Journal of Alloys and Compounds, 211/212 (1994) 480–483
JALCOM 142

Non-linear mechanical relaxation associated with the viscous sliding of grain boundaries in aluminium bicrystals

X.S. Guan and T.S. Kê
Laboratory of Internal Friction and Defects in Solids, Institute of Solid State Physics, Academia Sinica, Hefei 230031 (China)

Abstract

The internal friction of high-purity aluminium bicrystals with a [110] symmetric tilt boundary having a misorientation angle of 129.5° was measured with a forced-vibration method. A pronounced internal friction peak (versus temperature) was observed around 200 °C with frequency of vibration about 1 Hz. The activation energy concerned was found to be 0.88 eV. Similar experiments were also performed with bicrystals having misorientation angle 60° and the activation energy was found to be 0.92 eV. An amplitude effect was observed within the temperature range of the internal friction peak. This shows that the relaxation process associated with the grain boundary relaxation of bicrystals is non-linear. It is considered that the basic process associated with the observed internal friction peak is viscous sliding of the boundary, which drags the dislocation substructure in the vicinity of the boundary. This dragging process controls the viscous sliding along the boundary, so that an internal friction peak can appear. However, by virtue of the interaction between the dislocation substructure and the boundary of the bicrystal during the boundary sliding, the controlling action is complicated and the relaxation process exhibits a non-linear behaviour.

1. Introduction

During an extensive study on the classical grain boundary internal friction peak, an internal friction peak situated at a somewhat lower temperature (260 °C) was observed in bamboo-crystalline aluminium specimens [1, 2]. The appearance of an internal friction peak associated with the bamboo boundary is puzzling. In a wire specimen consisting of bamboo crystals, all the bamboo boundaries are perpendicular to the axis of the specimen. No grain edges and corners exist in such a specimen, so that the boundary sliding under torsion (shear) stress should not be blocked, and the sliding should proceed freely, and thus should not give rise to an internal friction peak; the internal friction should increase monotonically with increasing temperature.

Experiments as well as theoretical analysis show that the irregular regions or ledges [3] that may exist along the boundary cannot effectively block the macroscopic viscous sliding of the boundary at high temperatures. Such ledges will be overwhelmed by boundary sliding during the first half-cycle of vibration in internal friction measurement and cannot give rise to a counter-stress so as to recover the original state of the boundary during the opposite half-cycle of vibration. Consequently, the question arises as to what is the factor limiting the relaxation process across the bamboo boundaries. Similarity of the activation energy associated with the fine-grained grain boundary peak and the bamboo boundary peak (1.4 eV) suggests that the mechanism of the relaxation process of the bamboo boundary peak is also viscous sliding along the boundaries, as has been established in the case of fine-grained grain boundaries.

Transmission electron microscopy studies show that a boundary in 99.999 Al coarse-grained polycrystals is intersected by a sub-boundary after a small amount of sliding during creep deformation [4] and dislocation substructures exist in the vicinity of 99.999 aluminium bamboo specimens prepared by successive high-temperature annealing of heavily cold-rolled sheets [5]. As such, we can consider that the basic process associated with the bamboo boundary peak is viscous sliding of the boundary dragging the dislocation substructure (dislocation network) that exists in the vicinity of the boundary. This dragging process controls the viscous sliding along the boundary so that an internal friction peak can appear. However, as the dislocation in the substructure can move during the boundary dragging, the limiting action exerted by the dislocation substructure is itself a relaxation type instead of purely elastic as offered by the grain edges and corners.

The present experiment is performed with bicrystals that contain only one large boundary, with the purpose of giving a definite answer to this question.

0925-8388/94/$07.00
SSDI 0925-8388(94)00142-Y

2. Experimental procedure

The aluminium bicrystals with [110] symmetric tilt boundary were prepared by the Bridgman method in the Institute of Metal Research, Academia Sinica, Shenyang. The raw material used was 99.999 aluminium produced by Fushun Aluminium Plant of China. The aluminium bicrystal as received is shown in Fig. 1(a). Sheet specimens were cut along the orientation line of this raw bicrystal. After polishing treatments, the specimens were soaked in a solution of 50% HCl + 47% HNO_3 + 3%HF for surface cleaning. The final size of the specimen is $47.8 \times 3.7 \times 1$ mm^3. This sheet specimen was clamped on both ends as shown in Fig. 1(b). The boundary of the bicrystal is situated in the middle portion of the specimen and the boundary area is quite large (1×47.8 mm^2). However, the clamps are gripped on the plane of the width of the specimen, so that when the specimen is twisted at the upper end with the lower end fixed during internal friction measurements, as shown in Fig. 1(c), the boundary will be subjected to a normal stress perpendicular to the boundary plane as well as to a torsional stress. It is the applied torsional stress that gives rise to the observed internal friction.

The internal friction was measured with an inverted torsion pendulum controlled by an IBM PC computer and an 8087 processor, and the data can be processed in real time. The range of the maximum excitation torsional strain amplitude used in the present experiment is 3×10^{-6} to 4.5×10^{-5}. The internal friction was measured by forced-vibration method and the resolution in internal friction measurement is 1×10^{-4}.

The aluminium bicrystal specimen was annealed *in situ* in the torsion apparatus at 350 °C for 2 h and internal friction measurements were taken at ascending and descending temperatures with constant excitation strain amplitude. Internal friction was also measured as a function of strain amplitude within the temperature region of the internal friction peak (versus temperature).

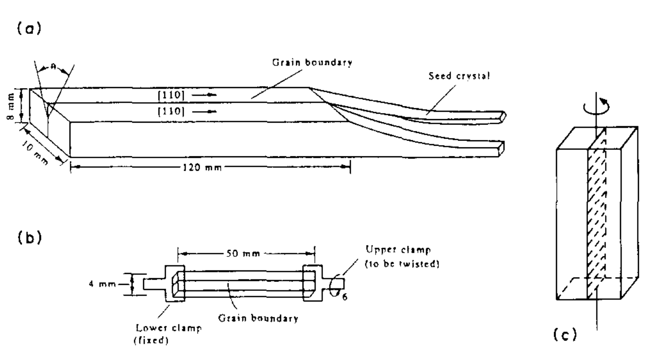

Fig. 1.(a) The as-received aluminium bicrystal; (b) specimen used in internal friction measurement; (c) torsional stress applied to the specimen.

The activation energy concerned was determined by the method of changing frequency.

3. Experimental results

For the aluminium bicrystal with misorientation angle 129.5°, an internal friction peak (versus temperature) was observed around 200 °C when the frequency of the applied periodic stress was 1 Hz, as shown in Fig. 2. The maximum excitation strain amplitude is 1×10^{-5}. This peak was absent for single-crystal aluminium specimens cut from the same raw bicrystal without containing the boundary. Accordingly, the peak observed is connected with the processes taking place around the boundary region.

Internal friction was measured with frequencies 1.5, 0.483, 0.155 and 0.05 Hz respectively, and the peak temperatures of the corresponding internal friction peaks are 210, 188, 175 and 152 °C, as shown in Fig. 3. The procedure adopted is as follows. At each temperature, the internal friction was measured successively with the four frequencies mentioned above. The tem-

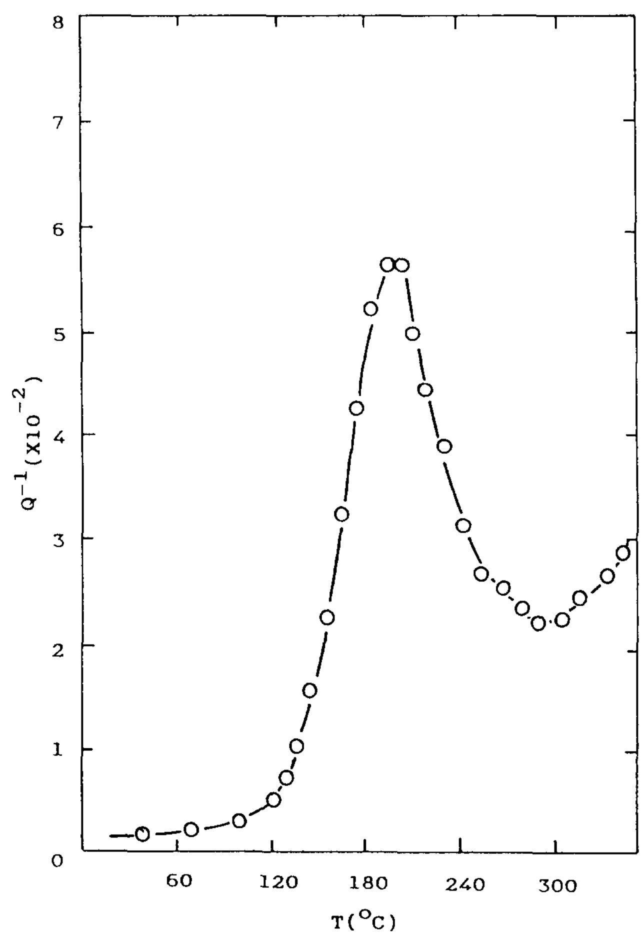

Fig. 2. Internal friction peak (versus temperature) of Al bicrystal with misorientation angle 129.5°. $f = 1$ Hz, $A_\epsilon = 1 \times 10^{-5}$.

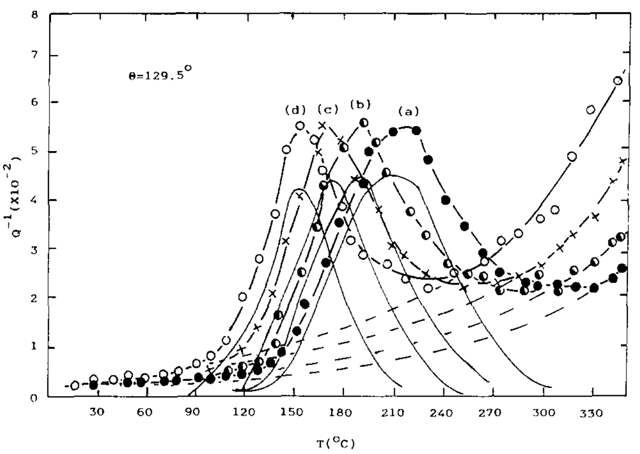

Fig. 3. Internal friction peaks of Al bicrystal with misorientation angle 129.5°, measured with frequencies: (a) 1.5, (b) 0.483, (c) 0.155, (d) 0.05 Hz. $f=1$ Hz, $A_\varepsilon=1\times10^{-5}$.

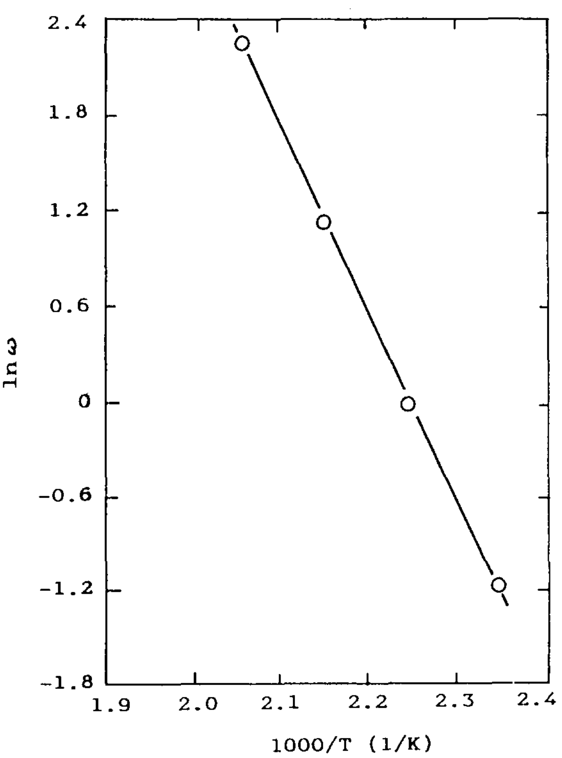

Fig. 4. The Arrhenius plot from the data shown in Fig. 3.

perature range covered was from 350 °C down to room temperature and the measurements were taken at descending and ascending temperatures. With the high-temperature internal friction background subtracted, assuming that it obeys an exponential relationship, we get the bare internal friction curves as shown in the figure. The Arrhenius plot obtained from these data is shown in Fig. 4. The activation energy thus determined is 0.88 eV with $\tau_0\approx7\times10^{-9}$ s.

Similar experiments were performed with aluminium bicrystals of misorientation angle 60°. An internal friction peak (versus temperature) was observed around

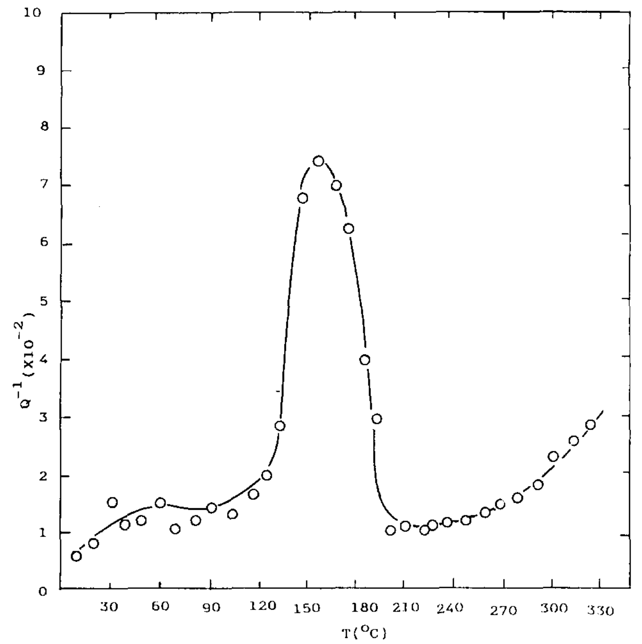

Fig. 5. Internal friction peak (versus temperature) of Al bicrystal with misorientation angle 60°. $f=1$ Hz, $A_\varepsilon=1\times10^{-5}$.

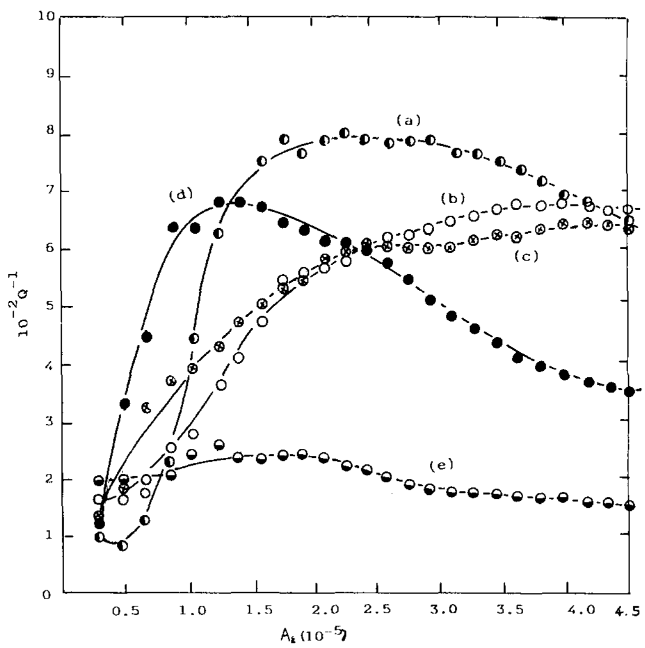

Fig. 6. Internal friction peaks (versus strain amplitude) of Al bicrystal with misorientation angle 60° measured at several temperatures within the temperature range of the internal friction peak shown in Fig. 5: (a) 55, (b) 105, (c) 128, (d) 188, (e) 247 °C.

160 °C, as shown in Fig. 5. The activation energy determined by measurements with various frequencies is 0.92 eV and $\tau_0\approx1.87\times10^{-10}$ s.

The internal friction peak described above was found to exhibit normal and anomalous amplitude-dependent effects. The internal friction peaks (versus strain amplitude) for several temperature points within the temperature range of the internal friction peak (versus temperature) for the 60° specimen are shown in Fig. 6. It is seen that the amplitude internal friction peak shifts to lower strain amplitude with an increase of the temperature of measurement. The amplitude-dependent effect exhibited by the internal friction peak of the 129.5° bicrystal is less pronounced than that for the 60° bicrystal.

4. Discussions

Experiments with aluminium bicrystals of misorientation angle 129.5° and 60° both showed the appearance of an internal friction peak (versus temperature) attributed to the presence of the boundary in the bicrystal. These results consolidated the finding in the case of aluminium specimens consisting of bamboo boundaries. In the case of bamboo crystalline specimens, we have proposed that the constraints limiting viscous sliding along the bamboo boundaries are the dislocation substructures that exist in the vicinity of the boundary [2, 6]. In answering the question concerning the appearance of an internal friction peak versus temperature in bicrystals, we tend to adhere to the same concept as adopted in the case of bamboo-crystalline specimens. It is conceivable that dislocation substructures already exist in the vicinity of the bamboo boundaries during the preparation of the bamboo-crystalline specimen by the method of dynamic strain annealing. The situation is different in the vicinity of the grain boundaries in fine-grained polycrystalline specimens prepared by annealing heavily cold-worked specimens to complete recrystallization, although the situation may be similar for bicrystals prepared by the growth of two seed crystals.

As to the appearance of an internal friction peak versus strain amplitude, a simple model may be conceived as follows. It is suggested that the relaxation process is connected with the interaction between the dislocation substructure interacting with the boundary in the bicrystal, and the controlling factor in the rate of the dragging process by the boundary is the promoted climbing of the dislocation segments in the substructures by the excess vacancies produced during the preparation of the bicrystal when the specimen was transformed from the liquid to the solid phase. Some of these vacancies may be trapped and survive during internal friction measurement. The amplitude effect is, thus, originated from the interaction between the jogs on the dislocation during the bowing out (through climbing) of the dislocation segments and the possible shift of the pinning point (the nodes of the dislocation network) at the ends of the dislocation segment under the action of successively higher applied stress or strain amplitude. This model has been adopted for the explanation of the anomalous internal friction peak observed in bamboo crystalline specimens after quenching from an elevated temperature, but not in furnace-cooled specimens [7].

Acknowledgment

This research has been subsidized by National Natural Science Foundation of China (Nr. 59341001).

References

1 T.S. Kê and B.S. Zhang, *Phys. Stat. Sol. (a), 96* (1986) 515.
2 T.S Kê, in T.S. Kê (ed.), *Proc. 9th Int. Conf. on Internal Friction and Ultrasonic Attenuation in Solids, Beijing, July 1989,* Int. Academic Publ., Beijing and Pergamon Press, Oxford, 1990, p. 113.
3 Y. Ogino and Y. Amano, *Trans. Jpn. Inst. Met., 20* (1979) 82.
4 H. Kokawa, T. Watanabe, and S. Krashima, *Phil. Mag., A44* (1981) 1239.
5 A.W. Zhu and T.S. Kê, *Phys. Stat. Sol. (a), 113* (1989) 393.
6 T.S. Kê and B.L. Cheng, *Phys. Stat. Sol. (a), 115* (1989) 119.
7 T.S. Kê, P. Cui and X.S. Guan, *Scr. Metall. Mater., 27* (1992) 1151.