the physical nature of forces, operating between these particles in a crystal body, the following types of interspatial bonds are probable: ionic, covalent, metal and molecular. Such classification allows us to make some generalizations concerning their properties. In the crystal lattice nodes of crystals with the ionic bonds, there are positive and negative ions. The forces of electrostatic attraction between opposite ions are greater, than the force of repulsion (pushing away) between them. The ionic bond is typical of an inorganic compound (for example, NaCl, CsCl).

The exchange interaction between atoms by means of electrons, having only quantum nature lies on the basis of occurrence of a covalent (homeopolar) bond. Under the influence of a covalent bond the atoms are not only located at certain distances from each other, but also form certain spatial configurations. The covalent bond arises



between two atoms when the formation of common pair of valence electrons takes place. Such bond forms not only between atoms of one element, but also between different ones (for example, Si and C). The covalent chemical bond is also very strong. The crystals with this type of bond are characterized by large values of strength, hardness and high melting temperature.

At the nodes of a crystal lattice with a metal bond, there are ions. Atoms forming a metal structure, approach so that there are blocking interactions between valence electrons. Because of that, the last electron has possibility to move freely over the volume of metal to become common ("collectivize"). The electronic gas is common for all crystals and creates "cementing" action, connecting in the strong system of the positively charged ions of a metal. The presence of repulsion forces between ions of metal and "tightening" as a result of collective action of electrons make the ions of the metal settle down at a certain equilibrium distance from each other (corresponding to the minimum of potential energy of the system) forming a strong metal bond.

In molecular bonds at the nodes of a crystal lattice, there are steady molecules, for example H<sub>2</sub>, N<sub>2</sub>, Br<sub>2</sub>, CO, which keep the individual features and are kept at the nodes of a lattice by the van der Waals forces.

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### **Biographical Sketch**

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Professional employment: 1972-1974: Junior Research Fellow of the Scientific Research Institute of Graphite Materials; 1974-1978: Junior Research Fellow of the Mechanical Engineering Research Institute of the Russian Academy of Sciences; 1978-1986: Senior Research Fellow at this Institute; 1986-1996: Conduction Research Fellow at this Institute; 1996 – Present: Head of the Laboratory of Modeling of Vibroacoustic Processes at this Institute; 1998 - Present: First deputy of general director of interindustry research complex “Reliability of Machines”

Author of about 84 articles and the monograph “*Influence of Damage on the Deformation and Strength Characteristics of Solids*” (in Russian, 1990).