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ELASTOPLASTIC PROPERTIES OF MULTICOMPONENT COMPOSITES

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Predicting the inelastic properties of materials with random discontinuities is one of the most important current developments in the mechanics of deformable solids. Modeling the macroscopic governing relations and calculating the effective characteristics of such media in many cases permits satisfactory estimation of the strain properties, limiting state, and load-carrying capacity of structural elements made of composites, powders, and other types of structural materials. The macroscopic behavior of multicomponent rigid-plastic and elastoplastic composites was examined in [1, 2] within the framework of flow theory.

Here, we examine the use of the method of generalized singular approximation of the theory of random fields to describe small elastoplastic strains of composite materials with an arbitrary number of constituents. A similar problem was solved in a correlation approximation in [3, 4].

Let a micro-inhomogeneous medium occupying a volume V bounded by the surface S be composed of n different elastoplastic constituents connected to each other with ideal adhesion. The governing relations for the material of each constituent are given by the equations

$$s_{ij} = 2\mu_s(\varepsilon_{kl})e_{ij},\ \sigma_{pp} = 3K_s\varepsilon_{pp}\ (s = 1, 2, \ldots, n). \tag{1}$$

Here, $s_{ij} = \sigma_{ij} - (1/3)\delta_{ij}\sigma_{pp}$; $e_{ij} = \varepsilon_{ij} - (1/3)\delta_{ij}\varepsilon_{pp}$; σ_{ij}, ε_{ij} are components of the stress and strain tensors; $\mu_s(\varepsilon_{kl})$ is the shear modulus of plasticity; K_s is the bulk modulus of the s-th constituent (K_s = const).

The structure of such a composite can be described by a set of random indicator functions of the coordinates $\varkappa_1(\mathbf{r}), \varkappa_2(\mathbf{r}), \ldots, \varkappa_n(\mathbf{r})$. Meanwhile, each function $\varkappa_s(\mathbf{r})$ is equal to unity on the set of points of the s-th constituent and is equal to zero outside this set. Using these functions, we can write the local governing equations (1) in the form

$$s_{ij}(\mathbf{r}) = 2\sum_{s=1}^{n}\mu_s(\varepsilon_{kl}(\mathbf{r}))\varkappa_s(\mathbf{r})e_{ij}(\mathbf{r}),\ \sigma_{pp}(\mathbf{r}) = 3\sum_{s=1}^{n}K_s\varkappa_s(\mathbf{r})\varepsilon_{pp}(\mathbf{r}). \tag{2}$$

All of the functions $\varkappa_s(\mathbf{r})$ of stress and strain are presumed to be statistically uniform and ergodically random fields, and their mathematical expectations are replaced by the mean values over the volumes of the constituents V_s and over the total volume of the composite $V = \sum_{s=1}^{n} V_s$: $\langle f\rangle_s = \frac{1}{V_s}\int_{V_s} f(\mathbf{r})\,d\mathbf{r}$, $\langle f\rangle = \frac{1}{V}\int_V f(\mathbf{r})\,d\mathbf{r}$.

Establishing the macroscopic governing equations and effective constants of such a composite mean determining the relation between the macrostresses $\langle\sigma_{ij}\rangle$ and the macrostrains $\langle\varepsilon_{ij}\rangle$. The general form of this relation is expressed in the present case by the formula

$$\langle\sigma_{ij}\rangle = E^*_{ijkl}(\langle\varepsilon_{mn}\rangle)\langle\varepsilon_{kl}\rangle \tag{3}$$

($E^*_{ijkl}(\langle\varepsilon_{mn}\rangle)$ are components of the fourth-rank tensor of the plastic moduli). Here and below, an asterisk denotes an effective value of a quantity.

To derive Eqs. (3), it is necessary to statistically average the system of equations describing the deformation of an inhomogeneous medium. This system consists of (2), the equilibrium equations

$$\sigma_{ip,p}(\mathbf{r}) = 0 \tag{4}$$

and the Cauchy formulas

$$2\varepsilon_{ij}(\mathbf{r}) = u_{i,j}(\mathbf{r}) + u_{j,i}(\mathbf{r}), \tag{5}$$

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linking components of the tensor of small elastoplastic strains with components of the displacement vector $u_i(\mathbf{r})$. The boundary conditions for system (2), (4), (5) are the conditions of the absence of fluctuations of the quantities on the surface S of the volume V: $f(\mathbf{r}) = \langle f\rangle$, $\mathbf{r} \in S$. System (2), (4), (5) is stochastically nonlinear. Thus, in order to be able to use the methods of the theory of elasticity to establish macroscopic governing relations, the first equation of (2) must be linearized – after certain assumptions have been made. With this in mind, within each constituent, we will ignore fluctuations of the strains under the sign of the plastic modulus and we will adopt the approximate equality $\mu_s(\varepsilon_{kl}) = \mu_s(\langle\varepsilon_{kl}\rangle_s)$. With allowance for this equality, Eqs. (2) take the form

$$s_{ij} = 2\sum_{s=1}^{n} \mu_s(\langle\varepsilon_{kl}\rangle_s)\varkappa_s e_{ij}, \quad \sigma_{pp} = 3\sum_{s=1}^{n} K_s\varkappa_s\varepsilon_{pp}. \tag{6}$$

Following the method of generalized singular approximation of the theory of random field, we introduce the Green tensor $G_{ik}(\mathbf{r}) = \frac{1}{8\pi\mu}\left(\delta_{ik}r_{,pp} - \frac{3K+5\mu}{3K+8\mu}r_{,ik}\right)$, $r = |\mathbf{r}|$. This tensor contains undetermined quantities μ and K that satisfy the inequalities

$$\min_s\{\mu_s(\langle\varepsilon_{kl}\rangle_s)\} \leqslant \mu \leqslant \max_s\{\mu_s(\langle\varepsilon_{kl}\rangle_s)\},$$
$$\min_s\{K_s\} \leqslant K \leqslant \max_s\{K_s\}.$$

Here, in contrast to the constant K, the value of μ in the general case may depend on the strains $\langle\varepsilon_{k\ell}\rangle_s$. System (4)-(6) can be replaced by a system of integral equations of equilibrium whose kernels are second derivatives of the Green tensor

$$\varepsilon'_{ij}(\mathbf{r}) = \int_V G_{ik,lj}(\mathbf{r}-\mathbf{r}_1)\,\tau'_{kl}(\mathbf{r}_1)\,d\mathbf{r}_1; \tag{7}$$

$$\tau_{kl} = -\sum_{s=1}^{n}(2[\mu_s]e_{ij} + \delta_{ij}[K_s]\varepsilon_{pp})\varkappa_s, \quad [f_s] = f_s - f \tag{8}$$

(the primes denote fluctuations of the quantities in the volume V).

In order to obtain the macroscopic governing equations of the composite being examined, it is necessary to average Eqs. (6) over the total volume:

$$\langle s_{ij}\rangle = 2\sum_{s=1}^{n} c_s\mu_s(\langle\varepsilon_{kl}\rangle_s)\langle e_{ij}\rangle_s; \quad \langle\sigma_{pp}\rangle = 3\sum_{s=1}^{n} c_sK_s\langle\varepsilon_{pp}\rangle_s \tag{9}$$

($c_s = V_sV^{-1}$ are the volumetric contents of the constituents). It is evident from (9) that establishing the effective governing relations requires expression of the mean-volume strain components $\langle\varepsilon_{ij}\rangle_s$ through the macrostrains $\langle\varepsilon_{ij}\rangle$. These quantities are connected by the relation [1, 2]

$$\langle\varepsilon_{ij}\rangle_s = \langle\varepsilon_{ij}\rangle + c_s^{-1}\langle\varkappa'_s\varepsilon'_{ij}\rangle. \tag{10}$$

Replacement of the second derivatives in Eqs. (7) and (8) by their singular parts in accordance with the hypothesis of singular approximation and substitution of the result into Eq. (10) leads to equations for the components of the tensor $\langle\varepsilon_{ij}\rangle_s$

$$\begin{gathered}\langle e_{ij}\rangle_s = \frac{2\mu(1-\alpha)\langle e_{ij}\rangle + \alpha\langle s_{ij}\rangle}{2\mu + 2[\mu_s]\alpha},\\ \langle\varepsilon_{pp}\rangle_s = \frac{3K(1-\gamma)\langle\varepsilon_{pp}\rangle + \gamma\langle\sigma_{pp}\rangle}{3K + 3[K_s]\gamma},\\ \alpha = \frac{2}{15}\frac{4-5\nu}{1-\nu}, \quad \gamma = \frac{1}{3}\frac{1+\nu}{1-\nu}, \quad \nu = \frac{3K-2\mu}{6K+2\mu}.\end{gathered} \tag{11}$$

Transformation of Eqs. (9) by means of Eqs. (11) makes it possible to describe the macroscopic equations of elastoplastic deformation (3) for the composite with an isotropic tensor of the effective plastic moduli $E^*_{ijkl} = \mu^*I_{ijkl} + \left(K^* - \frac{2}{3}\mu^*\right)\delta_{ij}\delta_{kl}$:

$$\langle s_{ij}\rangle = 2\mu^*(\langle\varepsilon_{kl}\rangle_s)\langle e_{ij}\rangle, \quad \langle\sigma_{pp}\rangle = 3K^*(\langle\varepsilon_{kl}\rangle_s)\langle\varepsilon_{pp}\rangle; \tag{12}$$
$$\mu^* = \mu\frac{(1-\alpha)\xi}{1-\alpha\xi}, \quad \xi = \sum_{s=1}^{n}\frac{c_s\mu_s(\langle\varepsilon_{kl}\rangle_s)}{\mu(1-\alpha) + \alpha\mu_s(\langle\varepsilon_{kl}\rangle_s)},$$

$$K^* = K\frac{(1-\gamma)\eta}{1-\gamma\eta}, \quad \eta = \sum_{s=1}^{n}\frac{c_sK_s}{K(1-\gamma)+\gamma K_s}, \tag{13}$$

$$\langle e_{ij}\rangle_s = \frac{(1-\alpha)\mu+\alpha\mu^*}{\mu+\alpha[\mu_s]}\langle e_{ij}\rangle, \quad \langle\varepsilon_{pp}\rangle_s = \frac{(1-\gamma)K+\gamma K^*}{K+\gamma[K_s]}\langle\varepsilon_{pp}\rangle.$$

Along with the macrostresses $\langle\sigma_{ij}\rangle$ and macrostrains $\langle\varepsilon_{ij}\rangle$, the closed system of equations of elastoplastic deformation of the composite (12)-(13) includes the components of the tensor $\langle\varepsilon_{ij}\rangle_s$. To eliminate them from system (12)-(13), it is necessary to specify the form of the plastic moduli functions of each component $\mu_s(\varepsilon_{kl})$ and to appropriately select μ and K. The form of the functions $\mu_s(\varepsilon_{kl})$ is assigned in accordance with the strain properties of the materials of the composite's constituents on the basis of experimental data. In the special case when all $\mu_1, \mu_2, \ldots, \mu_n$ are constants, Eqs. (12) and (13) coincide with the familiar results obtained from the generalized singular approximation in the theory of linear elasticity of micro-inhomogeneous media [5].

The method of participation of the constituents in the deformation of the composite depends on the choice of the undetermined quantities μ and K. By assigning suitable values to μ and K, we can obtain different models of multicomponent composites with any degree of connectedness of the constituents. For example, if we seek $\mu = \mu_1(\varepsilon_{kl})$, $K = K_1$ in general formulas (13), we obtain a model of a composite in which the first component plays the role of the binding matrix and the other components function as individual inclusions. The expressions for these effective quantities take the form

$$\mu^* = \mu_1\frac{(1-\alpha_1)\xi_1}{1-\alpha_1\xi_1}, \quad \xi_1 = \sum_{s=1}^{n}\frac{c_s\mu_s}{\mu_1(1-\alpha_1)+\alpha_1\mu_s},$$

$$K^* = K_1\frac{(1-\gamma_1)\eta_1}{1-\gamma_1\eta_1}, \quad \eta_1 = \sum_{s=1}^{n}\frac{c_sK_s}{K_1(1-\gamma_1)+\gamma_1K_s}, \tag{14}$$

$$\langle e_{ij}\rangle_s = \frac{(1-\alpha_1)\mu_1+\alpha_1\mu^*}{(1-\alpha_1)\mu_1+\alpha_1\mu_s}\langle e_{ij}\rangle, \quad \langle\varepsilon_{pp}\rangle_s = \frac{(1-\gamma_1)K_1+\gamma_1K^*}{(1-\gamma_1)K_1+\gamma_1K_s}\langle\varepsilon_{pp}\rangle.$$

In the theory of elasticity, similar formulas for the effective moduli of isotropic composites of the matrix-inclusion type show good agreement with experimental data both for elastic and rigid inclusions and for pores [6, 7].

Another type of connection between phases occurs in an inhomogeneous medium in which the matrix is composed of several interpenetrating components. The governing relations for such a composite are obtained from general formulas (12), (13) if we put the following in these equations

$$\mu = \{\mu\} = \sum_{s=1}^{m} c_s\mu_s, \quad K = \{K\} = \sum_{s=1}^{m} c_sK_s, \quad m \leqslant n.$$

In this case, the expressions for the effective quantities (13) take the form

$$\mu^* = \{\mu\}\frac{(1-A)X}{1-AX}, \quad X = \sum_{s=1}^{n}\frac{c_s\mu_s}{\{\mu\}(1-A)+A\mu_s},$$

$$K^* = \{K\}\frac{(1-\Gamma)H}{1-\Gamma H}, \quad H = \sum_{s=1}^{n}\frac{csK_s}{\{K\}(1-\Gamma)+\Gamma K_s}, \tag{15}$$

$$\langle e_{ij}\rangle_s = \frac{(1-A)\{\mu\}+A\mu^*}{(1-A)\{\mu\}+A\mu_s}\langle e_{ij}\rangle, \quad \langle\varepsilon_{pp}\rangle_s = \frac{(1-\Gamma)\{K\}+\Gamma K^*}{(1-\Gamma)\{K\}+\Gamma K_s}\langle\varepsilon_{pp}\rangle,$$

$$A = \frac{2}{15}\frac{4-5N}{1-N}, \quad \Gamma = \frac{1}{3}\frac{1+N}{1-N}, \quad N = \frac{3\{K\}-2\{\mu\}}{6\{K\}+2\{\mu\}}.$$

The matrix of the composite whose effective characteristics are found from Eqs. (15) is composed of the first m interpenetrating components of the composite. The remaining n − m components are individual inclusions. In the theory of elasticity, formulas similar to (15) accurately describe the agreement between the elastic moduli of composites having interpenetrating constituents and experimental data [5, 8].

We will use Eqs. (14) and (15) to calculate the elastoplastic properties of certain micro-inhomogeneous materials. Here, sections of the tension (compression) curves of the constituents will be approximated by the exponential relation

$$\sigma = \tau(1 - \exp(-E\varepsilon/\tau)), \tag{16}$$

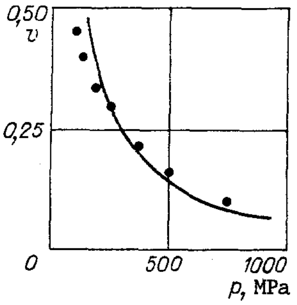

Fig. 1

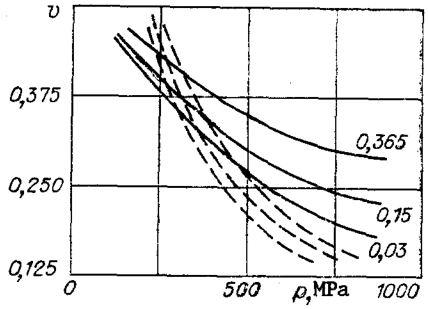

Fig. 2

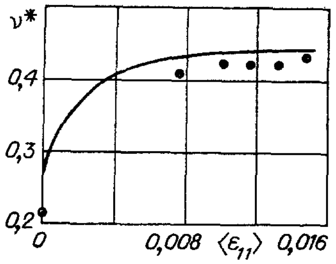

Fig. 3

where E is the Young's modulus; τ is the limiting value of stress on the given section of the curve (yield point); σ and ε are the tensile (compressive) stress and strain.

We will use (14) to calculate the elastoplastic characteristics of porous media in which the matrix is composed of one or two constituents. Results will be obtained for different methods of loading. For a one-component porous medium ($n = 2$, $\mu_2 = K_2 = 0$, $c_2 = v$), it follows from (14) that $\xi_1 = \eta_1 = 1 - v$. For a two-component porous medium ($n = 3$, $\mu_3 = K_3 = 0$, $c_3 = v$), Eqs. (14) yield $\xi_1 = c_1 + \frac{c_2\mu_2}{(1-\alpha_1)\mu_1 + \alpha_1\mu_2}$, $\eta_1 = c_1 + \frac{c_2K_2}{(1-\gamma_1)K_1 + \gamma_1K_2}$, $c_1 + c_2 + 1 - v$ (v is the volumetric content of pores).

Let us compare the results obtained here with experimental data from the pressing of porous materials in an axisymmetric mold. The connection between axial pressure $p = \langle\sigma_{11}\rangle$ and porosity v follows from Eqs. (12), in which it is necessary to set $i = j = 1$. Considering that the macroscopic strains of the medium in the compression mold are connected with the volumetric content of pores by the relations $\langle\varepsilon_{11}\rangle = \ln\,[(1 - v_0)/(1 - v)]$, $\langle\varepsilon_{22}\rangle = \langle\varepsilon_{33}\rangle = 0$, we obtain the following equation for the pressing operation

$$p = \left(K^* + \frac{4}{3}\mu^*\right)\ln\frac{1 - v_0}{1 - v} \tag{17}$$

(v_0 is the initial porosity of the material). In calculating curves describing the consolidation of porous media, we solved Eq. (17) numerically together with Eqs. (14) by the method of successive approximation.

Figure 1 shows a theoretical curve describing the consolidation of powdered electrolytic nickel in a symmetrical mold. The curve was constructed from Eqs. (14) and (17) for a one-component porous material. The points denote experimental values obtained without removal of the work-hardening which takes place. These values were obtained in [9]. Here $v_0 = 0.53$.

Figure 2 compares theoretical curves of the consolidation of two-component porous media calculated from Eqs. (14) and (17) (dashed lines) with experimental curves of the pressing of a mixture of powders of iron and glass (solid lines). The latter curves were obtained in [10]. The numbers next to the curves denote the volumetric contents of glass, $v_0 = 0.55$.

Let us examine the elastoplastic behavior of a one-component porous medium under conditions of uniaxial tension. In this case, Eq. (12) takes the form

$$\langle\sigma_{11}\rangle = 9\frac{K^*\mu^*}{3K^* + \mu^*}\langle\varepsilon_{11}\rangle, \quad \langle\varepsilon_{22}\rangle = \langle\varepsilon_{33}\rangle, \quad \langle\varepsilon_{22}\rangle = -\nu^*\langle\varepsilon_{11}\rangle_s \tag{18}$$

where $\nu^* = \nu^*(\langle\varepsilon_{kl}\rangle_s)$ is the elastoplastic Poisson's ratio of the porous material. Numerical estimates obtained with Eqs. (14), (16), and (18) were used to obtain the theoretical dependence of the Poisson's ratio on the axial strain.

Figure 3 compares this dependence (solid line) with experimental data from [11] (points) obtained by measurement of the Poisson's ratio of porous reduced iron that was sintered for 2 h in hydrogen at 1200°C.

We will use Eqs. (15) to calculate the elastoplastic behavior of a composite formed by two interpenetrating constituents. The effective characteristics of this medium are obtained from the constituents with $m = n = 2$:

$$\{\mu\} = \langle\mu\rangle = c_1\mu_1 + c_2\mu_2, \ \{K\} = \langle K\rangle = c_1K_1 + c_2K_2, \\ N = \langle\nu\rangle = c_1\nu_1 + c_2\nu_2. \tag{19}$$

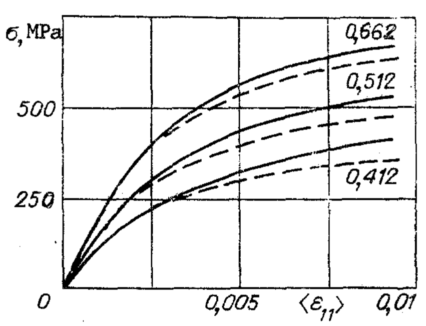

Fig. 4

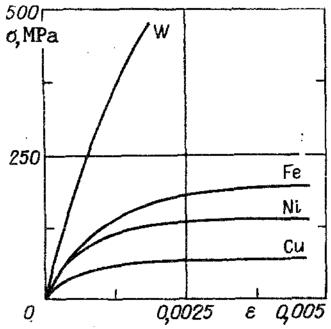

Fig. 5

TABLE 1

Materials of the components	E, MPa	ν	τ, MPa
Nickel	204 000	0,28	140
Copper	123 480	0,33	69
Iron	205 926	0,28	200
Tungsten	404 740	0,28	750
Glass	78 000	0,25	—

To construct the theoretical curve of uniaxial tension of the composite, we solved Eqs. (15), (16), (18), and (19) numerically by the method of successive approximations.

Figure 4 compares theoretical (dashed lines) and experimental (solid lines) tension curves of specimens obtained by impregnation of a sintered framework of powdered tungsten with a copper melt. The numbers next to the curves denote the volumetric content of tungsten [8].

Table 1 shows values of the mechanical constants of the metals used in the calculations. The values of the constants were taken from [8-12].

Figure 5 shows approximations of sections of the stress–strain curves of the metals used in the numerical calculations.

If we put $\mu = \mu^*$ and $K = K^*$ in Eqs. (13), we obtain the following equations for the effective quantities

$$\sum_{s=1}^{n} \frac{c_s\mu_s}{\mu^* + \alpha^*(\mu_s - \mu^*)} = 1, \quad \sum_{s=1}^{n} \frac{c_sK_s}{K^* + \gamma^*(K_s - K^*)} = 1,$$

$$\langle e_{ij}\rangle_s = \frac{\mu^*}{\mu^* + \alpha^*(\mu_s - \mu^*)}\langle e_{ij}\rangle, \quad \langle \varepsilon_{pp}\rangle_s = \frac{K^*\langle \varepsilon_{pp}\rangle}{K^* + \gamma^*(K_s - K^*)},$$

which in the theory of micro-inhomogeneous media correspond to the self-consistent field method [5].

It is interesting to note that although K_s are constants, the effective values K^* in all of the models exhibit some dependence on the strain state of the composite.

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MECHANICS OF FRACTURE OF COATINGS AND FILMS

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Introduction. The thin surface layer of any material has specific properties which can be attributed to interaction of the material with its environment. The nature of this interaction may be chemical, thermal, or physicomechanical in nature. As a rule, an initial fatigue crack is initiated in the surface layer of materials and structures, and the growth of this crack ultimately leads to exhaustion of the safe life of the structure or structural element. It is therefore natural that the condition of the surface layer (and the control of its properties) is one of the foremost problems currently occupying technologists and engineers [1, 2]. The efficient utilization of materials in industry depends in large part on the solution of this problem.

The surface layer and the body of a material can be regarded together as a composite, one of the components of which is the surface layer [3]. The most important characteristics of this layer are its special protective properties, which depend on its chemical composition and microstructure, the adhesive strength and crack resistance of the layer proper, and the contact of the layer with the substrate. The properties of the surface layer are affected by hydrogen and corrosion in gaseous media and aqueous solutions, wear, catalysis, welding and soldering, erosion, passivation, adhesion, sintering and ablation, and the presence of inhibitors.

Various methods are used to control the mechanical, chemical, magnetic, electrical and other properties of the surface layer. These methods can be classified as follows.

Mechanical Methods. This class of methods includes shot-blasting (to work-harden the surface), hammering, and impact strain-hardening. These methods produce high compressive residual stresses in the surface layer and retard crack nuclei in the layer.

Lacquer Coating and Oxide Films. Lacquer coatings and oxide films serve as chemical protection for the material from the effects of the environment.

Deposition Methods. Deposition methods make it possible to obtain new surface layers with a composition and microstructure different from the composition and microstructure of the substrate material. This class of methods includes plasma deposition, ion deposition, chemical and physical deposition from vapors, and electrolytic deposition.

Methods of Chemico-Physical Modification. Methods of chemico-physical modification of a material make it possible to change the mechanical and physicochemical properties of the surface layer. This class of methods includes special heat treatments, ion nitriding and cementation, ion implantation, and treatment with laser and electron beams. Under natural conditions, metal is usually protected by an oxide film.

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