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Nonlinear mechanical relaxation associated with dislocation–point defect interaction

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Abstract

The concept of nonlinear anelasticity is proposed to denote that property of solids in virtue of which mechanical relaxation is acompanied by nonlinear relationship between stress and strain, so that a strong amplitude effect appears even under low stress levels. Seven internal friction peaks (*vs.* temperature) were observed in cold-worked and partially annealed aluminium containing copper or magnesium solute atoms. These peaks exhibit nonlinear anelastic behaviour manifested by the appearance of normal and anomalous amplitude effect within the temperature range of these peaks. The origin of these seven peaks was attributed to the short-ranged or long-ranged diffusion of the solute atoms (single or complex) caused by their interaction with dislocation kinks. A unified "dislocation kink–solute atom atmosphere" model in correlation with a "following, dragging, breaking away" relaxation process was suggested for these seven peaks so that the specific explanations for each peak are self-consistent and support each other.

1. Introduction

Anelasticity has been chosen by Zener to denote that property of solids, by virtue of which stress and strain are not single-valued functions of one another, in the low stress range in which no permanent set occurs and in which the relation of stress to strain is still linear [1]. The manifestations of anelasticity include internal friction, modulus defect, creep (strain relaxation) under constant stress, and stress relaxation under constant strain. These can be converted from each other according to mathematical formulae derived on the basis of Boltzmann's superposition principle.

By nonlinear anelasticity we mean that property of solids by virtue of which mechanical relaxation is accompanied by a nonlinear relationship between stress and strain, so that a strong amplitude effect is exhibited even under low stress levels. This is manifested by an increase of the anelastic effect with increasing strain amplitude (the normal amplitude effect) and a subsequent decrease with increasing strain amplitude (anomalous amplitude effect). In 1950, Kê observed anomalous internal friction peaks (*vs.* temperature and *vs.* strain amplitude) in cold-worked and partially annealed aluminium containing 0.5% copper in the temperature range of -5 to 125 °C (frequency of vibration $f \sim 1$ Hz), and an atmosphere dragging model was suggested [2, 3]. The fundamental idea is that when dislocation drags its atmosphere with it, extra resistance is exerted on the movement of the dislocation and gives rise to an additional internal friction. In China since 1965, amplitude internal friction peaks (*vs.* strain amplitude) accompanying a strain ageing peak (*vs.* ageing time) and a temperature internal friction peak (*vs.* temperature of measurement) were observed in Al containing 0, 0.6, 0.5, 0.1 and 0.01 wt.% Cu [$f \sim 1$ Hz, excitation strain amplitude $A_e \sim 10^{-7}$ to 10^{-3}, optimum temperature of the peak $T_p \sim 25$ °C) and in Al containing 0.36, 0.1, 0.12, 0.03 wt.% Mg ($f \sim 1$ Hz, $A_e \sim 10^{-6}$ to 10^{-4}, $T_p \sim 50$ °C). A "dislocation kink–atmosphere model" was suggested in 1966 (*cf.* ref. 4). These early works have been reviewed in several papers [4–7]. In 1966 and afterwards, anomalous internal friction was observed in France in Al–Zn and Al containing a small amount of impurities [8], and in Canada in α-Zr (containing oxygen) and in MgO [9].

It seems that the appearance of nonlinear anomalous internal friction in cold-worked specimens containing a small amount of impurities is a general phenomenon. Now the problems to be answered are:

(1) Whether the nonlinear anomalous internal friction exhibits relaxation behaviour and is associated with an activation energy?

(2) Where the solute atoms or solute atom atmosphere interacting with the dislocation are located, within the dislocation core or around the vicinity of the dislocation?

(3) What is the diffusion mode of the solute atoms under the action of the applied stress and the stress field of the dislocation, long-ranged or short-ranged?

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(4) What is the route of the diffusion of the solute atoms, longitudinal or transverse?
(5) Is the point defect constituting the atmosphere a single one or a complex one? *etc.*

Systematic experimental research and thorough theoretical analysis are required for a successful solution of these fundamental problems and for the elucidation of the mechanism of these anomalous internal friction peaks and their mathematical formulation.

In this paper, the recent progress in the research of nonlinear mechanical relaxation associated with dislocation–point defect interaction at the Institute of Solid State Physics (Hefei) since 1984 will be reported. Numerous exploratory experiments were carried out aiming at this anomalous internal friction peak observed in 1950 at around room temperature, and eventually found out the experimental procedure to ensure its appearance and the determination of its activation energy. This peak (designated the P_1 weak) was found to have a fine structure consisting of three sub-peaks (P_0, P'_1 and P''_1). A series of seven internal friction peaks were observed in both Al–Cu and Al–Mg specimens. These seven peaks are related to each other. A unified dislocation kink–point defect atmosphere model was suggested for these seven peaks so that the specific explanations for each peak are self-consistent and support each other.

2. Seven anomalous internal friction peaks associated with dislocation–point defect interaction

These seven internal friction peaks (both in Al–Cu and Al–Mg specimens), arranged according to the sequence of increasing temperature, are originated from the following processes. Only the relaxation parameters for Al–Mg specimens are cited as examples.

1. P_{L2} peak: originated from the interaction between dislocation and "solute atom–divacancy pair" [10]. This peak for Al–0.02 wt.% Mg specimen is situated around -70 °C ($f \sim 1$ Hz) and is associated with an activation energy H of 0.8 eV. This value is larger than the activation energy of diffusion for divacancy (0.46 eV), indicating that the relaxation involves the "Mg atom–divacancy" pair as a whole unit.

2. P_{L1} peak (or R peak): originated from the interaction between dislocation and "solute atom–vacancy pair". The optimum temperature T_p of this peak is about -50 °C (for Al–0.02 wt.% Mg) and $H = 1.2$ eV [10]. This value is also larger than the activation energy of diffusion for single vacancy (0.65 eV). The P_{L1} peak was found to be complementary with the room temperature peak (P_1 peak). The Mg–vacancy pair decomposes by annealing at a temperature around 100 °C and leaves the Mg atom free so that the individual Mg atom can interact with the dislocation giving rise to the P_1 peak.

3. P_0 peak (a sub-peak of the P_1 triplet: P_0, P'_1, P''_1): originated from the short-ranged longitudinal core diffusion (LCD) of the solute atom situated on the straight portion along the line of the kinked dislocation. The solute atom ahead of the knee of a moving kink is pushed forward along the direction of the advancing kink. The motion of the kink is thus controlled by the LCD of such a solute atom. The P_0 peak for Al–0.12 wt.% Mg is situated around -30 °C. It appears simultaneously with the P'_1 and P''_1 peaks [11, 12].

4. P'_1 peak: originated from the short-ranged longitudinal core diffusion (LCD) of the solute atom situated on the kink. While the kink moves sideways to and fro under applied cyclic stress, the solute atom on the kink is dragged along with the moving kink. This gives rise to the P'_1 peak [13]. P'_1 peak is situated around -10 °C (for the Al–0.12 wt.% Mg specimen). The activation energy associated with this peak is 0.51 eV [14]. This value is much smaller than that for the long-ranged diffusion process which is known to be 1.354 eV for the lattice diffusion of Mg atom in aluminium.

5. P''_1 peak: originated from the short-ranged transverse core diffusion (TCD) of the solute atom situated on the straight portion of the kinked dislocation, tracing the loci of the moving kink [13]. The solute atom moves successively perpendicularly to the dislocation line while the kink moves sideways in the direction of the dislocation line in order to accommodate the requirement of the stress field of the kink. Thus the solute atom always lies on the kink while the kink executes its sideways motion under cyclic applied stress. The P''_1 peak is situated around 30 °C and its activation energy for Al–0.12 wt.% Mg specimen is 0.6 eV [14], which is also much smaller than the value for a long-ranged diffusion process.

The triple peak P_0, P'_1 and P''_1 of the P_1 peak has been observed both in Al–Mg and Al–Cu specimens.

6. P_2 peak: originated from the re-orientation of "solute atom–solute atom dumbbell pair" situated close to the vicinity of a dislocation kink (through a Snoek-type relaxation) [15]. This peak is situated around 128 °C with an activation energy of 0.7 ± 0.1 eV (for Al–1.1 wt.% Mg specimen) [15], which is much lower than that associated with the volume diffusion of Mg in Al (1.354 eV) but is somewhat larger than the short-ranged core diffusion (0.5 eV for P'_1 peak, 0.6 eV for P''_1 peak). Consequently, this peak cannot be attributed to volume diffusion or short-ranged core diffusion. The high value of τ_0 associated with P_2 peak (10^{-8} s) suggests that the basic unit involved in the relaxation process may not be a single Mg atom. The "Mg–divacancy pair" and the "Mg–vacancy pair" have already been consid-

ered to be responsible for the P_{L2} and P_{L1} peaks. Thus the only composite defect left is a "Mg–Mg pair".

7. P_3 peak: originated from the long-ranged diffusion of solute atoms constituting a Cottrell atmosphere [16]. This peak is situated around 260 °C (for Al–1.1 wt.% Mg specimen) with an activation energy of 1.3 ± 0.1 eV and τ_0 is 10^{-13} s [16], which is close to that of the diffusion of Mg atoms in aluminium (1.354 eV) and the τ_0 is close to the reciprocal of the attempted jumping frequency of the bulk diffusion of Mg atoms. This shows that the motion of the solute atoms participating in the relaxation process giving rise to the P_3 peak is bulk diffusion, the long-ranged diffusion of the Mg atoms in a Cottrell atmosphere. Theoretical analysis on the diffusion data concerned showed that the Mg atoms can be caught and dragged along by the dislocation within the temperature range of the P_3 peak.

3. Discussion

Since the discovery of the anomalous internal friction in 1950 [2], the concept of "following–dragging–breaking away" was suggested in which the solute atom, as the pinning agent to the dislocation, was considered to be mobile. A "dislocation kink–atmosphere model" was then proposed [4]. With the strain amplitude of vibration becoming successively larger, the speed of the dislocation kink will increase successively higher, and the solute atoms can re-adjust themselves instantly ("following") at first, then will be dragged by the dislocation kink to move along ("dragging"), and finally be left behind ("breaking away") by the dislocation kink. In Granato and Lücke's model of the normal amplitude-dependent internal friction, the pinning agents were considered to be immobile [17]. In 1975, Winkler-Gniewch *et al.* [18] considered the pinning agents as mobile and suggested the concept of longitudinal and transverse core diffusion on the basis of the string model. In 1977, Simpson and Sosin [19] suggested the concept of dragging the pinning point by dislocation. They considered a linear dragging process which is amplitude-independent. Actually, this linear dragging concept is only the "following" stage in our model suggested early in 1950 [2]. This stage can only lead to an amplitude-independent internal friction. Only a nonlinear dragging process can lead to an internal friction exhibiting a normal amplitude-dependent effect. The nonlinear dragging is referred as the "dragging" in our model. When the "breaking away" stage becomes dominant, the internal friction will decrease pronouncedly with increasing strain amplitude with the anomalous amplitude-dependent effect and thus an internal friction peak appears.

The paper published by Granato and Lücke in 1981 [20] considered the mobility of the pinning agents, but the whole analysis is still within the framework of the string model. Amplitude-dependent effect has also been considered in the latest publications of Oğurtani and Seeger [21] in deriving the internal friction associated with the interaction of heavy interstitial atoms with dislocations in body-centred cubic metals basing on the kink concept, whereas only the linear case was considered in their numerous early publications, *i.e.* the internal friction is independent of strain amplitude. Such a tendency indicates that the basic viewpoint of our model suggested in 1950 and 1966 has been adopted by two of the main theoretical groups working on the internal friction associated with dislocation–point defect interaction. The discovery and the elucidation of the seven internal friction peaks consolidated the foundation of the nonlinear mechanical relaxation associated with dislocation–point defect interaction.

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