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Amplitude-dependent internal friction in dilute copper–aluminium alloys with three kinds of peaks

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Abstract

Amplitude-dependent internal friction is measured on 99.999% Cu and dilute Cu–Al alloys, annealed and lightly prestrained. The measurements are made with an inverted torsion pendulum, at temperatures between 300 K and 90 K, and at about 1.6 Hz. Three kinds of peaks are observed: (1) the peak in the amplitude dependence, which is shifted to higher amplitude, and the peak height increases, either with increasing concentration or with decreasing temperature; (2) the peak in the concentration dependence, which exhibits the 'peaking effect'; the peak is shifted to higher concentration, and the peak height increases, as the amplitude increases; (3) the peak in the temperature dependence, which is shifted to lower temperature, and the peak height increases as the amplitude increases. These results are interpreted in terms of frictional forces and the associated relaxation of dislocations oscillating in random solid solution.

1. Introduction

There are two kinds of models for the amplitude-dependent internal friction in crystals containing small amounts of impurities. One is that it is caused by the interaction of dislocations with the Cottrell atmosphere [1]. The other is that it is due to dislocations oscillating in the lattice, where impurities are randomly distributed. Schlipf and Schindlmayr [2] and Schlipf [3] developed the theory of internal friction of this kind. One of the conclusions was that a relaxation peak occurs in the frequency dependence, which is shifted to higher $\omega\tau$ as the amplitude increases. Peaks both in the temperature dependence and in the amplitude dependence were also predicted. Ritchie *et al.* [4] observed two kinds of peaks in α-Zr. One is the peak in the temperature dependence, which is shifted to lower temperature as the amplitude increases, and the other the peak in the amplitude dependence, which is shifted to higher amplitude as the temperature decreases. The results were interpreted to be due to the interaction of dislocations with included oxygen atoms. Ritchie *et al.* further compared the results with calculations of both the amplitude dependence and the temperature dependence, based on a model proposed by Schlipf and Schindlmayr [2], and qualitatively good agreement was obtained.

In addition to the peaks, the dislocation velocity and the frictional force which acts against the motion of dislocations are also of use to interpret the experimental results of amplitude-dependent internal friction [5–8]. In a previous study, the amplitude-dependent internal friction was measured on dilute Cu–Al alloys at low frequencies [9]. One of the results was that in the case of very dilute alloys, for example Cu–0.01at.%Al, the internal friction at strain amplitudes higher than about 2×10^{-6} exhibited an initial increase and subsequent decrease in damping as a function of aging time. It was explained to be due to the increase in the frictional force as a result of segregation of impurities around dislocations. In the present study, the amplitude-dependent internal friction is measured using the same kinds of specimens in more detail at room and lower temperatures, and the results are discussed in terms of frictional force and relaxation, which are mutually closely related.

2. Experimental procedure

The specimens were prepared from 99.999% pure copper and the following four kinds of dilute Cu–Al alloys: nominally Cu–0.01at.%Al, Cu–0.02at.%Al, Cu–0.1at.%Al and Cu–1at.%Al. Each kind of raw material was drawn to a wire of 0.6 mm diameter and cut to 40 mm length. An inverted torsion pendulum was used for the measurements. After it was excited at a high amplitude, the amplitude-dependent internal friction was measured during the free decay, at frequencies of about 1.6 Hz. Before the measurements,

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the specimen was annealed at 1273 K for 1 h and twisted *in situ* by 0.4% in one direction and then back to the initial position, at 300 K.

3. Experimental results

Figure 1 shows typical examples of the internal friction *vs.* strain amplitude taken with the five kinds of specimens. For each kind of specimen, the magnitude of the internal friction has some scatter, and the curve having the intermediary values is shown in the figure. The result shows that the internal friction has a broad peak in the amplitude dependence. The peak is shifted to higher amplitude, and the peak height increases, as the concentration increases. In Fig. 2, the measured values of internal friction are replotted against concentration, at two strain amplitudes, 10^{-6} and 10^{-5}. The internal friction in this case also has a peak. The peak is shifted to higher values of concentration, and the peak height increases, as the strain amplitude increases.

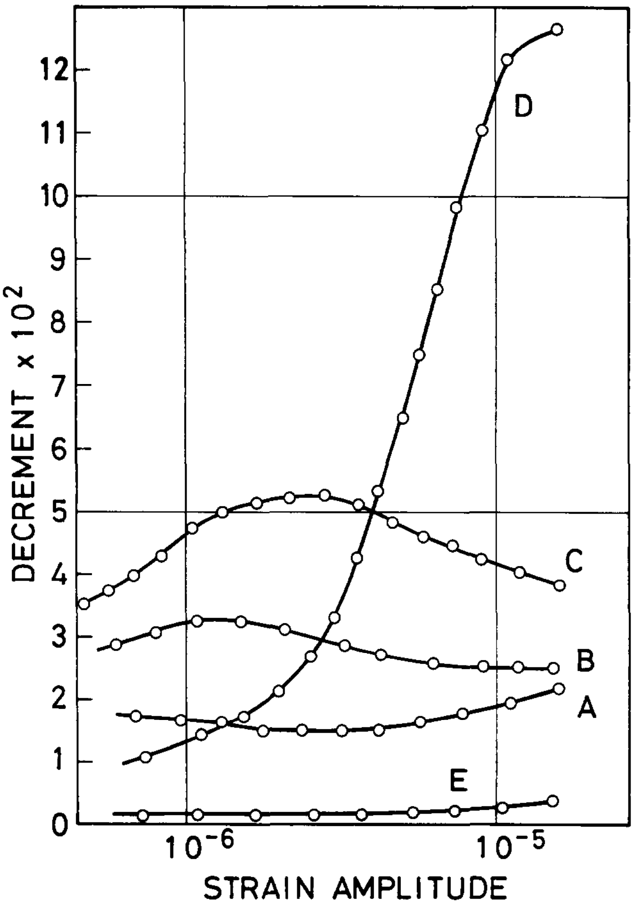

Fig. 1. Internal friction *vs.* strain amplitude for five kinds of specimens: 99.999% Cu (curve A), Cu–0.01%Al (curve B), Cu–0.02%Al (curve C), Cu–0.1%Al (curve D) and Cu–1%Al (curve E). Measurements were made at about 1.6 Hz and at 300 K.

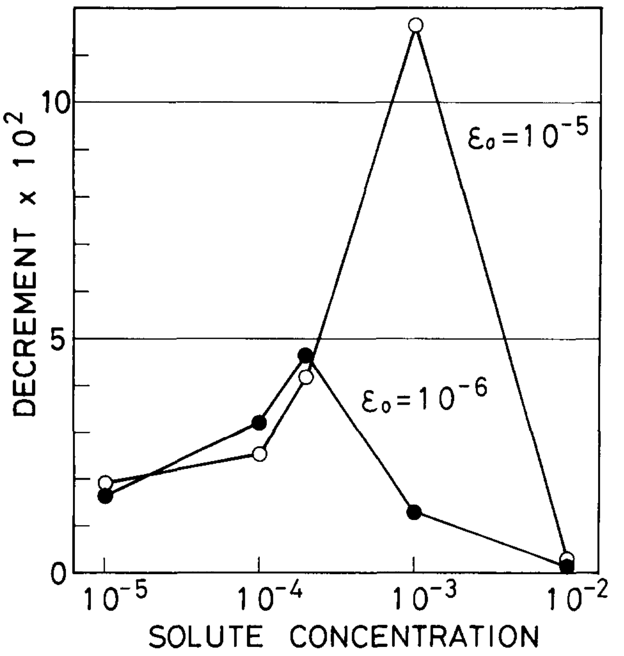

Fig. 2. The measured values of internal friction that are shown in Fig. 1 are replotted against concentration, at two strain amplitudes, 10^{-6} and 10^{-5}. The concentration of the 99.999% Cu specimen is taken to be 10^{-5} as an expedient.

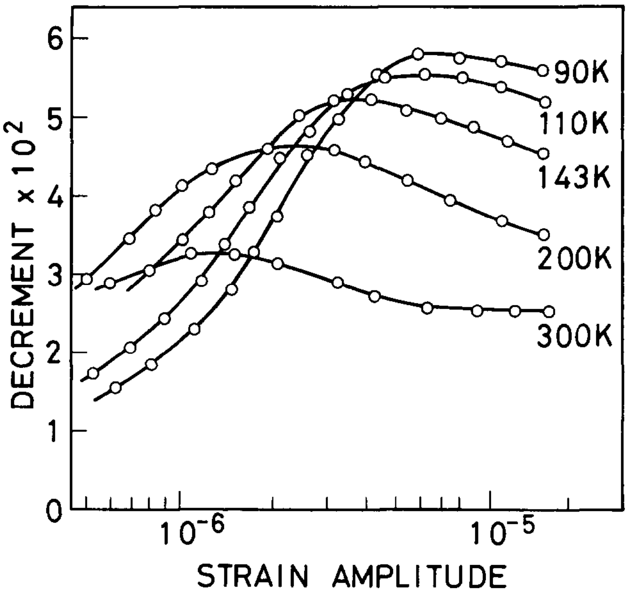

Fig. 3. Internal friction *vs.* strain amplitude for a specimen of Cu–0.01%Al, measured at temperatures from 300 K to 90 K.

Figure 3 shows the internal friction *vs.* strain amplitude measured at temperatures between 300 K and 90 K, for a specimen of Cu–0.01%Al. It is observed that the peak in the amplitude dependence is shifted to higher amplitude, and the peak height increases, as the temperature decreases. In Fig. 4, the measured values of the internal friction are replotted against reciprocal temperature at three strains. The internal

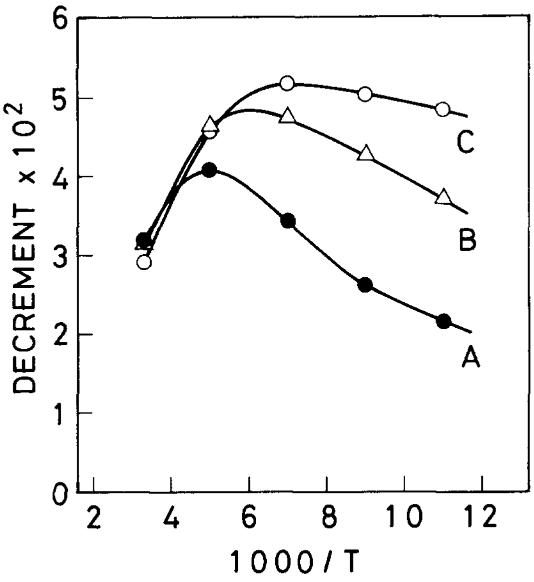

Fig. 4. The measured values of internal friction that are shown in Fig. 3 are replotted against temperature, at three strain amplitudes, 10^{-6} (curve A), 2×10^{-6} (curve B) and 3×10^{-6} (curve C).

friction in this case also has a peak. The peak is shifted to lower temperature, and the peak height increases, as the amplitude increases.

4. Discussion

The results obtained show that the amplitude-dependent internal friction in dilute Cu–Al alloys has three kinds of peaks, *i.e.* the peaks in the amplitude dependence, in the concentration dependence and in the temperature dependence. It is considered that the observed results are due to dislocations oscillating in a random solid solution, for the measurements have been made in a short time after the prestrain. The peaks both in the amplitude dependence and in the temperature dependence behave in similar ways to those of α-Zr referred to above [4]. This gives a good support for the present interpretation.

The appearance of peaks in the concentration dependence is a phenomenon known as the 'peaking effect'. Simpson *et al.* [10] observed in electron-irradiated copper an initial increase and subsequent decrease in damping as a function of irradiation time. Lauzier *et al.* [11] observed also in electron-irradiated copper a change with amplitude: a peaking effect which is present at higher amplitude diminishes and subsequently disappears as the amplitude is lowered. The peaking effect has also been observed in quenched Cu [12] and CuZnAl [13] as a function of vacancy concentration and in gold-based dilute solid solution as a function of impurity concentration [14, 15]. The peaking effect observed in the present study is interpreted to be due to dislocations oscillating in a random solid solution, because it has been observed as a profile of the amplitude-dependent internal friction. In the following, it will be shown that the peaking effect is associated with relaxation, as well as the other peaks.

When a dislocation loop is oscillating in the lattice, the internal friction can be expressed in simple forms in the two limiting cases: one is the case of high frictional forces, where the motion of dislocation is limited by frictional forces, and the other, the case of low frictional forces, where the motion is mainly limited by tension forces, onto which a small frictional force is superposed. The two types are shown in Fig. 5. In the case of viscous forces, Granato [16] predicted that the two types take place at high and low frequencies respectively.

For high frictional forces, the internal friction, denoted by Δ, is expressed in the form [5]

$$\Delta = \frac{4\mu bN}{\sigma_0\omega}\int_0^{\pi/2} v(\sigma)\sin\theta\,\mathrm{d}\theta \tag{1}$$

where N is the dislocation density, σ_0 the stress amplitude, $v(\sigma)$ the dislocation velocity as a function of applied stress σ, and the other terms have their usual meanings. For low frictional forces, the internal friction is given by [7]

$$\Delta = \frac{2NL^2}{3\sigma_0}\int_0^{\pi/2} \sigma_{\mathrm{F}}(v)\cos\theta\,\mathrm{d}\theta \tag{2}$$

where L is the loop length and $\sigma_{\mathrm{F}}(v)$ the frictional stress which is the inverse function of dislocation velocity $v(\sigma)$. For viscous forces, eqns. (1) and (2) give the amplitude-independent internal friction at high and low frequencies respectively which are obtained from the theory of Granato and Lücke [1]. For thermally activated motion of dislocations, eqn. (1) gives a rapidly increasing function of stress amplitude and eqn. (2) a gradually decreasing function.

Figure 6 shows schematically the internal friction *vs.* frictional force $f_s = b\sigma_{\mathrm{F}}$ at constant frequency and amplitude. There is no internal friction at $f_s = 0$, and it increases as the frictional force increases, according to eqn. (2). As the frictional force further increases, the motion of dislocations changes to the high friction type, and then the internal friction decreases, because the

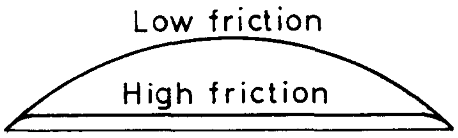

Fig. 5. The two types of dislocation motions at high and low frictional forces.

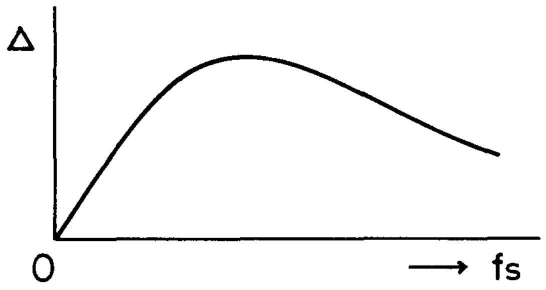

Fig. 6. Schematic internal friction *vs.* frictional force f_s, showing that the internal friction passes through a maximum as the frictional force increases.

velocity of dislocations is retarded. In terms of relaxation, the dislocation oscillates under an almost unrelaxed condition at high frictional forces, under an almost relaxed condition at low frictional forces, and there is a relaxation peak between the two limits.

The low friction type will take place at low frequencies, at high temperatures and at low concentration, and the high friction type in the contrary cases. The change in frictional force with frequency leads to the peak in the frequency dependence, the change with temperature to the peak in the temperature dependence, and the change with concentration to the peaking effect.

The peak in the amplitude dependence can be also associated with the change in the type of motion. The low friction type will take place at high amplitudes, because the ratio of the frictional force to the dislocation velocity decreases at high amplitudes [8]. The high friction type will take place at low amplitudes: at low amplitudes, the velocity determined by thermally activated motion can be small enough so that the motion of dislocations is limited by frictional forces. This is consistent with the experimental result that the peaking effect disappears at low amplitude, for the internal friction decreases as the concentration increases in the case of the high friction type of motion.

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