Moving Dislocations and Solute Atoms

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In the stress field of a moving dislocation, stress-induced local rearrangement of solute atoms takes place. From this rearrangement there results a friction force, which depends on the velocity of the dislocation. It should be possible to detect this effect in creep experiments.

THE interaction between moving dislocation lines and solute atoms has been treated by several investigators. Mott and Nabbaro[1] considered the motion of a dislocation line through a random solid solution where the solute atoms are in fixed positions. Cottrell and Jaswon[2] treated the case of a moving dislocation dragging along an atmosphere of solute atoms.

There is another possibility for certain solute atoms to interact with the dislocation even if the time is too short to allow the formation of an atmosphere around the dislocation by long range diffusion.[3] In the stress field of a moving dislocation, local atomic rearrangement or short-range ordering may take place. This is possible, however, only if the solute atoms in different lattice positions have different interaction energies with the dislocation. An example is the case of a solute atom which causes a distortion with a symmetry different from the symmetry of the lattice. It may also apply for pairs of solute atoms[4] or pairs of vacancies. A more general case is an alloy where the lattice dimensions depend on the degree of short-range order.[5] Here the degree of short-range order changes in the stress field of the dislocation. Since in all these processes only atomic interchanges between neighboring lattice sites are necessary, they take place in a relative short time.

Let us first consider a dislocation at rest. In its stress field a redistribution of solute atoms may take place by single atomic jumps with the mean frequency $\bar{\nu}$. With each jump into a preferred lattice position an amount of energy Δu_i is released. Since the stresses around a dislocation decrease with r^{-1} (r being the distance from the dislocation line), Δu_i can be expressed as

$$\Delta u_i = A_i/r, \tag{1}$$

where A_i depends on the solute atom and the special configuration. In typical cases Δu_i is from 0.1 to 0.5 ev at one atomic distance from the dislocation line.

When local thermal equilibrium is reached around the dislocation there are, depending on Δu_i, different numbers of solute atoms in different types of lattice positions. (We consider here only thermal equilibrium with respect to the population of different types of lattice sites and not with respect to the change in concentration around the dislocation since to establish the latter requires a time longer by orders of magnitude.) The total energy of the dislocation is then decreased by

$$U_0 = \sum_i \Delta u_i \tag{2}$$

compared with a dislocation with a random distribution of solute atoms around it.

Since the thermal energy of the lattice tends to randomize the distribution, the ordered atmosphere has a certain "radius" R. This radius is given by the distance at which the thermal energy kT is equal to the energy difference Δu_i, or from Eq. (2) the radius of the atmosphere is

$$R = A_i/kT. \tag{3}$$

If we now move the dislocation through a solid solution where the solute atoms are in a random distribution, this ordering effect produces a dragging force which depends on the velocity v of the dislocation. The dragging force vanishes only at infinitely low velocities where the ordering always reaches thermodynamical equilibrium and at infinitely high velocities, where no redistribution takes place.

The dragging force results from the fact that the "center" of the ordered distribution lags behind the dislocation; and therefore, the dislocation has to move against an energy gradient. A critical velocity v_{cr} is reached when the time for the dislocation to move over the distance of the radius R of the distribution is about the time $1/\bar{\nu}$ to form the ordered distribution[6]

$$v_{cr} \approx \bar{\nu} R. \tag{4}$$

At this velocity the force F to push the dislocation against the energy gradient of its ordered distribution reaches a maximum which is given by

$$F_{cr} \approx \tfrac{1}{2} U_0/R. \tag{5}$$

At higher velocities the dislocation cannot build up an essential ordering and therefore the force drops.

A detailed analysis has been made for the movement of a screw dislocation in α-iron with carbon impurities.[6]

[1] N. F. Mott, *Imperfections in Nearly Perfect Crystals* (John Wiley and Sons, Inc., New York, 1952), p. 173.

[2] A. H. Cottrell and M. A. Jaswon, Proc. Roy. Soc. (London) A199, 104 (1949).

[3] F. R. N. Nabarro, *Conference on the Strength of Solids at the University of Bristol* (The Physical Society, London, 1948), p. 38.

[4] C. Zener, Phys. Rev. 71, 34 (1947).

[5] A. D. LeClaire and W. M. Lomer, Acta Metallurgica 2, 731 (1954).

[6] G. Schoeck, Gordon Conference on Chemistry and Physics of Metals, New Hampton, New Hampshire, 1955 (to be published elsewhere).

At a carbon concentration of 2×10^{-4} the critical velocity is about 20 atomic distances per second at room temperature. The corresponding shear stress to obtain this movement is $\tau_{cr}\approx5\times10^7$ dyne/cm^2 which is about a fifth of the yield strength of iron single crystals.

The effects described above should show up in experiments on internal friction and on microcreep.[7] It might be difficult to detect the described energy dissipation of dislocations in the background of the

[7] B. Chalmers, Proc. Roy. Soc. (London) A156, 427 (1936).

internal friction due to the external forces. There should be, however, a pronounced influence on microcreep. At stresses below τ_{cr} the dislocations can move in typical cases only several atomic distances per second. The corresponding strain rate should be of the order of 10^{-8} sec^{-1}, if we assume a density of moving dislocations of 10^6. Above τ_{cr} the dislocations can move too fast to build up a substantially ordered atmosphere and their velocity is limited by other forces. At τ_{cr}, therefore, a break in creep rate should occur.

Hall Coefficient and Thermoelectric Power of Thorium Metal*

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The Hall coefficient of two samples of thorium metal was measured at room temperature in magnetic fields on the order of 4000 gauss, and an average value of -1.2×10^{-11} volt-cm/abampere gauss obtained. The voltage of a thorium-platinum thermocouple in the temperature range 400°C to 1100°C is also reported.

MEASUREMENT of the Hall coefficient of thorium metal at room temperature was performed on two samples of rolled sheet of nominal thickness two and five mils, obtained from A. O. Mackay, Inc. Hall specimens of approximately $\frac{3}{8}$-inch width and $2\frac{1}{2}$-inch length, with an attached potential probe on the midpoints of each of the long sides, were cut from the sheet so that as the Hall current passed longitudinally through the specimen these probes were on an approximate equipotential. These probes were about $\frac{1}{32}$ in. wide at the junction with the side of the specimen and $\frac{3}{8}$ in. long. Each end of the specimen and the Hall probes were held between separate pairs of brass jaws, the latter mounted on a lucite plate and the entire assembly thermally shielded from air currents. The assembly was mounted between the poles of an electromagnet capable of producing fields of the order of 4000 gauss. Hall currents of the order of 5 amperes were passed through the specimen, and readings were taken of the change in probe potential difference as the magnetic field was applied and then reversed. The Hall voltage changes were measured by a null method using a galvanometer of sensitivity 7.7×10^{-11} amp/mm and resistance 600 ohms, the "bucking" potential being supplied and measured by a battery and a calibrated voltage divider. The results obtained are shown in Table I. According to the simple theory of the Hall coefficient of metals,

TABLE I. Hall coefficient of thorium.

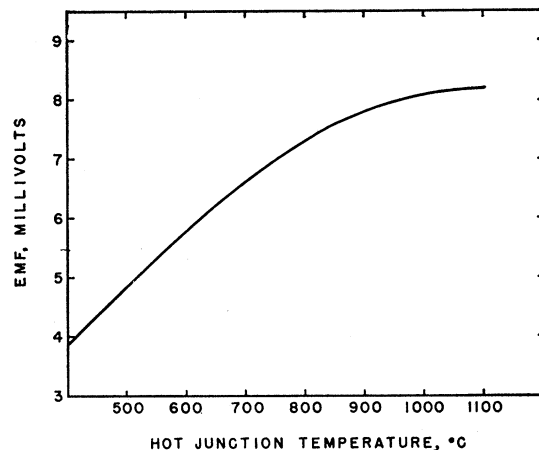| Specimen No.	Specimen thickness, mils	Hall current range, amp	Magnetic field range, gauss	R_H Hall coefficient, volt cm/abamp gauss
1	2.9	4–5	3700–4500	-1.3×10^{-11}
2	5.2	4–5	3700–4500	-1.1×10^{-11}

FIG. 1. Emf vs junction temperature. Thorium-platinum thermocouple with 0°C cold junction. Th positive with respect to Pt.

these results indicate conduction in thorium by electrons with a carrier density of approximately 4.7×10^{22} per cc or 1.6 electrons per atom at room temperature. The variation in R_H between the two specimens, exceeding the standard deviations of either specimen, may well be due to differences in past histories of the specimens.

A "triple" theormocouple of platinum, platinum-10% rhodium, and thorium was constructed, the thorium wire being strips of the nominal 5-mil sheet spot-welded end to end. This was placed in a thoria insulating cylinder in the heating coil of a vacuum furnace, with the three wires running out through a teflon plug into an ice bath. The resultant emf generated by the thorium-platinum thermocouple (measured with a Beckman portable potentiometer) as a function of the junction temperature, measured by the platinum and platinum-rhodium thermocouple, in the 400°C to 1100°C range, is shown in Fig. 1.