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STEADY-STATE STRAINING OF SOLIDS

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The concept of the dynamic yield point σ_d is used in investigations concerned with the mechanics of plastically deformable solids. It is understood that, for sufficiently large values of the plastic strain γ, the straining process is stabilized in a certain manner, and the stress causing further straining becomes a certain function of the deformation rate $\dot{\gamma}$ and the temperature T, $\sigma = \sigma_d(\dot{\gamma}, T)$, which is characteristic for the material in question and determines the dynamic yield point. The problem of the existence of $\sigma_d(\dot{\gamma}, T)$ is solved within the framework of the mechanics of continuous media on the basis of experimental data. If the experimental data agree with the existence of $\sigma_d(\dot{\gamma}, T)$, the problem consists in choosing the continuous medium model that has a suitable determining equation. However, if the concept of discrete elemental structure of matter is used, it becomes necessary to interpret the existence of the function $\sigma_d(\dot{\gamma}, T)$ on the basis of the dislocation theory. The experimental data presently available are apparently still insufficient for a definitive solution of this problem. Let us discuss the existing possibilities, using, for the sake of convenience (as an illustrating example), the simple case of pure shear, produced by an "effective system of dislocation glide" with suitably averaged characteristics.

Assume that the maximum shearing stress σ acts in the direction of glide, G is the shear modulus, N is the dislocation density, v is the rate of dislocation glide, ε is the elastic (potential) part of the total energy of formation of a unit-length dislocation filament, and b is the absolute value of the Burgers vector. We shall represent the rate of change in shearing strain as the sum of the elastic and the plastic components:

$$\dot{\gamma} = \dot{\gamma}_e + \dot{\gamma}_p = \dot{\sigma}/G + bNv.$$

In particular, $\dot{\sigma} = 0$ and $\dot{\gamma} = bNv$ under steady-state conditions; then the necessity for the existence of a single-valued dependence $Nv = f(\sigma, T)$ follows from the assumption about the existence of a dynamic yield point. Such a dependence could exist in the following cases:

1. The value of N is arbitrary, but the law of collective motion of dislocations differs from the law of motion of a single dislocation and also has a special form:

$$v(\sigma, T, N) = f(\sigma, T)/N,$$

while the establishment of flow constitutes the establishment of a regular structure in the aggregate of dislocations. We shall confine ourselves to the statement of this variant without touching upon the possibility of its realization and pass to the following, more probable, variants.

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2. The solutions of the kinetic equations of moving dislocations are characterized by the asymptotic behavior $N(t) \to N^*$ (t is the time), just as there is asymptotic behavior for fixed dislocations [1]. The establishment of flow constitutes the approach of the dislocation density to its asymptotic value.

3. Since there are no experimental data which would indicate that the relationships $N^* = \text{const}$ and $\dot{\gamma} = \text{const}$ v are always satisfied exactly for a certain given material, one must assume that $N^* = N^*(\sigma, T)$. We can try to explain this relationship by the fact that the equations of dislocation kinetics are not characterized by unambiguous asymptotic behavior so that, from the many possible asymptotic conditions, we choose the set of conditions under which the state of the material approaches thermodynamic equilibrium most closely. Let us consider the interesting limiting case where the kinetics permits achievement of the exact equilibrium. We shall define the equilibrium condition in steady-state strain as the condition under which the potential energy

$$U = \sigma^2/2G + N\varepsilon$$

reaches the minimum of the allowable values for the assigned $\dot{\gamma}$ and T. Searching for the minimum of $U(\sigma, N)$ according to Lagrange's method under the condition of stability for $\dot{\gamma}_p(\sigma, N)$, we obtain the equation

$$N^{*2}\left(\frac{\partial\varepsilon}{\partial N}\frac{\partial v}{\partial\sigma} - \frac{\partial\varepsilon}{\partial\sigma}\frac{\partial v}{\partial N}\right) + N^*\left(\varepsilon\frac{\partial v}{\partial\sigma} - v\frac{\partial\varepsilon}{\partial\sigma} - \frac{\sigma}{G}\frac{\partial v}{\partial N}\right) - \frac{\sigma v}{G} = 0. \tag{1}$$

Equation (1) cannot be compared with the experimental results because of a lack of necessary data. We shall simplify (1) by putting $\varepsilon = \text{const}$ and $\partial v/\partial N = 0$, so that it assumes the following form:

$$N^* = \sigma v/\varepsilon G(\partial v/\partial\sigma).$$

In particular, for the law of dislocation motion in the form $v = C(\sigma - \sigma_0)^\alpha$, where C and α are constants, and σ_0 is the static yield point, we obtain

$$N^* = \sigma(\sigma - \sigma_0)/\alpha\varepsilon G,$$
$$\dot{\gamma} = bC\sigma(\sigma - \sigma_0)^{\alpha+1}/\alpha\varepsilon G. \tag{2}$$

It should be expected that the approach to equilibrium is facilitated by increasing the stress and the deformation rate, since an increase in the elastic energy density of a crystal promotes the activation of a large number of elementary kinetic processes. In connection with this, we note that expressions (2) can be satisfactorily matched with respect to the order of magnitude to the well-known experimental data on high-speed metal deformation (see, for example [2] and the literature cited therein). Additional experimental data are necessary for more definite conclusions concerning the closeness with which (1) approaches the actual processes.

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