Effect of Twinning on the Amplitude-Dependent Internal Friction in Tin Crystals

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Abstract. Amplitude-dependent internal friction is measured on white tin single crystals to observe the change with the formation of mechanical twins. The material used is 99.9% pure, and the measurements are made by the transverse vibration method. After twinning, the internal friction, amplitude-independent at low amplitudes, rapidly increases above a breakpoint and then steeply increases as the driving force is increased. Above the breakpoint, the internal friction measured during the free decay is much higher than that measured before with increasing amplitude. The stress amplitude at which the internal friction steeply increases is independent of temperature, within the range observed, between 25°C and 80°C. It is also observed that above the breakpoint the internal friction increases with the time of excitation and decreases with the time of rest after the excitation. The results are interpreted in terms of the multiple-pole mechanism of twin dislocation discussed before. The high internal friction observed is due to the annihilation of twin dislocation loops of opposite signs, which sweep every twin layer at high speeds

1. INTRODUCTION

Mechanical twinning of crystals such as tin and zinc takes place in three stages; the nucleation of a small twin under the influence of local stresses, the propagation of wedge shaped twin across the crystal and the thickening which is caused by the migration of twin boundaries in the direction normal to the twin plane. Thompson and Millard [1] proposed a mechanism for the thickening that the twin dislocation in cadmium crystals may be generated when the major dislocation, with the Burgers vector equal to c , crosses the twin boundary and that the twin dislocation thus formed will rotate about the major dislocation, leading to the thickening of the twin.

In the case of white tin crystals, Ishii and Kiho [2] later showed that all the steps caused in the twin boundary by the passage of slip dislocations are composed of twin dislocations. The step will be formed between a pair of the pole dislocation of opposite signs. The stress needed for the step to bow out and move in the twin boundary was then estimated and compared with the data for the migration. In the case of tin crystals, it takes place at low stresses of about 0.1 kg/mm² either by impact [3] or by steady [4] loading, so long as it is not disturbed by the preceding slip.

In the present study, the amplitude-dependent internal friction is measured on white tin crystals to study the dynamical behaviour of twin dislocation. Mason et al. [5] made an ultrasonic observation of twinning in tin, and interpreted the result to be due to the motion of twin dislocation approaching the velocity of sound. Chalmers [6] early measured the energy absorption of twinning in tin, using a set of ballistic pendulums. With a refinement of his method, Kiho and Ishii [7] observed a high energy absorption for the migration. These former results suggest that for the migration of twin boundary a high energy absorption, and accordingly a high internal friction, will take place in an appropriate range of stress amplitude, while the twin dislocation moves at high velocities.

2. EXPERIMENTAL PROCEDURE

White tin single crystals, 3.6 mm in diameter and 80 mm long, were grown from the melt of 99.9% pure tin. The orientation is arranged so that the maximum shear stress is applied on the (301) twinning plane in the [103] direction under transverse vibration: both the [001] axis and the [100] axis lie in the same plane with the specimen axis, and the angle between the [103] direction and the specimen axis is 45° . After the growth, the specimen was overnight annealed at 80°C . To observe the effect of twinning, a number of thin twin layers were formed near the middle part of the specimen by falling it lightly on an iron block.

The internal friction was measured by the transverse vibration method. After the specimen was excited at each amplitude of excitation, the amplitude-dependent internal friction was measured during the free decay. It is known in metals such as aluminium [8] and tin [9] that the magnitude of amplitude-dependent internal friction depends upon the speed with which the measurements are made. In the present study, the measurements were made in such a way that each measurement was taken after the specimen had been excited for 30 seconds, rested for 30 seconds after the free decay and then excited at a higher amplitude, etc.

3. EXPERIMENTAL RESULTS

Figure 1: Decrement vs. tensile-stress amplitude for a white tin crystal measured a) at 25°C and b) at 80°C . Curves A and C show the results obtained before twinning and Curves B and D, after twinning.

Figure 1 shows the decrement vs. amplitude taken with a specimen before and after twinning, at two temperatures, 25°C and 80°C , respectively. In the measurements, the driving force is increased by steps. The open circles represent the decrement at the amplitude of excitation, and the solid circles, those measured during the free decay. The result shows that after twinning the internal friction is displaced to higher values than before, and that the internal friction, amplitude-independent at low amplitudes, becomes amplitude-dependent at a breakpoint (about 100 g/mm^2 in tensile stress, at 25°C) and then steeply increases as the driving force is further increased. It is also shown that above the breakpoint the internal friction measured during the free decay is higher than that measured before as the amplitude is increased by steps. Comparison of the results at the two temperatures shows that the breakpoint is displaced to lower values as the temperature increases but the stress amplitude at which the internal friction steeply increases coincides for the two temperatures.

The internal friction of the twinned crystal is observed to increase with the time of excitation and to decrease with the time of rest after the excitation. In the measurements of the former, the driving force is interrupted at intervals while the excitation is continued and then the decrement is measured. For simplicity of procedure, both the output power and the frequency of the oscillator were kept at constant values, respectively, throughout a set of excitation and rest, and consequently the amplitude of vibration changed to a small extent. Figure 2 shows the results of measurements. The specimen was first excited at an ampli-

Figure 2 : The change in the decrement a) with the time of excitation and b) with the time of rest after the excitation. Curve A shows the result obtained at an amplitude, where little change occurred after the excitation of 600 sec. Curves B, C and D show the results obtained after the driving force is increased by 2 dB, and with the time of excitation of 1, 10 and 600 sec., respectively. Curves E and F show the results after the rest time of 10 and 600 sec., respectively.

tude near the breakpoint (curve A), where little change occurred after the excitation of ten minutes. When the driving force is increased by 2 decibels, the internal friction is observed to increase with the time of excitation. Figure 2 b) shows that the internal friction decreases with the time of rest after the excitation.

4. DISCUSSION

4.1. Amplitude dependence

The result obtained shows that above the breakpoint the internal friction measured during the free decay is higher than that measured before with increasing amplitude. This shows that some irreversible change has occurred during the measurements. The interpretation for this is that the twin dislocation has been anchored by slip dislocation and is released from it under oscillating stresses. The internal friction measured during the free decay will be caused by the twin dislocations which have been released.

As discussed before [2], the twin dislocation will be formed between a pair of screw dislocations cutting through the twin boundary. The critical stress to start the migration is given by

$$\sigma_c = \mu b_t / \ell, \quad (1)$$

where σ_c is the critical stress, μ the modulus of rigidity and b_t the Burgers vector of the twin dislocation. The critical stress is interpreted to be equal to the stress at the breakpoint in the free decay curve. It is about 10 g/mm² as will be read from Fig.1(a). With the values of $b_t = 0.164 \times 10^{-8}$ cm and $\mu = 2 \times 10^{11}$ dyn/cm², a value of $\ell = 3 \times 10^{-4}$ cm is obtained, being a reasonable value for the distance between the forest dislocations.

In the above estimation, each step is assumed to be composed of single segment of twin dislocation, for simplicity. Also, the effect of stacking fault is ignored. It was proposed that the stacking fault will be formed in the twin as a result of twinning [2]. It is because the [001] dislocation in the parent crystal is transformed into the (1/2)[101] partial dislocation in the twin. The stress to form the stacking fault will be a part of the migration stress.

4.2. Origin of the energy loss

Besides the effect of stacking fault, the energy absorption observed can be attributed to the annihilation of twin dislocation. When the stress is applied, the steps distributed in the twin boundary will bow out and expand, interacting with each other. It is noted that the steps will resume the same configuration as before, when the migration has taken place by one twin layer. This means that the stress to keep up the migration is expressed in Eq.(1), as well. Also, this means that the steps expanded have contracted to the initial short steps, which leads to the energy dissipation. An estimation for this is as follows.

Figure 3 shows an example of the motion and interaction of the steps AB and CD. The forest dislocations are taken to be equally spaced at a distance ℓ with alternating signs, and then the steps to be formed in equal distance ℓ . Under applied stress, the steps

Figure 3 : Schematic motion and interaction of twin dislocation loops.

will expand and eventually come into contact. Then the steps will be dissociated and recombined, and the new configuration is the steps AC and BD. In each step, the expansion takes place from a straight segment to a half circle, which is then dissociated to

straight segments. The energy consumed in this process is for unit area,

$$(\pi \ell - 2 \ell) / \ell^2 \times (1/2) \mu b_t^2 \approx 0.6 \mu b_t^2 / \ell, \quad (2)$$

where $(1/2) \mu b_t^2$ is the line energy per unit length of the twin dislocation. The energy loss can be represented in terms of the frictional stress which acts against the motion of twin dislocation. The work w needed to the migration by one twin layer against the frictional stress σ_f is

$$w = b_t \sigma_f, \quad (3)$$

for unit area. If this work is done to expand the loops, then from Eqs.(2) and (3),

$$\sigma_f = 0.6 \mu b_t / \ell = 0.6 \sigma_c. \quad (4)$$

The result shows that the magnitude of frictional stress due to the annihilation is about half the critical stress to start, and to keep up, the migration. This would account for the major part of the high internal friction. The annihilation of twin dislocation would be also responsible for the increase in the amplitude-independent internal friction after twinning, for the twin dislocation will expand and then contract under oscillating stresses, moving fairly large distances up to the length of segment, even below the critical stress.

4.3. Estimation of the velocity of twin dislocation

The migration of twin boundary takes place by one twin layer, when each segment of twin dislocation makes one revolution about the pole dislocation. In other words, the time required for the migration is equal to the time for the revolution. It is expressed in following relation,

$$h / v_m = L / v, \quad (5)$$

where h is the twin layer distance, v_m the velocity of migration, L the distance the twin dislocation moves and v the velocity of twin dislocation. Hence,

$$v_m = (h / L) v, \quad (6)$$

is obtained for the migration velocity. In the case shown in Fig.3, the value of L can be estimated as follows. The middle part of each step moves along a square of side ℓ , and therefore will move a distance 4ℓ in one revolution. With this value of L , and with the values of $\ell = 3 \times 10^{-4}$ cm, $h = 1.66 \times 10^{-8}$ cm, and if it is assumed that the twin dislocation moves at a velocity near the velocity of sound, 1.66×10^5 cm/s, then a value of $v = 2.3$ cm/s is obtained from Eq.(6). This will be a reasonable value in order of magnitude.

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