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The motion and dynamic interaction of dislocations in lithium and sodium

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In-situ transmission electron microscopy observations have been made of the motion and interaction of dislocations in lithium. Under a thermally induced stress, dislocation segments observed at room temperature are often seen to bow out in a manner consistent with the shapes of dislocations predicted by anisotropic elasticity calculations of the dislocation line tension. Both attractive and repulsive dislocation interactions have been observed, lending further support to the importance of forest dislocation intersection as the rate controlling mechanism to dislocation motion above one fifth of the absolute melting temperature of the alkali metals. The formation of a Saada-type attractive dislocation reaction has been dynamically recorded in lithium. Attractive reactions have also been observed in sodium.

1. Introduction

"Loaded state" dislocation structures of deformed materials are often related to macroscopic mechanical measurements by *in situ* straining experiments in the high-voltage transmission electron microscope or by transmission electron microscopy (TEM) observations of specimens in which the dislocations have been pinned in the loaded state by neutron irradiation [1]. Although the interpretation of results of direct TEM observations is complicated by the influence of surface effects in thin foils [2], and although the pinning of dislocations in the loaded state precludes investigation of dynamic effects, both techniques have contributed significantly to the understanding of the deformation behaviour of materials.

The bcc alkali metal lithium possesses a number of interesting physical properties which make it most attractive as a material for *in situ* studies. In particular, its low atomic number results in high electron transparency. Furthermore, the ability to generate dislocations with the thermal stress gradient induced by the electron beam during the observation of a TEM specimen makes lithium quite amenable to *in situ* experiments. From a crystallographic point of view the motion of dislocations in lithium is interesting, since the geometry of the bcc crystal lattice imposes restrictions on the glide of dislocations. Moreover, the crystal symmetry of the bcc lattice has been shown to have a strong influence on the low-temperature deformation behaviour of the bcc transition elements below a critical temperature, T_k [3], suggesting a similar effect in lithium. In conjunction with the glide restrictions imposed by the glide plane and Burgers vector, elastic anisotropy determines the shape of a dislocation loop [4, 5]. Lithium, which has the highest anisotropy factor, $A = C_{44}/(C_{11} - C_{12})$ of all metals (8.4) is an excellent material in which to establish the effect of elastic anisotropy on dislocation shapes.

The temperature dependence of the dislocation behaviour in lithium and its relation to the measured temperature dependence of the flow stress have been previously considered [6]. It is the objective of this paper to present: (1) examples of dislocation motion and interaction in lithium and in sodium and to compare the dynamically observed dislocation shapes with calculated equilibrium configurations, and (2) further support for recent observations of the importance of forest dislocation cutting as the rate controlling

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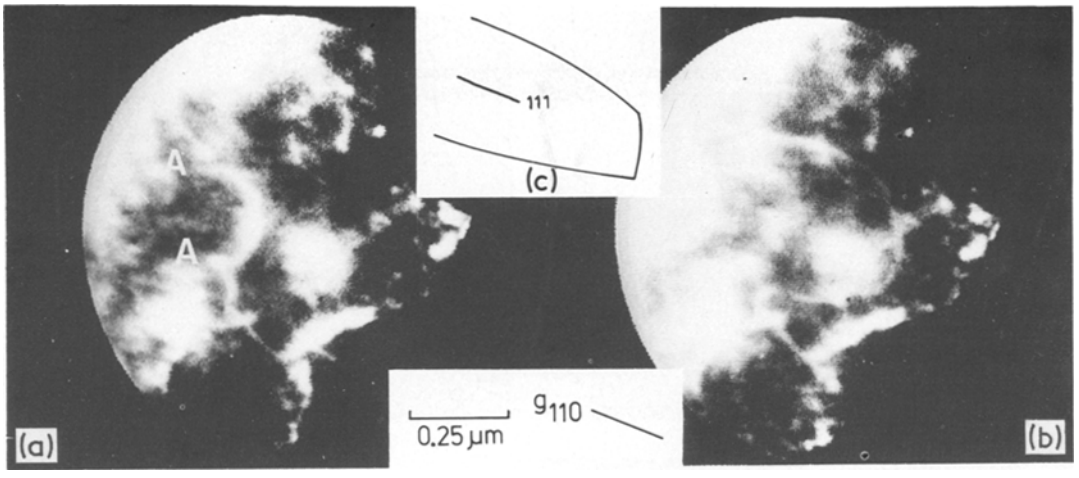

Figure 1 (a) The bowing out of a dislocation half-looped, in lithium, pinned at points labeled A, (b) further bow-out after having overcome the obstacles and (c) calculated equilibrium shape of a dislocation half-loop with an $a[1\,1\,1]/2$ Burgers vector and a $(0\,\bar{1}\,1)$ glide plane [5].

mechanism for plastic deformation above the predicted critical temperature, T_k [3].

2. Experimental technique

TEM specimens of lithium and sodium were prepared by vacuum evaporation, (pressure less than 1×10^{-5} torr) of bulk material onto a carbon coated copper grid (< 10 nm thick carbon film). Transfer of the TEM specimen from the evaporator to a glove box was accomplished under vacuum using a transfer lock. In the glove box, within which a constantly circulating atmosphere of high-purity argon was maintained, the transfer lock was opened and the specimen mounted in a modified Philips liquid nitrogen stage. The modification consisted of a retractable sleeve which provided an enclosure for maintaining an atmosphere of argon around the specimen until the specimen was inserted into the microscope. Once the specimen passed through the air-lock of the goniometer, two forks attached to the goniometer retracted the sleeve, exposing the specimen to high vacuum.

TEM of lithium and sodium was performed at room temperature using a Philips EM300 TEM operated at 80 kV. All TEM images were recorded using two-beam conditions in the dark-field mode. During observation of lithium and sodium, it was observed that dislocations are continuously generated and their motion activated by the thermal stress induced by the electron beam. The dynamic recording of dislocation movement in lithium was accomplished using a Philips magnetic tape/video recording system with the aid of a TV camera and image intensifying unit. Micrographs of the dislocations in sodium were taken only using conventional plate techniques.

3. Results and discussion

A micrograph of a bowed-out dislocation half-loop observed at room temperature in lithium is presented in Fig. 1. The initial stage of the bow-out process is shown in Fig. 1a while a later stage is shown in Fig. 1b. In the (001) pole used for the above observations, the projection of the ⟨1 1 1⟩-type directions onto the (001) plane are parallel to the ⟨1 1 0⟩-type directions, so that dislocations with $a\langle 1\,1\,1\rangle/2$-type Burgers vector lying parallel to the ⟨1 1 0⟩ direction must be screw in character. Therefore, it is seen that the half-loop bows out in the screw direction with the leading segment primarily edge in character.

The nature of the obstacles, labeled A in Fig. 1a, which impede the motion of the bowing dislocation, was not determined. For the case of two intersecting forest dislocations, where the line tension of the gliding and forest dislocations are similar, the bow-out angle at which the dislocations cut through one another is expected to be only a few degrees [7]. In an anisotropic material such as lithium, the line tension of $a\langle 1\,1\,1\rangle/2$-type edge dislocations is seven times less than that of the screw dislocations. Also, ranges of orientation with negative line tension exist [5, 6]. Therefore, if a gliding edge encounters a forest dislocation of screw character, the gliding edge should bow out substantially before reaching the critical angle where the two

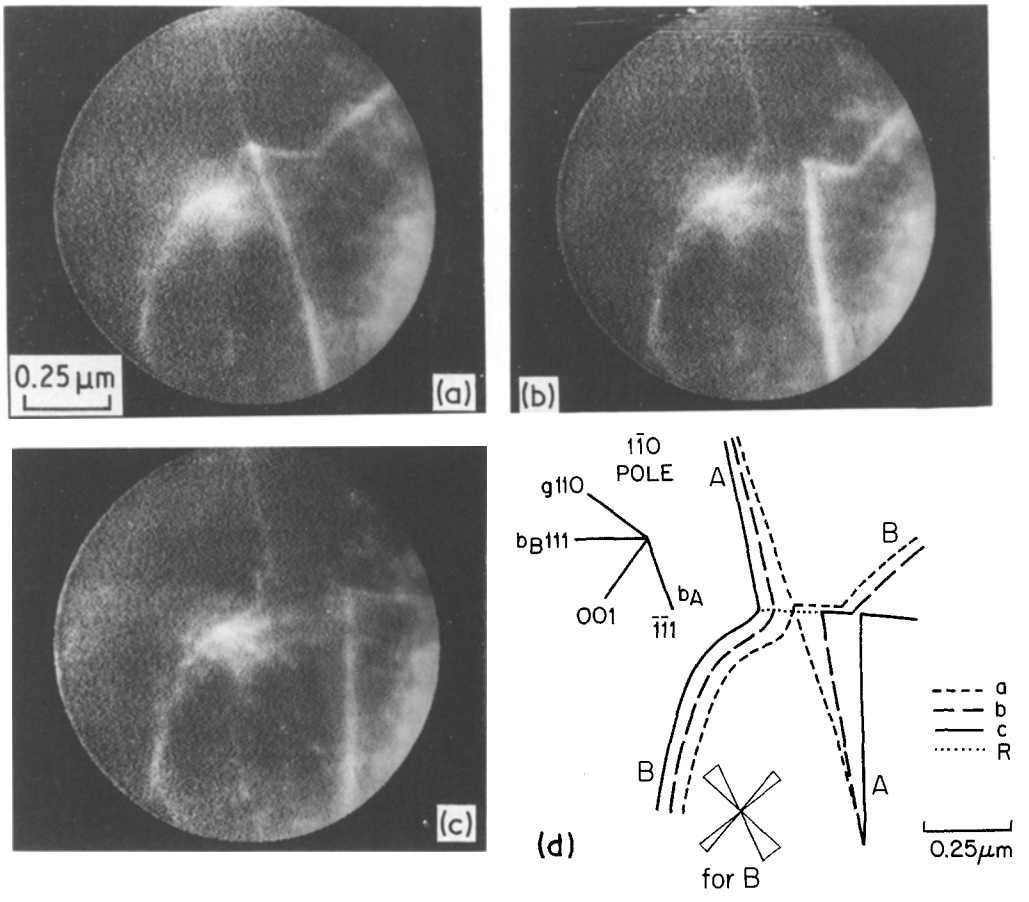

Figure 2 The dynamic formation of a dislocation junction in lithium, (a) dislocations approach one another, (b) two dislocation nodes and the reaction product, R are formed, (c) the reaction proceeds further and (d) a schematic illustration of the intersection of dislocations A and B, the crystallographic orientation of Burgers and g vectors and the regions of negative line tension of dislocation B represented by the open triangles is shown.

dislocations can cut through each other. Such a situation may have occurred in Fig. 1a and b where the bowing dislocation is initially soft due to its edge character, and is able to bow out significantly before overcoming the obstacle. Detailed computer simulations of dislocation intersection processes taking account of elastic anisotropy are yet to be performed.

The calculated shape of a dislocation half-loop with Burgers vector $a[111]/2$ bowing out on the $(\bar{1}01)$ plane is shown in Fig. 1c. Determination of the shape of the dislocation half-loop presented in Fig. 1c was carried out using anisotropic elasticity theory to calculate the line energy and tension [5]. The shape of the dynamically observed loop shown in Fig. 1b apparently tends to adopt the equilibrium shape, reducing the stored elastic free energy. The ratio of the screw to edge axial lengths of the half-loop presented in Fig. 1b (taking into account the 45° tilt of the loop with respect to the foil surface) is approximately 2.6 while that of the calculated loop in Fig. 1c is 2.9. The elongated shape arises from the high ratio of screw to edge line tension.

Comparison of dynamically expanding and theoretically calculated equilibrium, dislocation loop shapes in lithium must be undertaken with caution since the screw segments of the former may be influenced by the Peierls stress while the latter is controlled by elastic anisotropy. Statistically-evaluated dislocation configurations [6] and mechanical deformation experiments [8] above $0.2T_m$ in lithium indicate that the influence of a Peierls stress, which, below $0.2T_m$ gives rise to a double kink mechanism of screw dislocation motion in the bcc transition elements, is small compared to the strength of the forces due to elastic anisotropy. The relatively good agree-

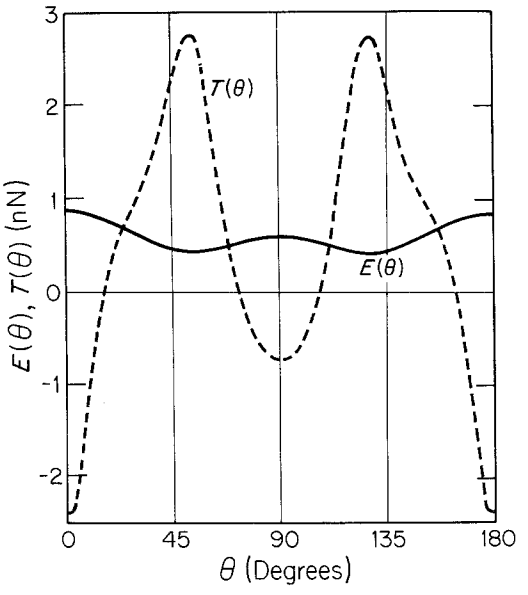

Figure 3 Line energy, $E(\theta)$, and line tension, $T(\theta)$ as a function of orientation, θ for a dislocation, in lithium, with a Burgers vector $a[0\,0\,1]$ and glide plane of $(1\,\bar{1}\,0)$. The calculations have been performed using an ANCALC-type computer program [9].

ment between the dynamic and equilibrium shapes presented in Fig. 1 suggests that it is reasonable to compare the two conditions.

A sequence of TEM micrographs showing the attractive interaction of two dislocations in lithium observed at room temperature is presented in Fig. 2a, b and c. The dislocations were observed using a $(1\,\bar{1}\,0)$ pole. An analysis of dislocation movement and the orientations of negative line tension (shown in the open triangles) are presented in Fig. 2d. For $a\langle 1\,1\,1\rangle/2$ glide dislocations on $\{1\,1\,0\}$-type glide planes, the orientation ranges having negative line tension are $41° \leqslant \theta \leqslant 55°$ and $119° \leqslant \theta \leqslant 144°$ (θ is the angle between the Burgers vector and the dislocation line measured in the anticlockwise direction) [5]. From the geometry of the diffracting condition the dislocations may be shown to form the following attractive dislocation reaction product:

$$a[\bar{1}\,\bar{1}\,1]/2 + a[1\,1\,1]/2 = a[0\,0\,1]. \quad (1)$$

Since dislocation A is parallel to $[\bar{1}\,\bar{1}\,1]$, it is screw in character and remains straight during the reaction process, a consequence of the high line tension of screw dislocations. Dislocation B is mixed in character. The reaction causes one part of dislocation B to adopt a screw character while the other remains mixed in character. It is seen that the majority of the dislocation orientations of dislocation B are within the orientation ranges having positive line tension. The Burgers vector of the dislocation reaction product is perpendicular to the diffraction vector, and therefore the dislocation does not exhibit contrast.

The stability of a [001] reaction product against gliding conservatively on the $(1\,\bar{1}\,0)$ plane has been considered. The line energy $E(\theta)$ and line tension $T(\theta)$ for lithium have been calculated as a function of the dislocation character, θ; these results are shown in Fig. 3. As seen from Fig. 2, the reaction product is formed along the [1 1 1] line of intersection, and the dislocation line is orientated 55° to the Burgers vector. Fig. 3 shows that $a[0\,0\,1]$ dislocations with a 55° character have a minimum line energy and maximum line tension. Consequently, in lithium 55°, $a[0\,0\,1]$ dislocations are regarded as stable reaction products, and obstacles to dislocation motion on $\{1\,1\,0\}$ planes.

TEM observations of dislocation motion in sodium, which has a level of elastic anisotropy similar to, and mechanical deformation behaviour reminiscent of, lithium have been made in the temperature range 95 to 300 K (0.21 to $0.65T/T_M$). An example of an attractive junction observed in sodium at room temperature is presented in Fig. 4. The behaviour of dislocations in sodium is seen to be similar to that in lithium where, above T_k, elastic anisotropy controls the shape of dislocation configurations, resulting in dislocation loops elongated in the screw direction: a consequence of the high line tension of screw dislocations. The presence of screw dislocations in Fig. 4, a result of the influence of elastic anisotropy, should not be confused with the effects of a Peierls friction stress, which predominates below $0.2T_k$ in the bcc transition elements and results in long straight screw dislocations (~5 to 10 μm long) during *in situ* deformation experiments [10] in the high-voltage electron microscope.

Indications that forest dislocation intersection is the rate controlling mechanism to the motion of dislocations in lithium and sodium above the predicted temperature, $T_k \sim 0.2T_M$, have been given by mechanical measurements of activation volumes (2000 to $20\,000b^3$) [8, 10] and the measured temperature dependence of the dislocation segment lengths [6]. Further support is given by the validity of Cottrell–Stokes law in lithium single crystals.

The present observations provide direct evi-

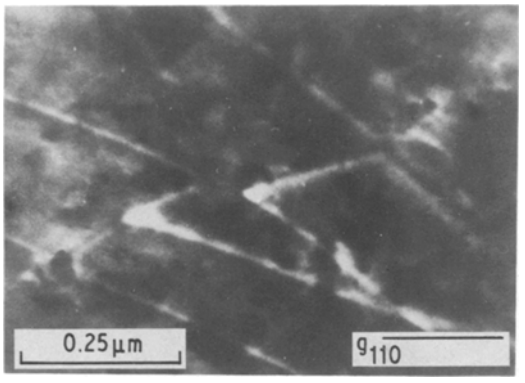

Figure 4 An attractive junction observed in sodium.

dence of local dislocation interactions in lithium and sodium. In the bcc transition elements, below the critical temperature, T_k, *in situ* observations of long straight screw dislocations demonstrate the importance of the Peierls friction stress, while above T_k, the general behaviour of dislocations has been found to be similar to that in fcc metals [10] and, aside from the influence of the high elastic anisotropy in lithium and sodium, also similar to that in our observations.

4. Conclusion

The motion and dynamic interaction of dislocations in lithium and sodium have been observed. The observed dynamic dislocation half-loops in lithium tend to adopt shapes as predicted by calculations of equilibrium half-loop shapes. The observed attractive and repulsive dislocation interactions in lithium and sodium support previous suggestions that forest dislocation intersection determines the rate of dislocation motion above one fifth of the absolute melting temperature of these materials.

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