THEORY OF IRRADIATION HARDENING OF METALS AND ALLOYS BASED ON THE ENERGY CONDITION OF PLASTICITY

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A conventional approach for estimating the yield strength consists in calculation of a critical shear stress for bowing out of gliding dislocation segments between barriers. According to Orovan theory, the critical shear stress τ_k is determined by the average distance l between obstacles: $\tau_k = \alpha Gb / l$, where α is the constant; G is the shear module; b is the Burgers vector.The superposition of various barriers is taken into account as additive of different contributions $\tau_k = \tau_1 + \tau_2 + \tau_3 + ...$, or as $\tau_k^2 = \tau_1^2 + \tau_2^2 + \tau_3^2 + ...$. Both procedures have yet no theoretical ground. On the basis of the maximum shear stress concept, the critical shear stress τ_k in polycrystals is related to the tensile yield strength σ_y as follows: $\sigma_y = 2\tau_k$ (Tresca criterion). On the basis of the effective stress concept this relationship has well known form: $\sigma_y = (\sqrt{3})\tau_k$ (Mises criterion). Sometimes the Taylor criterion is used, according to which $\sigma_y = 3.06\tau_k$.

In the present paper an another method of calculating the yield strength of metals and alloys is proposed. The energy condition of plasticity (Mises criterion) is used. According to this condition the plastic flow of a material occurs when the deformation potential energy which is proportional to the square of the effective stress σ_{eff}, reaches a certain limiting value proportional to the square of the yield stress σ_y under uniaxial tension.

In this paper, it is assumed that for the onset of plastic flow the specific potential energy of deformation caused by external forces should exceed the limiting value equal to the potential energy of deformation created by all microstructure defects (dislocations, dislocation loops, voids, precipitates, etc.). Such an approach allows to calculate barrier strengthening coefficients α. Also, according to this approach the total yield stress is equal to the square root of the sum of yield stress squares for different types of crystal defects («geometric superposition of strengthening barriers contributions»).

Key words: irradiation hardening, yield strength, metals, alloys, dislocations, voids, precipitates.

INTRODUCTION

A common approach for the explanation of the yield strength change in irradiated materials (irradiation hardening) is based on the model of hardening by barriers for gliding

dislocations. According to such an approach the motion of dislocations under an applied shear stress τ_k is impeded by localized obstacles randomly distributed in the glide plane. To initiate a macroscopic plastic strain, dislocations should overcome these obstacles. This overcoming can be realized by bowing out of dislocations between the barriers (Orowan mechanism) or by cutting them. The stress τ_k is determined by the mean distance l_k between two neighbor obstacles of the same type: $\tau_k = A_k/l_k$, where $A_k = \alpha_k Gb$ for the Orowan mechanism (α_k is the constant, G is the shear modulus, and b is the Burgers vector) and $A_k = F_k(T)/bl_k$ for the cutting mechanism [1 – 4]. The constants α_k are usually determined by fitting experimental data on the yield strength. The superposition of various barriers is taken into account as additive of different contributions $\tau_k = \tau_1 + \tau_2 + \tau_3 + \ldots$, or as $\tau_k^2 = \tau_1^2 + \tau_2^2 + \tau_3^2 + \ldots$ [4 – 6]. Both procedures have yet no theoretical ground. On the basis of the maximum shear stress concept, the critical shear stress τ_k in polycrystals is related to the tensile yield strength σ_y as follows: $\sigma_y = 2\tau_k$ (Tresca criterion). On the basis of the effective stress concept this relationship has well known form: $\sigma_y = 3^{1/2} \cdot \tau_k$ (Mises criterion). Sometimes the Taylor criterion is used, according to which $\sigma_y = 3.06 \cdot \tau_k$.

In the present work a new approach for calculating the yield strength is developed. The yield strength of a material is considered to be the square root of the squared effective stress σ_{eff}, created by all barriers in an arbitrary point of a material. As is known, the tensile yield strength equals the effective stress. Such an approach allows to obtain explicit expressions for hardening constants. Besides, in this approach $\sigma_y^2 = \sigma_{y1}^2 + \sigma_{y2}^2 + \sigma_{y3}^2 + \ldots$, if lattice defects of different type i ($i = 1, 2, 3, \ldots$) are present in the microstructure.

ENERGY CONDITION OF PLASTICITY

According to the energy condition (criterion) of plasticity proposed by Mises (see, for example, [7]), the plastic deformation occurs when the effective stress ("stress intensity") reaches some value σ_y, which depends only on the material properties. For isotropic materials, this energy condition consists in the requirement that the square of the effective stress is to be invariant (Mises law): $\sigma^2_{eff} = 3I_2$, where $I_2 = s_{ij}s_{ji} / 2$ is the second invariant of the deviatoric part of the stress tensor $s_{ik} = \sigma_{ik} - \delta_{ik} (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$ (δ_{ik} is the unit tensor). The effective stress square can be expressed as follows:

$$\sigma^2_{eff} = [(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)] / 2. \quad (1)$$

As is known, the energy condition of plasticity is derived from the following requirement: the plastic deformation occurs when the potential energy of deformation which is proportional to σ^2_{eff} reaches some limiting value, so that $\sigma^2_{eff} = \sigma^2_y$.

From the existing theoretical models and experiments it follows that σ_y is determined by the microstructure of a material. It is natural to assume that the square of the yield stress $\sigma_y^2 = \sigma^2_{eff}$ is determined by elastic stress fields created at an arbitrary point of the crystal by all lattice defects. As a first approximation, it will be assumed that each crystal defect creates a potential energy of deformation independently of other defects, that is, the square of the effective stress is equal to the sum of the squares of the effective stresses created by lattice defects. As shown below, such an approach allows to derive contributions of various types of crystal defects (dislocations, voids and gas bubbles, precipitate particles, etc.) to the yield strength and substantiate the method of their superposition.

As it will be shown below, well known contributions to hardening of crystal defects such as dislocations, voids, gas bubbles, dislocation loops, precipitates, etc. can be derived if to suppose that at each point of a material the square of the yield strength is determined by the expression (1) averaged over the spatial distribution of these defects, the stress tensor is determined by elastic strain fields caused by the defects. The approach consists in calculation of σ^2_{eff} at an arbitrary point of the matrix taking into account elastic stresses produced by all components of microstructure.

HARDENING BY DISLOCATIONS

Screw dislocations. Let's consider a straight screw dislocation, which line coincides with the coordinate axis z. According to Ref. [8], in cylindrical coordinate system all components of the stress tensor at an arbitrary point around of the screw dislocation are equal to zero, excluding the component $\sigma_{z\varphi}$, which is equal to

$$\sigma_{z\varphi} = Gb/(2\pi r), \tag{2}$$

where G is the shear modulus of the matrix, b is the Burgers vector. By writing eq. (1) in the cylindrical coordinates (by replacing 1, 2, 3 $\rightarrow$ z, r, φ) and substituting eq. (2) in eg. (1), one obtains the following expression for σ^2_{eff} :

$$\sigma^2_{eff} = 3\sigma^2_{z\varphi} = 3(Gb)^2/(2\pi r)^2. \tag{3}$$

In order to take into account the contribution of all screw dislocations, the right part of eq. (3) should be multiplied by $\rho'_s 2\pi r\, dr$, where ρ'_s is the dislocation density measured by the etching method. The value of ρ'_s is linearly related to total density of screw dislocations ρ_s, measured using an electronic microscope: $\rho'_s = \rho_s / a$, where $a \approx 2$. Integrating over r from r_0 (r_0 is the radius of the dislocation core) to maximum distance R_s, which can be taken mean grain or crystal size, one obtains:

$$\sigma_s = \alpha_{ds} Gb_s \sqrt{\rho_s}, \tag{4}$$

where

$$\alpha_{ds} = [(3/2\pi a)\ln(R_s/r_0)]^{1/2}. \tag{5}$$

Edge dislocations. Let's take into account the contribution of straight edge dislocations to the square of effective stress using well known result of the theory of elasticity, according to which for an edge dislocation only the following stress tensor components are non-zero [3]:

$$\sigma_{rr} = \sigma_{\varphi\varphi} = -D \sin \varphi / r, \qquad \sigma_{r\varphi} = D \cos \varphi \nu / r, \tag{6}$$

where $D = Gb_e/2\pi(1-\nu)$, ν is the Poisson ratio, b_e is the Burgers vector of the edge dislocation.

By averaging σ^2_{eff} over angle φ and over distance r of edge dislocations from a given point, one obtains:

$$\sigma_e = \alpha_{de} Gb_e \sqrt{\rho_e}, \tag{7}$$

where $\alpha_{de} = [(4\pi/a)\ln(R_e/r_0)]^{1/2}/[2\pi(1-\nu)]$.

The coefficients α_{ds} and α_{de} depend slightly on material parameters and dislocation densities.

It is easy to calculate the contribution of both screw and edge dislocations to σ^2_{eff} , if spatial distributions of these dislocations are random. Apparently, in this case the value of σ^2_{eff} is equal to

$$\sigma_d = G\sqrt{\alpha^2_{ds}\, b^2_s\, \rho_s + \alpha^2_{de}\, b^2_e\, \rho_e}. \tag{8}$$

In the case, when $\alpha^2_{ds} b^2_s \approx \alpha^2_{de} b^2_e$, the yield strength is determined in fact, by the square root of the total dislocation density $\rho_d = \rho_s + \rho_e$.

STRENGTHENING BY VOIDS

According to the theory of elasticity (see, for example, [9]) stresses around of a spherical cavity of radius R with the internal pressure p, in spherical coordinates have the following form:

$$\sigma_{yy} = -p(R/r)^3, \qquad \sigma_{\theta\theta} = \sigma_{\varphi\varphi} = (p/2)(R/r)^3, \tag{9}$$

where r is the distance from the void center up to a given point. Non-diagonal components

of the stress tensor are equal to zero. In the case of a gas-filled cavity, the pressure p is equal to

$$p = p_g - (2\gamma/R), \tag{10}$$

where p_g is the gas pressure in the cavity, γ is the surface energy.

Writing eq. (1) in spherical coordinates ($1, 2, 3 \rightarrow r, \theta, \varphi$), one can be easily convinced that at the distance r from the cavity center the square of effective stress is given by

$$\sigma^2_{eff} = (9/4)\, p^2\, (R/r)^6. \tag{11}$$

In order to take into account the contribution of all gas-filled cavities, is necessary multiply eq. (11) by $f_v(R)\, dR\, 4\pi r^2 dr$, where $f_v(R)$ is the cavity size distribution function and to integrate over r from R to ∞, and then over R from 0 to ∞. As a result one obtains that

$$\sigma^2_{void} = 3\pi \int_0^\infty R^3 (p_g - 2\gamma/R)^2 f_v(R) dR. \tag{12}$$

It is seen from the expression (12), that in the case when the gas pressure in the cavities is counterbalanced by surface tension (cavities are equilibrium gas bubbles), such cavities do not contribute to the effective stress.

For voids ($p_g = 0$) from eq. (12) it follows that

$$\sigma_{void} = \alpha_v Gb \sqrt{N_v < d_v >}. \tag{13}$$

where N_v and $<d_v>$ are the void number density and the mean void diameter, respectively, and

$$\alpha_v = (6\pi)^{1/2}(\gamma/Gb) = 4.34(\gamma/Gb). \tag{14}$$

Apparently, the surface energy γ is the most uncertain value because even in pure metals it can strongly vary due to radiation-induced segregation of impurity atoms on the void surface, especially of interstitial impurities, such as carbon. For γ magnitudes in the range of $1 - 2$ J/m^2 and Gb magnitudes ranging from 20 J/m^2 (Ni, α-Fe) to 40 J/m^2 (W) one finds, that magnitudes of barrier constant for voids fall in the interval from 0.11 to 0.43. It should be pointed out that in the framework of the traditional approach, strengthening by voids is determined by the energy per unit length of dislocation and by the mean distance of $(N_v <d_v>)^{-1/2}$ between two neighbor voids on the dislocation line. In such an approach, eq. (14) can be derived, if to consider that the dislocation segment does not bow between two neighbor voids and that the elastic force with which these voids act on the segment, arises due to increase of the void surface after a shift of upper part of the voids (above a slip plane) with respect to their bottom part, i.e. due to origin of ledges on void surface.

HARDENING BY PRECIPITATES

According to Ref. [10] in an infinite isotropic matrix containing an isotropic misfitting spherical sphere (the elastic model of a precipitate) the displacements are radial, i.e. the displacement vector $\mathbf{u}$ has the form $\mathbf{u} = u_r \mathbf{r}/r$, where r is the distance from precipitate center and

$$\begin{aligned} u_r &= \varepsilon r_p^3 / r^2, \quad r \geq r_p, \\ u_r &= \varepsilon r, \qquad\quad r \leq r_p, \end{aligned} \tag{15}$$

where r_p is the radius of the precipitate, ε is a parameter describing the strength of the elastic strain field. For a coherent precipitate ε is related to $\delta = \Delta V/(3V)$, the misfit between the unstrained lattices of precipitate and matrix ($\Delta V/V$ is the fractional difference in atomic volume between precipitate and matrix material) [5] by

$$\varepsilon = G_p(1 + v_p)\delta / [G_p(1 + v_p) + 2G(1 - 2v_p)], \tag{16}$$

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where G_p, n$_p$ are the shear modulus and Poisson ratio of precipitate material, G is the shear modulus of the matrix. If $G_p = G$ and $v_p = 1/3$, $\varepsilon = (2/3)\delta$. For elastic moduli usually found $0.5\delta \leq \varepsilon \leq \delta$ [5].

From eq. (15) it follows, that the strain tensor components are equal to

$$\varepsilon_{rr} = \begin{cases} -2\varepsilon r_p^3 / r^3, & r \geq r_p; \\ \varepsilon, & r \leq r_{p;} \end{cases}$$

$$\varepsilon_{\theta\theta} = \varepsilon_{\varphi\varphi} = \frac{u_r}{r} = \begin{cases} \varepsilon r_p^3 / r^3, & r \geq r_p; \\ \varepsilon, & r \leq r_p; \end{cases} \tag{17}$$

$$\varepsilon_{r\theta} = \varepsilon_{r\varphi} = \varepsilon_{\theta\varphi} = 0.$$

The components of the stress tensor are linearly related to the strain tensor components. Using the well known relations, one obtains that $\sigma_{r\theta} = \sigma_{r\varphi} = \sigma_{\theta\varphi} = 0$ and

$$\sigma_{rr} = 2G[(1 - \nu) \varepsilon_{rr} + 2\nu \varepsilon_{\theta\theta}]/(1 - 2\nu), \tag{18a}$$

$$\sigma_{\theta\theta} = \sigma_{\varphi\varphi} = 2G[(1 - \nu) \varepsilon_{\theta\theta} + \nu (\varepsilon_{rr} + \varepsilon_{\theta\theta})]/(1 - 2\nu), \tag{18b}$$

where ν is the Poisson ratio of matrix.

The substitution of eq. (17) into (18a) and (18b) results in

$$\sigma_{rr} = \begin{cases} -4G\varepsilon r_p^3 / r^3, & r \geq r_p; \\ 2G\varepsilon(1+\nu)/(1-2\nu), & r \leq r_p; \end{cases}$$

$$\sigma_{\theta\theta} = \sigma_{\varphi\varphi} = \begin{cases} 2G\varepsilon r_p^3 / r^3, & r \geq r_p; \\ 2G\varepsilon(1+\nu)/(1-2\nu), & r \leq r_p. \end{cases} \tag{19}$$

Within coherent precipitate the effective stress is equal to zero. In matrix around the precipitate the square of effective stress is given by

$$\sigma^2_{eff} = (\sigma_{rr} - \sigma_{\theta\theta})^2 = 36G^2\varepsilon^2 r_p^6/r^6. \tag{20}$$

To obtain the square of effective stress produced in an arbitrary point of a material by all precipitates having the radius r_p, let us assume that the spatial distribution of the precipitates is uniform. Multiplying the right-hand side of eq. (20) by $f_p(r_p)dr_p{\times}4\pi N_p r^2 dr$, ($f_p(r_p)$ is the distribution of precipitates on radii) and integrating over r from r_p to infinity, one obtains

$$\sigma_p^2 = 36G^2\varepsilon^2(\frac{4\pi}{3}r_p^3 f(r_p)dr_p). \tag{21}$$

Further, integrating the right hand side of eq. (21) over r_p from zero to infinity and taking square root of the result, one finally obtains

$$\sigma_p = 6|\varepsilon|G\sqrt{V_p}, \tag{22}$$

where

$$V_p = \frac{4\pi}{3}N_p\left\langle r_p^3 \right\rangle, \tag{23}$$

is the volume fraction of coherent precipitates, N_p is the precipitate concentration, brackets denote the mean value.

In Ref. [11] it was found, that precipitate-induced strengthening and hardening of a series of model steels and commercial reactor pressure vessel steels vary according to the square root of the volume fraction of precipitate. As it was pointed out in Ref. [11] current models [12 – 14] of the hardening produced by irradiation-induced copper-rich precipitates include such a dependence.

By assumption, stresses around of a spherical incoherent precipitate are determined by the interfacial surface energy γ_{mp}. In this case inside and outside of the precipitate only

diagonal components of stress tensor are non-zero. Moreover, inside of the particle the diagonal components equal each to other and,. consequently, the effective stress vanishes. Outside of the particle the stress field is similar to the field around of a void. Thus, the mean effective stress in an arbitrary point can be described with expressions similar to eqs. (13), (14) (Orowan formula), if to replace $N_v \rightarrow N_p$, $<d_v> \rightarrow <d_p>$ ($d_p = 2r_p$) and $\gamma \rightarrow \gamma_{mp}$:

$$\sigma_p = (32\pi / 3)^{1/2}(\gamma_{mp} / Gb) \cdot Gb\sqrt{N_p < d_p >}. \tag{24}$$

STRENGTHENING BY DISLOCATION LOOPS

According to Refs. [15,16] in a cylindrical coordinate system r, z, φ the displacements around of a circular interstitial loop of radius R and with the Burgers vector **b**, directed along z-axis, in an infinite and elasticity isotropic medium are:

$$u_r = -[b/4(1 - \nu)][(1 - 2\nu)I_1^{(0)}(\rho\zeta) - \zeta I_1^{(1)}(\rho\zeta)], \tag{25a}$$

$$u_z = -[b/4(1 - \nu)][2(1 - \nu)I_0^{(0)}(\rho\zeta) + \zeta I_0^{(1)}(\rho\zeta)], \tag{25b}$$

$$u_\varphi = 0, \tag{25c}$$

where $\rho = r/R$, $\zeta = z/R$ ($z > 0$).

$$I_n^{(m)}(\rho\zeta) = \int_0^\infty t^m J_n(t\rho)J_1(t)\exp(-t\zeta)dt, \tag{26}$$

J_n is the nth-order Bessel function of the first kind.

Determining with the help of eqs.(25a) – (25c) the components of strain tensor and using the well known relationship between components of stress and strain tensors, one obtains, that

$$\sigma_{rr} = A[-I_0^{(1)} + (1 - 2\nu)I_1^{(0)}/\rho + \zeta I_0^{(2)} - \zeta I_1^{(1)}/\rho], \tag{27a}$$

$$\sigma_{zz} = A[-I_0^{(1)} - \zeta I_0^{(2)}], \tag{27b}$$

$$\sigma_{\varphi\varphi} = A[-(1 - 2\nu)I_1^{(0)}/\rho + \zeta I_1^{(1)}/\rho - 2\nu I_0^{(1)}], \tag{27c}$$

$$\sigma_{rz} = - A\zeta I_1^{(2)}, \qquad \sigma_{r\varphi} = \sigma_{z\varphi} = 0, \tag{27d}$$

where

$$A = Gb/[2R(1 - \nu)]. \tag{28}$$

The expressions (27a) – (27d) allow to calculate the square of effective stress σ_{eff}, caused by the loop of radius R at an arbitrary point of matrix. Introducing the loop size distribution $f_l(R)$, so, that $f_l(R) dR$ is the concentration of loops having radius R, one obtains the square of the effective stress produced by all loops:

$$\sigma^2_{loop} = 4\pi\int_0^\infty R^3 A^2 f(R)dR\int_0^\infty \rho d\rho\int_0^\infty d\zeta(\sigma_{eff} / A)^2 =$$
$$= \frac{\pi G^2 b^2}{2(1-\nu)^2}\int_0^\infty 2Rf(R)dR\int_0^\infty \rho d\rho\int_{-\infty}^\infty d\zeta(\sigma_{eff} / A)^2. \tag{29}$$

Due to a complexity of the function $(\sigma_{eff}/A)^2$, no attempts were undertaken to calculate integrals on ρ and ζ in eq. (29). However it is clear, that the main contribution to these integrals will origin from zones adjacent to the dislocation loop core, because at large distances $r = R(\rho^2 + \zeta^2)^{1/2}$ from the loop the function σ_{eff}/A behaves as $1/r^3$ [10], and, hence, large distances bring a small contribution. In immediate loop proximity the effective stress differs only slightly from the effective stress of a straight edge dislocation, and the integrals on ρ and ζ diverge logarithmically. Taking the minimum distance from loop edge

equal to the dislocation core radius r_0, and the maximum distance equal to the loop radius, one finds that the integral on ρ and ζ will be proportional to $\ln(R/r_0)$. Since the logarithm is the slight function of argument, when integrating on R it can be taken approximately as $\ln(<R_{loop}>/r_0)$, where $<R_{loop}>$ is the mean loop radius, and without a large error can be taken out of the integral. Seemingly, the final result of calculations will be similar to eq. (6), where the following replacements is made $(\rho_e/a) \to 2\pi<R_{loop}>N_{loop}$ and $\ln(R_e/r_0) \to \ln(<R_{loop}>/r_0)$. In these approximations from eq. (29) it follows that

$$\sigma_{loop} = \alpha_{loop} Gb \sqrt{\langle d_{loop} \rangle N_{loop}}, \tag{30}$$

where N_{loop} is the loop concentration, the constant α_{loop} is close to α_{disl} in magnitude.

SUPERPOSITION OF VARIOUS LATTICE DEFECTS IN HARDENING

According to the approach proposed in this paper, if there are barriers of different types in the material, the square of the effective stress will be equal to the sum of the squares of effective stresses created by the various barriers, so that

$$\sigma_y = \sqrt{\sigma_{disl}^2 + \sigma_{void}^2 + \sigma_p^2 + \dots} . \tag{31}$$

In Ref. [16] it was shown, that Eq. (31) fits better experimental data on hardening of niobium at low neutron irradiation doses as compared with the arithmetical sum of different hardening increments. According to Ref. [17] fitting the temperature dependence of hardening in molybdenum, niobium and their dilute alloys irradiated with fast neutron fluences close to 10^{22} n/cm^2, is considerably improved if to use eq. (31) instead of $\sigma_y = \sigma_{disl} + \sigma_{void} + \sigma_{loop} + \dots$.

CONCLUSIONS

A hypothesis, according to which the yield strength is determined by the square of effective stress at an arbitrary point of a material created by all components of the microstructure (by dislocations, voids, precipitate particles, dislocation loops etc.), allows to derive analytically the hardening constants.

In the approach developed above the yield strength is equal to the root square of the total squares of effective stress caused by different hardening mechanisms in the case, if the spatial distributions of these barriers are random and independent.

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ТЕОРИЯ РАДИАЦИОННОГО УПРОЧНЕНИЯ МЕТАЛЛОВ И СПЛАВОВ НА ОСНОВЕ ЭНЕРГЕТИЧЕСКОГО УСЛОВИЯ ПЛАСТИЧНОСТИ

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РЕФЕРАТ

Общепринятый подход при оценке упрочнения состоит в вычислении критического скалывающего напряжения при продавливании сегмента скользящей дислокации между двумя однотипными барьерами. Согласно теории Орована, критическое

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сдвиговое напряжение τ_k определяется средним расстоянием l между препятствиями: $\tau_k = \alpha Gb/l$ (α – константа; G – модуль сдвига; b – вектор Бюргерса). Суперпозиция различных барьеров учитывается либо простым суммированием их вкладов τ_i ($i = 1, 2, 3, \dots$) в критическое скалывающее напряжение $\tau_k = \tau_1 + \tau_2 + \tau_3 + \dots$, либо как $\tau_k^2 = \tau_1^2 + \tau_2^2 + \tau_3^2 + \dots$. Оба способа суммирования вкладов не имеют до сих пор теоретического обоснования. На основе принципа максимального сдвигового напряжения (критерий Треска) τ_k для поликристаллических образцов связывается с пределом текучести в испытаниях на растяжение σ_y соотношением $\sigma_y = 2\tau_k$. На основе понятия эффективного напряжения (энергетическое условие пластичности) эта связь имеет вид $\sigma_y = (\sqrt{3})\tau_y$ (критерий Мизеса). Иногда используется критерий Тейлора, согласно которому $\sigma_y = 3.06 \cdot \tau_k$.

Предлагается другой способ вычисления предела текучести металлов и сплавов. Использовано энергетическое условие пластичности (критерий Мизеса), согласно которому пластическое течение материала происходит тогда, когда удельная потенциальная энергия формоизменения, пропорциональная квадрату эффективного напряжения σ_{eff}, достигает некоторого предельного для данного материала значения, пропорционального квадрату предела текучести σ_y при одноосном растяжении.

Предполагается, что для начала пластического течения обусловленная внешними силами удельная потенциальная энергия формоизменения должна превысить предельное значение, равное удельной потенциальной энергии формоизменения, созданной всеми дефектами микроструктуры (дислокациями, дислокационными петлями, порами, выделениями и др.). Такой подход позволяет вычислить коэффициенты барьерного упрочнения α. Согласно предлагаемому подходу, предел текучести равен корню квадратному из суммы квадратов вкладов всех типов дефектов («геометрическое» суммирование вкладов).

Ключевые слова: радиационное упрочнение, предел текучести, металлы и сплавы, дислокации, поры, частицы фазовых выделений.

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