:hives of Mechanics • Archiwum Mechaniki Stosowanej • 29, 6, pp. 811–820, Warszawa 1977

Interaction of elastic wave with defects of finite volume and interaction between defects

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THE PRESENT paper deals with the problems of interaction of structural defects of solid with mechanical fields and mutual interactions between defects. The method of multipole moments, developed and elaborated for mechanical fields, was applied. Using Green function for elastic continuum the energy of interaction of defects, the self energy of defects and the energy of interaction with elastic wave were evaluated. The mobile and immobile defects were considered. The cases of point defect and prismatic dislocation loop are examined in detail. Finally the application of the performed computations to the problem of initiation of the Cottrell's atmospheres was demonstrated.

Praca poświęcona jest problemom oddziaływania defektów strukturalnych ciała stałego z polami mechanicznymi i wynikającego stąd wzajemnego oddziaływania pomiędzy defektami. Zastosowana została metoda momentów multipolowych, opracowana i rozwinięta dla pól mechanicznych. Stosując funkcję Greena kontinuum sprężystego, obliczono energię wzajemnego oddziaływania defektów, ich energię własną oraz energię oddziaływania z falą sprężystą. Rozpatrzono przypadki zarówno ruchomych jak i nieruchomych defektów. Szczegółowo rozpatrzono przypadki defektu punktowego i pryzmatycznej pętli dyslokacyjnej. W końcowej części pracy pokazano zastosowanie uzyskanych obliczeń do problemu powstawania atmosfer Cottrella.

Работа посвящена проблемам взаимодействия структурных дефектов твердого тела с механическими полями и следующего оттуда взаимодействия между дефектами. Применен метод мультипольных моментов разработанный и развитый для механических полей. Применяя функцию Грина упругого континуума вычислена энергия взаимодействия дефектов, их собственная энергия и энергия взаимодействия с упругой волной. Рассмотрены случаи так подвижных, как и неподвижных дефектов. Подробно рассмотрены случай точечного дефекта и призматической дислокационной петли. В заключительной части работы показано применение полученных расчетов для проблемы возникновения атмосфер Котрелла.

IN THE PRESENT paper, an attempt is made, using a volume-force model for defects in a continuous medium, to explain certain phenomena concerning the interaction and motion of crystal structure defects. The intention was to compare the effects examined with the experimental results obtained in papers [1, 2, 3, 4, 5]. These papers investigated the effects associated with a change of mechanical properties of metals examined under action of an elastic wave. In the experiments described, specimens made of aluminium were subjected to heat treatment to ensure a uniform dislocation structure. The dislocation structure obtained was composed mainly of prismatic dislocation loops. The specimens so prepared were then subjected to the action of an elastic wave of different intensity, their dislocation structure being subsequently examined by means of an electronic microscope and the plastic yield limit, the strength of the material and its ability to creep were estimated with a strength testing machine.

The results of the experiment made it seem worth while to compute the interaction energy of immobile defects, the interaction energy of mobile defects, the proper energy of the mobile and immobile defects and the energy of defects in a field of elastic wave. The computations were performed on the basis of the force-volume model of defects developed in [6, 7, 8, 9]. In view of the simplicity of computations, only the defects with symmetry centers were analyzed (the volume-force model may be applied with success also to other defects, but the computations become much more complex). The expressions derived in the paper [9], describing the interaction energy of mobile and immobile dislocations of arbitrary type were used here.

The interaction energy of finite volume and arbitrary type immobile defects has the form [9]:

$$E_{12} = -\sum_{n=0}^{\infty} \frac{1}{n!} P^{(1)}_{ip_1\dots p_n} \sum_{s=0}^{\infty} \frac{(-1)^s}{s!} P^{(2)}_{kq_1\dots q_s} \nabla_{p_1} \dots \nabla_{p_n} \nabla_{q_1} \dots \nabla_{q_s} G_{ik}(\mathbf{r}). \tag{1}$$

The functional of the action describing the interaction of finite volume and arbitrary type mobile defects is:

$$W_{12} = -\int_{t_1}^{t_2} dt \sum_{n=0}^{\infty} \frac{1}{n!} P^{(1)}_{ip_1\dots p_n} \nabla_{p_1} \dots \nabla_{p_n} \int_{-\infty}^{t} d\tau \sum_{s=0}^{\infty} \frac{(-1)^s}{s!} P^{(2)}_{kq_1\dots q_s} \nabla_{q_1} \dots \nabla_{q_s} \overset{\text{ret}}{G}_{ik}(\mathbf{r}, t+\tau), \tag{2}$$

where $P_{ip_1\dots p_n}$ and $P_{kq_1\dots q_s}$ are the multipole moments which may be written in a form:

$$P^{(a)}_{p_1\dots p_n} = \int_V X_i(r') \varrho_{p_1} \dots \varrho_{p_n} dV, \quad a = 1, 2. \tag{3}$$

Here $G_{ik}(\mathbf{r})$ is the static Green function for an infinite isotropic elastic medium [4, 7, 8], $\overset{\text{ret}}{G}_{ik}(\mathbf{r}, t)$ is the dynamic Green function for an infinite isotropic elastic medium, [10], $\mathbf{r}$ denotes the distance vector between points lying inside the volume of the two defects with respect to which the general expression was expanded in Taylor series, $X_i(\mathbf{r})$ denotes the force in the volume of defect, and ϱ_{p_1}, ϱ_{p_n} is the arm of action of the force with respect to the point $\mathbf{r}$ distinguished in the volume.

Mutual interaction of immobile defects

Assuming for analysis the defects with a centre of symmetry, and utilizing the properties of the multipole moments, simple expressions for the energy of interaction of symmetric defects may be obtained:

$$E_{12} = P^{(1)}_{im} P^{(2)}_{jk} G_{mk,ij}(\mathbf{r}) + \frac{1}{3} P^{(1)}_{im} P^{(2)}_{kpst} G_{mk,pstl}(\mathbf{r}) + \frac{1}{3} P^{(1)}_{mpst} P^{(2(}_{kl} G_{mk,ipst}(\mathbf{r}) + \dots. \tag{4}$$

Modeling the point defects (vacancy, inclusion atom) in the form of the centre of compression or expansion, the dipole moments may be written in the form:

$$P^{(a)}_{im} = P^{(a)} \delta_{im}, \quad a = 1, 2. \tag{5}$$

But taking into account the shape and size of defects of the type of a prismatic dislocation loop [11], the dipole moments will assume the form:

$$P_{lm}^{(a)} = P^{(a)}\delta_{3l}\delta_{3m}, \quad a = 1, 2. \tag{6}$$

The octupole moment may be modelled in the form:

$$P_{kpst}^{(a)} = P_{1111}^{(a)} A_{kpst} + P_{1122}^{(a)}(\delta_{kp}\delta_{st} + \delta_{ks}\delta_{pt} + \delta_{kt}\delta_{ps}), \quad a = 1, 2, \tag{7}$$

where

$$A_{kpst} = \begin{cases} 0, & \text{where} \quad k \neq s \neq t \neq n, \\ 1, & \text{where} \quad k = s = t = n. \end{cases}$$

The quantities $P^{(a)}$, $P_{1111}^{(a)}$, $P_{1122}^{(a)}$, are respectively the dipole and octupole moments, which characterize a given defect. The manner of evaluation of these moments is presented in [12]. Substituting the relations (5), (6), (7) into the Eq. (4), using the properties of the Green function, and assuming that the distances between defects are not smaller than the diameter of the loop, the following final expressions for the interaction energy of defects are obtained:

a) point defect-dislocation loop:

$$E_{12}^{(12)} = P^{(1)}P^{(2)}[8\pi\mu(1-\nu)]^{-1}r^{-3}(1-2\nu)(3b_3^2-1), \tag{8}$$

where μ and ν are the material constants, $r = |\mathbf{r}|$ is the absolute value of the distance vector, $b_3 = r_3/r$ is the direction cosine of the angle lying between the radius vector and the axis x_3 which passes through the centre of the loop and is perpendicular to its plane, and $P^{(1)}$, $P^{(2)}$ are the dipole moments of the loop and point defect, respectively. In a further part of this paper the upper index indicates whether the point defect (number 2) or the loop (number 1) is analyzed;

b) point defect-point defect:

$$E_{12}^{(22)} = \frac{7}{4}[\pi(\lambda+2\mu)]^{-1}P^{(2)}(P_{1111}^{(2)} - 3P_{1122}^{(2)})r^{-5}, \tag{9}$$

where all quantities are determined in the formulae (7), (8);

c) two arbitrarily oriented loops:

$$E_{12}^{(11)} = (P^{(1)})^2[16\pi\mu(1-\nu)]^{-1}r^{-3}\{[15b_3^2 - 6b_3^2(1+2\nu) + 4\nu - 1](b_3^{(0)})^2 + [15b_2^2(1-b_2^2) - 2](b_2^{(0)})^2 + 3b_2b_3b_2^{(0)}b_3^{(0)}[10b_3^2 - (2\nu+1)]\}, \tag{10}$$

where $b_2^{(0)}$, $b_3^{(0)}$ are the direction cosines between the two normals to the loops. The remaining notations are the same as in the Eqs. (7), (8). From analysis of the expressions (8), (9), (10), the following conclusions result: Around the prismatic dislocation loop there are regions in which the other loops or point defects are attracted; there also exist repulsion regions. In the case of the loop-point defect system, the geometry of the interaction is as follows:

(a) $$b_3 > \frac{1}{\sqrt{3}} \text{ then} \begin{cases} E_{12}^{(12)} > 0, & \text{when} \quad \begin{cases} P^{(1)} > 0, & P^{(2)} > 0, \\ P^{(1)} < 0, & P^{(2)} < 0, \end{cases} \\ E_{12}^{(12)} < 0, & \text{when} \quad \begin{cases} P^{(1)} < 0, & P^{(2)} > 0, \\ P^{(1)} > 0, & P^{(2)} < 0, \end{cases} \end{cases}$$

(b) $$b_3 < \frac{1}{\sqrt{3}} \text{ then} \begin{cases} E_{12}^{(12)} < 0, & \text{when} \quad \begin{cases} P^{(1)} > 0, & P^{(2)} > 0, \\ P^{(1)} < 0, & P^{(2)} < 0, \end{cases} \\ E_{12}^{(12)} > 0, & \text{when} \quad \begin{cases} P^{(1)} < 0, & P^{(2)} > 0, \\ P^{(1)} > 0, & P^{(2)} < 0, \end{cases} \end{cases}$$

(c) $$b_3 = \frac{1}{\sqrt{3}} \text{ then } E_{12} = 0;$$

in the case of the "loop-loop" interaction, the geometry of interaction has the same character, although it is highly significantly complex (a detailed analysis is given in [13]);

two point defects interact without change of the sign of interaction in dependence of the mutual positions;

interaction of the loop with the point defect and the loop with the loop decreases as r^{-3};

interaction of the point defects decreases as r^{-5}.

Mutual interaction of mobile defects

To compute the interaction energy of the mobile dislocation loop with the point defect, the functional (2) and the procedure given in [10] for expansion of $\overset{\text{ret}}{G}_{ik}$ on the instantaneous potentials was applied.

Analysis of the relation (2) from the point of view of the multipole moments for symmetric defects yields the following form of the functional:

$$W_{12}^{(12)} = \int_{t_1}^{t_2} dt P_{ks}^{(1)} \nabla_s \int_{-\infty}^{t} d\tau P_{il}^{(2)}(\tau) \overset{\text{ret}}{G}_{ik,l}(\mathbf{r}, t-\tau). \tag{12}$$

After expansion on the instantaneous potentials, utilizing the Eqs. (5) and (6) and making certain algebraic transformations, the final form the functional action was obtained:

$$\begin{aligned} W_{12}^{12} = \int_{t_1}^{t_2} dt \Big\langle & \frac{1}{8\pi\mu(1-\nu)} r^{-3}(1-3b_3^2)(2\nu-1) \\ & + \frac{1}{16\pi\varrho} \Big\{ \frac{1}{2} \dot{P}^{(1)} \ddot{P}^{(2)} [(c_1^{-4} - c_2^{-4})(1-b_3^2) 3r^{-1} + (c_1^{-4} + 3c_2^{-4}) r^{-3}(3b_3^2 - 1)] \\ & + \frac{1}{2} P^{(1)} P^{(2)} v^2 6r^{-3}(3b_3^2 - 1)(c_1^{-4} + 3c_2^{-4}) + \frac{1}{2} v_t (P^{(1)} \dot{P}^{(2)} - \dot{P}^{(1)} P^{(2)}) \big[(c_1^{-4} \\ & - c_2^{-4}) 3r^{-3} [r_t (3b_3^2 - 1) - 2r_3 \delta_{3t}] - (c_1^{-4} - 3c_2^{-4}) 3r^{-5} [r_t (5b_3^2 - 1) - 2r_3 \delta_{3t}] \big] \Big\} \Big\rangle. \end{aligned} \tag{13}$$

Substituting the Lagrangian from the Eq. (13) into the equation of motion, it was possible to determine the momentum of defects in a field of action of the other defect,

and then the energy of the mobile defect in a field of action of the other mobile or immobile defect [13]:

$$H_{12}^{(12)} = -\{[8\pi\mu(1-\nu)]^{-1}r^{-3}(3b_3^2-1)(1-2\nu)P^{(1)}P^{(2)} + 3(16\pi\varrho)^{-1}P^{(1)}P^{(2)}v^2(3b_3^2-1)r^{-3}(c_1^{-4}+3c_2^{-4}), \tag{14}$$

where v is a relative velocity of defects and c_1 and c_2 are the velocities of the longitudinal and transverse waves, respectively.

Energy of defects in a field of action of elastic waves

The functional of the action of the elastic wave on the defect may be written in the form:

$$W^{(f)} = -\int_{t_1}^{t_2} dt \int_V X_i(\mathbf{r}(t), t)u_i^{(f)}(\mathbf{r}(t), t)dv, \tag{15}$$

where $u_i^{(f)}(\mathbf{r}(t), t)$ is the displacement in a volume of defect in time t, generated by elastic wave.

Let us now expand the function $u_i^{(f)}(\mathbf{r}(t), t)$ appearing in the Eq. (15) into Taylor series with respect to the point determining, according to the assumed model, the position of the defect. The functional of action may now be written in the form:

$$W^{(f)} = -\int_{t_1}^{t_2} dt\left\{P_i(t)u_i^{(f)}(\mathbf{a}(t), t)+P_{ik}(t)\nabla_k u_i^{(f)}(\mathbf{a}(t), t)+\frac{1}{2}P_{ikm}\nabla_k\nabla_m u_i^{(f)}(\mathbf{a}(t), t)+\ldots\right\}. \tag{16}$$

Instead of $u_i^{(f)}(\mathbf{a}(t),t)$, the displacement vector of the arbitrary elastic wave may be introduced. For simplicity of computations, the simple plane harmonic wave is assumed:

$$\mathbf{u}_1 = A\mathbf{e}_1 \sin\omega\left(t-\frac{a_1}{c_1}\right). \tag{17}$$

The fact that in the analysis the symmetric defects were assumed, together with P_i and P_{ikm} equal zero, significantly simplifies the Eq. (16):

$$W^{(f)} = -\int_{t_1}^{t_2} dtP_{ik}(t)\nabla_k u_i(\mathbf{a}(t),t) = -\int_{t_1}^{t_2} dtL^{(f)}(\mathbf{a}(t), t), \tag{18}$$

where ω is the frequency of the wave, A is the wave amplitude, c denotes the velocity of the propagation of the signal, and the remaining quantities have been determined earlier. Replacing in the Eq. (18) P_{ik} by $P\delta_{ik}$, and performing the necessary computations, the Lagrangian of defect in a field of elastic wave is obtained in the form:

$$L^{(f)}(\mathbf{a}(t), t) = -P(t)\frac{\omega}{c_1}\cos\omega\left(t-\frac{a_1}{c_1}\right). \tag{19}$$

The total Lagrangian of the point defect, taking into account the self-action, becomes:

$$L^{(\omega,f)} = L^{(f)}+L^{(\omega)}. \tag{20}$$

The equation of motion

$$\frac{d}{dt}\frac{\partial L^{(\omega f)}}{\partial v}-\frac{\partial L^{(\omega f)}}{\partial a}=0$$

assumes the form:

$$\frac{d}{dt}\frac{\partial L^{(\omega)}}{\partial v}-\frac{\partial L^{f}}{\partial a}=0. \tag{21}$$

The Hamiltonian of the defect on which the wave falls has the form:

$$H^{(\omega,t)}=E^{(\omega,t)}=pv-L^{(\omega,t)}=\frac{\Delta' P^2(t)}{2\pi\varrho}3c_1^{-5} \tag{22}$$
$$+\left[\frac{\Delta' P^2(t)}{2\pi\varrho}\left(\frac{9}{7}c_2^{-7}-\frac{95}{14}c_1^{-7}\right)+\frac{1}{2}M\right]v^2+P(t)\frac{\omega}{c_1}A\cos\omega\left(t-\frac{a_1}{c_1}\right).$$

In the Eqs. (20), (21), (22), the form of the Lagrangian describing self-action of the point defect, derived in [9] and corrected [13], is used:

$$L^{(\omega)}=\frac{\Delta' P^2(t)}{2\pi\varrho}\left[-3c_1^{-5}+v^2\left(-\frac{95}{14}c_1^{-7}+\frac{9}{7}c_2^{-7}\right)+v^4\left(-\frac{239}{24}c_1^{-9}+\frac{17}{6}c_2^{-9}\right)\right]+\frac{1}{2}Mv^2. \tag{23}$$

Δ' is assumed as a quantity of order Δt^{-3}, where Δt is the time necessary for the signal to pass through the region occupied by the defect [9, 13], and v and M respectively denote the velocity and mass of the defect ($M=\int\varrho dv$). The Eq. (22) describes the growth of the energy of the defect on which the elastic wave falls. The elastic wave causes no change in either the velocity or the direction of motion. The motion which may appear if there are no other interactions will be chaotic. The incident elastic wave will facilate the motion of the defect only by lowering the energy barriers impeding it.

Summing up the above considerations, it may be concluded that the total energy of the point defect on which act the defect of loop type and the elastic wave, is presented for immobile defects by the Eq. (24) and for mobile defects by the expression (25):

$$E_{\Delta}^{c}=P^{(1)}\left\{P^{(2)}[8\pi\mu(1-\nu)]^{-1}r^{-3}(1-2\nu)(3b_3^2-1)+P^{(1)}3\Delta^1(2\pi\varrho c_1^5)^{-1}\right. \tag{24}$$
$$\left.+\omega c_1^{-1}A\cos\omega\left(t-\frac{a_1}{c_1}\right)\right\},$$

$$E^{c}(t)=\frac{(P^{(1)})^2\Delta'}{2\pi\varrho}3c_1^{-5}+\left[\frac{(P^{(1)})^2\Delta'}{2\pi\varrho}\left(\frac{9}{7}c_2^{-7}-\frac{95}{14}c_1^{-2}\right)+\frac{1}{2}M\right]v^2 \tag{25}$$
$$+P^{(1)}(t)\frac{\omega}{c_1}A\cos\omega\left(t-\frac{a}{c_1}\right)+\frac{P^{(1)}P^{(2)}}{8\pi\mu(1-\nu)}r^{-3}(3b_3^2-1)(2\nu-1)$$
$$-\frac{3}{16\pi\varrho}P^{(1)}P^{(2)}v^2(3b_3^2-1)r^{-3}(c_1^{-4}-3c_2^{-4}).$$

Generation of Cottrell's atmospheres in the light of derived relations

The relations derived in this paper may constitute the basis for describing and explaining the ageing mechanism of metal and the influence of an elastic wave on its magnitude. The defects of the given shape and size are analyzed. The relation obtained cannot be generalized to the whole range of defects appearing in reality. But the character of the particular phenomena observed will be more or less similar to more general cases. The relations derived can be applied immediately, if in the metal under consideration prismatic loops prevail — as is sufficiently frequent in real structures [1, 2, 3, 4, 11]. The phenomenon of spontaneous change of mechanical properties of metals subjected to plastic working is well known in practice. In metallurgy, this phenomenon is known as the ageing of metal.

Cottrell was the first to explain this phenomenon. According to the theory, dislocations accumulate around the point defects (atom of inclusions, vacancies) which block the motion of dislocations. The concentrations of point defects around the dislocations are called Cottrell's atmospheres.

As the experiments [1, 4, 14, 15, 16] shows, the velocity of the diffusion of the point defects, and thus the intensity of formation of the atmospheres, increases with increase in temperature or when a small intensity elastic wave acts on the metal.

Let us now perform the analysis of the phenomenon discussed, in the light of the relations derived:

at each point defect lying in the vicinity of the loop, there acts an attraction or repulsion force, the magnitude of which may be found from the formula

$$F = \frac{\partial E_{12}}{\partial r},$$

where E_{12} may be evaluated from the Eq. (8) or the Eq. (14), and r is a mutual distance between the symmetry centers of the point defect and prismatic dislocation loop. In the vicinty of the loop there exists repulsion and the attraction of defects. The defects will mutually attract if $E_{12} < 0$, or mutually repel when $E_{12} > 0$. The condition under which the defects will mutually attract or repel have been determined by the relations (11a), (11b), (11c);

the fact of the appearance of the forces which attract or repel the point defects from the loops is not always sufficient to set them in motion. It should be borne in mind that defects are situated in the crystal lattice and the forces resulting from the periodicity of the structure of the lattice act against the motion of defects. In other words the defects to be set in motion must overcome a certain energy barier;

in addition to the interaction energy with the loop, the point defect has its own energy determined by the Eq. (22) (its two terms);

summing up the earlier remarks, it may be a certained that around the dislocation loop in certain strictly determined regions the atoms of inclusion or vacancies accumulate, and make its motion more difficult. Due to the effective diffusion force resulting from the mutual attraction with the loop, the point defects travel to the vicinity of the loop. Only these defects will diffuse toward the region of the loop, the total energy of which is greater then the energy barier acting against the motion:

$$E_{12} + E_w > E_p;$$

around the loop in the region of attraction there are defects whose concentration is described by the Eq. (26)

$$C = C_0 \exp\left[-\frac{Q}{kT}\right], \tag{26}$$

where C_0 is the average concentration of defects in a crystal and its magnitude may be computed on the basis of knowledge of the enthalpy of the formation of point defects (the enthalpy of the formation of point defects in general is computed and tabulated); k is the Botzmann constant; T denotes the temperature and Q is the enthalpy of the activation of diffusion; $Q = \Delta H_f + \Delta H_m$ for diffusion occurring by means of vacancies or natural interlattice atoms; $Q = \Delta H_m$ in the case of motion of foreign atoms; ΔH_m is the enthalpy activating the motion of the atom; and ΔH_f is the enthalpy of the vacancy formation. Assuming that at the instant of analysis, the new defects are not creating $\Delta H_f = 0$, and using the relation

$$\Delta H_m = \Delta U - pdV,$$

where U is the activation energy of motion, V is the body volume and p is the pressure, for constant number of the point defects and constant temperature $\Delta V = 0$, the Eq. (28) will take the form:

$$C = C_0 \exp\left[-\frac{\Delta U}{kT}\right]. \tag{27}$$

The Eqs. (26) and (27) hold for defects on which act neither external forces nor forces coming from the other defects. If the effective diffusion forces (i.e. electric and magnetic forces or the forces resulting from the stresses appearing in the crystal) act on the defects in a solid, then the Eq. (27) may be written in a slightly different form:

$$C = C_0 \exp\left[-\frac{\Delta U}{kT}\right] \exp\left[-\frac{\Delta U_{ef}}{kT}\right]. \tag{28}$$

Let us write:

$$U = E_p - E^W,$$

where E_p is the energy barier of the motion of defect, and E^W is the self energy (Eq. (22)) and

$$\Delta U_{ef} = E_{12},$$

where E_{12} is the interaction energy of defects.

Let us rewrite the Eq. (28) in terms of the new quantities in the form:

$$C = C_0 \exp\left[-\frac{(E_p - E^W) + E_{12}}{kT}\right]. \tag{29}$$

This equation means that with the increase of the interaction energy, depending on its sign, the concentration of defects around the loops increases or decreases (all terms in the Eq. (29) may be calculated from the formulas derived in this paper or found in the tables).

From known experimental facts it results that when the elastic wave acts on a medium with defects, the intensity of motion increases [1, 2, 3]. For elastic waves of small intensity, the process of diffusion of the defects in the direction of dislocation loops is accelerated. The action of a large intensity elastic wave on the medium causes separation of the loops from the conglomeration of the point defects. Due to operation of the elastic wave on the medium, the energy of defects as also the energy of the whole body increase, the temperature of the medium increases, a large number of point defects and dislocations appear, condensation of vacancies takes place, and a series of other effects occur.

Using such a simple model of the medium and defects as that applied in this paper, it is impossible to describe the phenomena indicated above by simple formulae of the type (29). But by restricting ourselves to analysis of the phenomenon due to the action of a small intensity elastic wave, it will be possible, without involving essential errors, to assume the additional factors as negligible, and, to take into account in the analysis only the increase in the energy of the defect under the action of an elastic wave. In this case, the Eq. (29) assume the form:

$$C = C_0 \exp\left[-\frac{(E_p - E^W - E^f + E_{12}}{kT} \right] \tag{30}$$

and explain the effect of accelerated diffusion of defects to the surroudings of the dislocation loop. If the effective diffusion force start to act on the point defect, then the chaotic motion of the defect will become directional motion towards the source or in the opposite direction. The frequency of jump in the direction of the action of the force, or in the opposite direction, may be expressed by the formula:

$$\Gamma_i = \nu_0 \exp\left[-\frac{E_p - E^\omega - E^f}{kT} \right] \left\{ \exp\left[-\frac{E_{12}}{kT} \right] \right\}, \tag{31}$$

where ν_0 is the frequency of thermal vibrations (circa 10^{13} s^{-1}), k is the Boltzmann constant (1.38×10^{-23} $J°K^{-1}$), and T denotes the $°K$ temperature. The speed of drift of the point defect in the direction of action of the effective diffusion force may be written as:

$$v = \nu_0 \exp\left[-\frac{E_p - E^\omega - E^f}{kT} \right] \left\{ \exp\left[-\frac{E_{12}}{kT} \right] - \exp\left[\frac{E_{12}}{kT} \right] \right\} b. \tag{32}$$

This expression results from the difference of the probability of a jump in a direction consistent with the action of the force, and in the opposite direction, multiplied by the path of the jump b on which such jump occurs.

Expanding the terms in braketes into series with respect to the energy E_{12}, we obtain the final expression for the velocity of drift of the point defect (expansion terms in which E_{12} enters in a power higher than one are disregarded):

$$v = -\nu_0 \exp\left[-\frac{E_p - E^\omega - E^f}{kT} \right] 2b \frac{E_{12}}{kT}. \tag{33}$$

From this equation, the strong dependence of the velocity on the temperature and the energy of interaction is observed. For example the velocity of the vacancies at a distance

of 800Å from the vacancy loop of diameter 150Å in aluminium, without action of the wave, is 0,05Å/S. The interaction energy for this example at this position is 0.22×10^{-3} eV. $P^{(1)}$ and $P^{(2)}$ assumed for computations, and found in [12], are:

$$P^{(1)} = 0.003 \cdot 10^{-6} R_p^2 \frac{N}{\text{Å}},$$

$$P^{(2)} = 0.04 \cdot 10^{-6} N\text{Å}.$$

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Received January 26, 1977.