VOLUME 44, NUMBER 14 PHYSICAL REVIEW LETTERS 7 APRIL 1980

Influence of Dislocation Drag on Twinning in Zinc

L. Motowidlo, P. Goldman, B. Yalamanchi, and J. M. Galligan
Department of Metallurgy and Institute of Materials Science, University of Connecticut, Storrs, Connecticut 06268

(Received 7 December 1979)

This paper presents measurements of the influence of magnetic fields on the plastic deformation of zinc. In particular it is shown that both slip processes and twinning are affected by the presence or absence of magnetic fields. Furthermore, it is shown that the motion of dislocations is required for twinning and that twinning can be altered through a change in magnetic field which determines the dislocation velocity. These results are explained by treating the dislocations as underdamped oscillators.

PACS numbers: 62.20.Fe, 61.70.Le

The interaction of mobile dislocations with the electrons of a metal has been previously studied in the case of a number of face-centered cubic metals[1,2] by varying the magnetic field, H, while the dislocations move. The previous observations in copper and aluminum show that the change in stress, $\Delta\sigma$, for a change in magnetic field of ~0.6 T, is relatively small, but measurable. Such changes in stress with changes in magnetic field are the result of a change in coupling between the mobile dislocations and the electrons. An increased coupling of the dislocations and the electrons, with increasing magnetic field, is a consequence of the fact that electrons in a magnetic field follow a helical path, thereby increasing the electron-dislocation interaction. In the present study we show that $\Delta\sigma$, in the case of zinc crystals, is a much more readily measurable quantity and amounts to as much as 3% of the stress for plastic deformation. Furthermore, we show experimentally that twinning of crystals can be related to elementary drag mechanisms. For this purpose we have chosen zinc crystals since this metal can be deformed on a single slip system without the complication of intersecting slip planes, such as occurs in face-centered cubic metals.

The experiments were carried out on zinc crystals grown from 99.999% pure zinc by a standard Bridgman method, with the orientation of the basal planes at ~ 45° to the tensile axis, and at roughly 90° to the tensile axis. The experiment is first undertaken on the zinc crystals with slip planes at 45° to the tensile axis and is carried out as follows: While the crystals are deforming, either plastically or elastically, we switch a magnetic field on or off. [The temperature throughout the experiment is measured to be 4.2 K with a calibrated Ge(Li) thermometer.] As a result of the change in field we see a change in stress, but only when the crystal is deformed plastically, Fig. 1. When we see a change in stress with field, it is associated with the following conditions: (a) The change in stress is fully reversible with magnetic field. (b) The change in stress is independent of the rate of change of field, at the limit of the present apparatus — ~0.6 T in 0.01 sec and 0.6 T in ~10 sec. (c) The measured homogeneity of the magnetic field in the volume in which the specimen, the grips, and the pulling tabs are contained is roughly one part in a thousand.

These conditions show that the change in stress is related solely to the motion of dislocations. In contrast to these results we have also deformed a zinc crystal with its basal planes at 90° to the tensile axis. In this case the elastic deformation

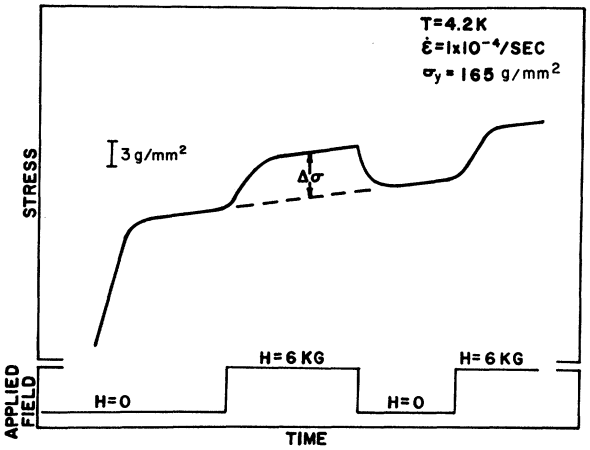

FIG. 1. The change in stress, with change in magnetic field, for a zinc crystal, while deforming at an applied strain rate of 1.2×10^{-4}/sec. Note that the change in stress in this case is, roughly, 2–3% of the stress at yielding; in this case the slip planes are at 45° to the tensile axis. Note also that the change in stress is composed of a transient and a steady-state change in stress. The steady-state change in stress rules out a heating effect.

range, in terms of stress, is very large compared to the case when the slip planes are at 45° to the tensile axis. As a result we can deform the sample to stresses well above those used in the crystals where slip is favored, without plastic deformation, and see what happens to the stress when we switch the magnetic field on or off. The results of this experiment are shown in Fig. 2 and, as shown, it is quite clear that no change in stress is observed when we change the magnetic field. This result shows that dislocations must be moving for a magnetic field to affect the stress. In addition, this observation, in conjunction with the results shown in Fig. 1, demonstrates that we are measuring the electron drag on mobile dislocations.

But the technique tells us more than that and shows that twinning can be related to dislocation drag mechanisms. This is shown, for example, by the observation that when we decrease the magnetic field, which decreases the drag on the mobile dislocations and, in turn, increases the dislocation velocity, then there is an *increase in twinning*, Fig. 3. The observed twinning events were associated with a rapid load drop which occurred shortly after the magnetic field was switched off, Fig. 3. Along with these load drops, one could frequently hear an audible click, which is characteristic of twinning.[3]

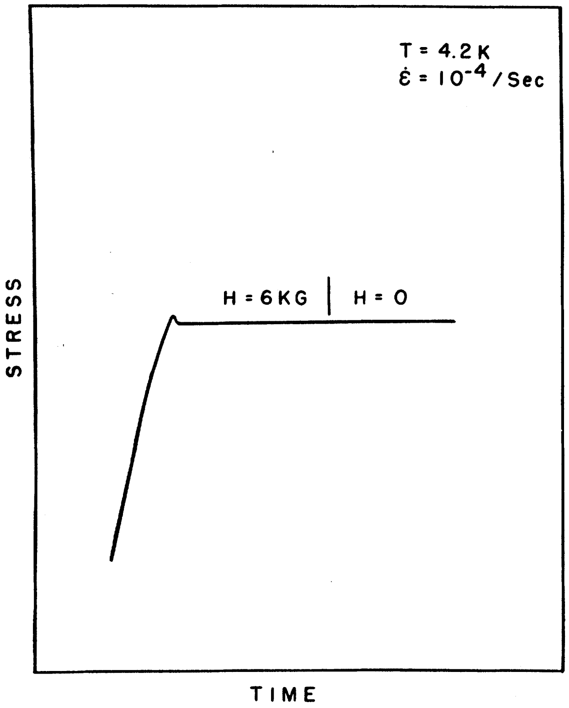

FIG. 2. The change in stress with change in magnetic field for a zinc crystal. In this case the crystal is defromed elastically, deformation stopped, and the machine allowed to relax, after which the field is switched on or off. Note that there is no observed change in stress when the field is switched. In this case the crystal is oriented such that the slip planes are at ~90° to the tensile axis and the resolved shear stress on the slip planes is close to zero.

The effect of a magnetic field on twinning was tested on five zinc crystals all in the easy glide orientation. The only distinguishing feature among these crystals was the amount of prestraining they received. For example, the data shown in Fig. 1 are from a crystal which received considerable room-temperature prestraining as indicated by its high yield strength. Prestraining at room temperature is known to reduce the occurrence of twinning,[3] and, in accordance with this fact, no significant twinning events were observed in this crystal, regardless of whether the magnetic field was on or off. Contrary to this, in those samples with little or no prestraining, twinning events, when they occurred, took place *after* the field was decreased. This observation refers to more than 90% of the twinning events. It is worthwhile emphasizing in this regard that the increased twinning occurs with a decreasing stress which, again, indicates that dislocation

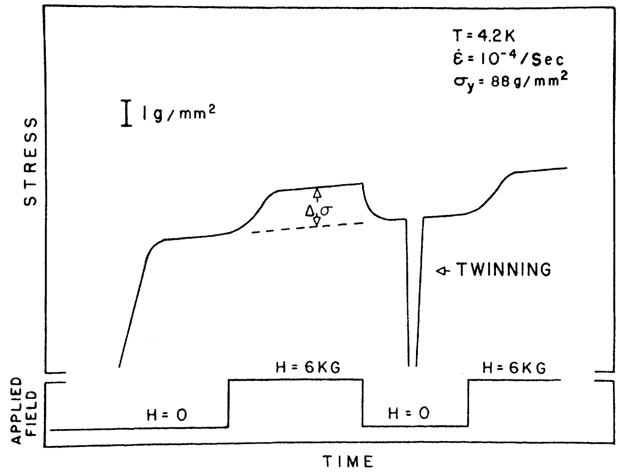

FIG. 3. The influence of a change on magnetic field in the process of mechanical twinning in zinc crystals. Notice that when the field is switched off twinning is observed, but twinning is not observed when the field is switched on. Twinning is observed, generally, after the crystals have been deformed extensively. In this case the crystals were oriented with the slip plane at 45° to the tensile axis.

velocities are involved.

The experimental results show that a magnetic field changes the electron drag on mobile dislocations to a very significant extent and that by altering the electron drag the process of mechanical twinning is altered. These results can be readily explained by recognizing that a portion of the dislocations move as underdamped oscillators, since in the case of an underdamped oscillators, since in the case of an underdamped oscillator,[2] the change in stress $\Delta\sigma$ should be related to the drag coefficient B_e as

$$\Delta\sigma = \mathrm{const}[U - kT\ln(\dot{\epsilon}_0/\dot{\epsilon})] \times [B_e(H) - B_e(0)],$$

where U is the barrier height a dislocation is up against, $B_e(H)$ is the drag for a field H, $B_e(0)$ is the drag at zero field, $\dot{\epsilon}_0$ is a constant, $\dot{\epsilon}$ is the applied strain rate, T is the temperature, and k is Boltzmann's constant. The fact that the electron drag is altered by a magnetic field has two major consequences as far as twinning is concerned. The first consequence, which is again related to the dislocations moving as underdamped oscillators, is that mobile dislocations may break through barriers without thermal activation. This means that dislocations may attain velocities that they might not have reached if this motion is treated as overdamped oscillator. Secondly, if they reach high velocities, then the interaction of the mobile dislocations with the forest dislocations is reduced.[4]

As suggested above, the reduction of the interaction of the mobile dislocations with the forest dislocations is a necessity for twinning to take place, since high-velocity dislocations are required for the process of twinning to occur.[3] This naturally leads to the question of just what velocities are needed for twinning to occur. In the treatment given by Venables[4] the reduction of the interaction between mobile dislocations and forest dislocations occurs when the dislocation velocity, V, reaches 30% of the velocity of the shear wave, V_c. This suggests that the drag coefficient, B_e, is given as[5,6]

$$B_e = \frac{b\sigma}{V} = \frac{b\sigma}{0.3V_c},$$

which results in a value of B_e equal to 3×10^{-6} dyn sec/cm^2 for the conditions where $\sigma = 10^7$ dyn/cm^2, $b = 2.6\times10^{-8}$ cm, and $V_c = 2\times10^5$ cm/sec, where σ is the stress and b is the Burgers vector for the zinc. We can also check this value of B_e by recalling that the condition under which a dislocation moves as an underdamped oscillator is given[5,6] as

$$B_e^2 < \frac{4\pi AC}{L^2},$$

where A is a constant related to the effective mass of the dislocation, C is a constant related to the shear modulus of the material, and L is the spacing between dislocations. This latter condition is satisfied readily for dislocation densities of 10^6/cm^2 or greater; these dislocation densities correspond to those found in deformed crystals.

In summary, we have shown that with changes in magnetic field of 0.6 T, the flow stress of zinc is changed by ~ 2–3%. Furthermore, twinning is enhanced by a decreasing magnetic field while it is much less likely to occur in an increasing magnetic field. These results are shown to be consistent with dislocations moving, in part, as underdamped oscillators.

This research has been sponsored by the U. S. Department of Energy, through the Materials Science program of the Basic Energy Studies Division. We appreciate the initial contribution of Larry Masur.

---

[1] J. M. Galligan, T. H. Lin, and C. S. Pang, Phys. Rev. Lett. 38, 405 (1977).

[2] J. M. Galligan and C. S. Pang, J. Appl. Phys. 50, 6253 (1979).

[3] D. A. Wigley, *Mechanical Properties of Materials at Low Temperatures* (Plenum, New York, 1971).

[4] J. Venables, Philos. Mag. 10, 771 (1964).

[5] A. V. Granato, Phys. Rev. B 4, 2196 (1971).

[6] M. Suenaga and J. M. Galligan, *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1972), Vol. 9, p. 1.