For E = 3.5 GeV and θ = 10°, the cross sections for the production of the concrete resonances are listed in the table.

Unlike Low [8], we took into account only the contributions of $|q_i^2| < m_e^2\tilde{\gamma}^2$. Allowance for large q_i^2 requires knowledge of the form factors and does not make an appreciable contribution to the cross section. In addition, we do not assume that $\ln k \ll \ln \tilde{\gamma}$, and this increases the estimate at high energies.

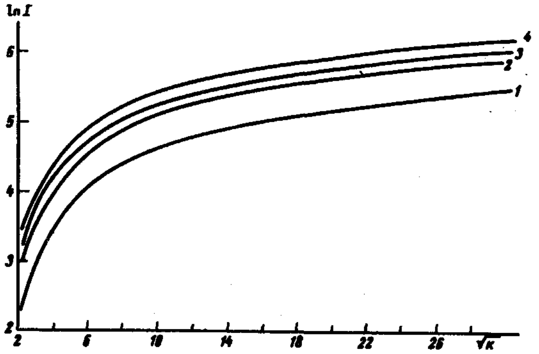

Fig. 3. 1 - $\tilde{\gamma}$ = 100, 2 - $\tilde{\gamma}$ = 500, 3 - $\tilde{\gamma}$ = 1000, 4 - $\tilde{\gamma}$ - 2000.

The authors are grateful to N.N. Achaseov, V.E. Balakin, A.I. Vainshtein, I.F. Ginzburg, V.G. Serbo, V.L. Chernyak, and I.B. Khriplovich for useful discussions.

[1] V.L. Auslender et al., Proc. Stanford Internal. Symp. on Electron and Photon Interactions, at High Energies, Stanford, 1967.
[2] M.J. Crentz and M.B. Einhorn, Phys. Rev. 1D, 2537 (1970).
[3] A.I. Vainshtein and I.B. Khriplovich, Paper at 15th Conf. on High-energy Physics, Kiev, 1970.
[4] V.M. Budnev and I.F. Ginzburg, Yad. Fiz. 13, 353 (1971) [Sov. J. Nuc. Phys. 13, No. 2 (1971)].
[5] G.M. Radutskii, ibid. 8, 115 (1968) [8, 65 (1969)].
[6] A.H. Rosenfeld, Review of Particle Properties, Phys. Lett. August 1970.
[7] W. Tybor and A-N. Zaslavsky, Preprint JINR E-2-4976 (1970).
[8] F.E. Low, Phys. Rev. 120, 1860 (1960).

INTERSTITIAL (CROWDION) MECHANISM OF PLASTIC DEFORMATION AND FAILURE

V.L. Indenbom
Crystallography Institute, USSR Academy of Sciences
Submitted 16 October 1970
ZhETF Pis. Red. 12, No. 11, 526 - 528 (5 December 1970)

Crowdions, interstitial atoms that move along close-packed directions like other possible configurations of interstitial atoms well known in radiation physics, are traditionally disregarded in the physics of plasticity. It is assumed that since the energy of formation of these defects is large, their concentration is negligibly small compared with the concentration of other point defects in the lattice. In diffusion, in particular, the decisive role is usually ascribed to vacancies and not to interstitial atoms. The latest data make it necessary, however, to reestimate the role of interstitial atoms in processes of plasticity and failure, and make it possible to refine the hypothesis previously advanced by us [1] concerning the possible conditions for the realization and macroscopic manifestation of the interstitial mass-transport mechanism.

We note that any vacancy sink should be converted into a source of interstitial atoms if the temperature is lowered sufficiently and the stress is sufficiently increased (the direction of mass transport remains the same as before). Let the chemical potential of the vacancies near the sink be lowered (and the chemical potential of the interstitial atoms raised) by an amount $\Delta\mu = \gamma\sigma$, where σ is the stress and γ the activation volume (the increment of deformation upon absorption of one vacancy or production of one interstitial atom). Then the equilibrium vacancy concentration near the sink will be lowered (and the equilibrium temperature of the interstitial atoms increased) by $\exp(\Delta\mu/kT)$ times. When $\Delta\mu >> kT$, the flux of vacancies to the sink is practically independent of the stress, and the opposing flux of interstitial atoms increases exponentially with increasing stress, and can have a higher efficiency of mass transport by the vacancies. The transition from the vacancy to the interstitial mechanism of mass transport occurs at

$$\Delta\mu = U_D^M - U_D^V - s\,kT. \qquad (1)$$

Here U_D^M and U_D^V are respectively the self-diffusion activation energies in the interstitial and in the vacancy mechanisms, $s = \ln(D_0^M/D_0^V\eta)$, where D_0^M and D_0^V are the pre-exponential factors in the coefficients of self-diffusion over the interstices and the vacancies, and η is the vacancy supersaturation far from the sink. At low temperatures, the change of the diffusion mechanism is reached at a stress

$$\sigma^* = \gamma^{-1}(U_D^M - U_D^V). \qquad (2)$$

With increasing temperature, the critical stress σ^* decreases with a temperature coefficient $s\gamma^{-1}k$. An estimate of the parameter s for different variants of vacancy sinks gives a value on the order of several units, and the difference $U_D^M - U_V^D$ usually does not exceed 1 eV. Therefore the suppression of the usual vacancy diffusion mechanism and the conversion of vacancy sinks into interstitial sources is far from being an exotic event.

At our request, B.N. Rozhanskii and co-workers verified the existence of the interstitial mass transport in the case of local deformation, when the stresses approach the theoretical strength of the material, and the criterion (1) can be satisfied for γ on the order of the atomic volume (i.e., for deformation via direct mass transport). It turned out that the interstitial atoms (in this case their appearance was to be expected in the most mobile crowdion configuration) indeed carry away an appreciable amount of material from under the indentor, and their contribution can be reliably revealed against the background of the dislocation motion, by the occurrence of interstitial loops far from the dislocation rosette [2].

The interstitial atoms should obviously play a noticeable role also in other cases when high stresses are applied (deformation by explosion, shock forces, high-speed deformation, etc.). Moreover, at low deformation stresses the interstitial atoms can be produced in places where there are high local internal stresses, which inevitably arise in connection with the heterogeneity of the plastic deformation. We can cite as an example various dislocation configurations. In the case of a local barrier located at a distance ℓ along the dislocation, we have $\gamma \approx a^2\ell$, where a is the lattice parameter and the applied external stress increases effectively by (ℓ/a) times. At the reasonable values $\ell \sim (10^2 - 10^3)a$, the criterion (1) is satisfied at relatively low stresses ($1 - 10$ kg/mm^2) and at ordinary temperatures.

The dependence of the interstitial flux coming from the former vacancy sink on the temperature and on the stress is described by the expression $\exp[-(U_D^M - \gamma\sigma)/kT]$, which is very similar to the Zhurkov formula [3] for the general laws governing creep and endurance of many materials in a wide range of temperatures and stresses. The constants U_D^M and γ agree with the empirical constants U_0 and γ in Zhurkov's formula. It was already noted earlier that U_0 coincides with the known theoretical and experimental estimates of the energy of the interstitial atoms [1, 4] (the migration energy of these defects is very low). The agreement between γ and the parameters of the dislocation grids was verified at our request by Myshlyaev [5]. The interstitial interpretation of Zhurkov's law is confirmed also by the influence of the character of the stress state on the activation energy of the creep and failure [6] and by direct experiments on the determination of the type of non-equilibrium point defects such as loops, produced when deformed samples are quenched [7].

The anomalies predicted by the interstitial hypothesis were observed recently in the creep and endurance curves, namely, the linear dependence of the activation energy on the stress indeed ceased at $\sigma = \sigma^*(T)$ and this energy decreased sharply by an amount skT, reaching the level of U_D^V [8]. The value of the constant s turned out to be in good agreement with the macroscopic estimate of this quantity based on the balance of the interstitial and vacancy fluxes. For a final establishment of the interstitial mechanism of such fundamental phenomena as creep and endurance of crystalline materials it is necessary, of course, to perform direct experiments aimed at determining the concentration of the interstitial atoms and to specify concretely the type of the vacancy sinks converted into interstitial sources. Such sinks, in particular, may be not only dislocation jogs that migrate in a non-conservative manner after the dislocations, but also the nuclei of cracks or pores.

We note that the interstitial hypothesis concerning the general (non-crowdion) variant admits of an obvious generalization to the case of non-crystalline bodies, since the energy of formation and migration of interstitial atoms depends in all but the crowdion configurations only on the short-range order in the arrangement of the atoms.

In conclusion, the author is deeply grateful to S.N. Zhurkov, A.N. Orlov, and B.R. Regel' for numerous discussions of this problem and to M.M. Myshlyaev, B.A. Stepanov, and B.N. Rozhanskii for experimentally verifying the interstitial hypothesis.

[1] V.L. Indenbom, in: Fizika shchelochno-galoidynkh kristallov (Physics of Alkali-halide Crystals), Riga, 1962; Deformatsionnoe uprochnenie (Deformation Hardening), Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences, Khar'kov, 1969; Internat. Conference on Crystal Lattice Defects, Abstracts 1 - 11, Kyoto, Japan, 1962; V.L. Indenbom and A.N. Orlov, Usp. Fiz. Nauk 76, 557 (1962) [Sov. Phys.-Usp. 5, 272 (1962)].

[2] B.N. Rozhanskii, M.P. Nazarov, et al., Deformatsionnoe uprochnenie (Deformation Hardening), Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences, Khar'kov, 1969; Phys. Stat. Solid, 1970, in press; VII Congres Internat de Microscopie Electronique, Grenoble, France, 2, 585 (1970).

[3] S.N. Zhurkov, Vestnik AN SSSR 27, 78 (1957); 38, 46 (1968).

[4] V.L. Indenbom and A.N. Orlov, Problemy prochnosti (Problems of Strength), No. 12 (1970).

[5] M.M. Myshlyaev, Fiz. Tverd. Tela 7, 591 (1965) [Sov. Phys.-Solid State 7, 468 (1965)].

[6] I.E. Kurov, V.A. Stepanov, and V.V. Shpeizman, in: Fizika metallov i metallovedenie (Physics of Metals and Metallurgy), Trudy, Leningrad Polytechnic Institute No. 305, p. 71 (1969).

[7] M.M. Myshlyaev, S.S. Olevskii, G.V. Vladimirova, and V.A. Likhachev, Dokl. Akad. Nauk SSSR 191, 1022 (1970) [Sov. Phys.-Dokl. 14, No. 10 (1971)]; M.M. Myshlyaev, S.S. Olevskii, S.I. Maksimov, V.A. Likhachev, and G.V. Vladimirova, Phys. Stat. Sol., in press.

[8] V.A. Stepanov and V.V. Shpeizman, FMM 29, 375 (1970); M.M. Myshlyaev, V.A. Stepanov, and V.V. Shpeizman, Phys. Stat. Sol., in press.