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The problem of kink pair formation in f.c.c. metals

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Abstract

There are experimental and theoretical arguments to indicate that the problem of the Peierls stress in f.c.c. metals can be due to the existence of several kinds of kink pair formation (KPF) mechanisms, presenting very different activation energies. Some interaction mechanisms between the intrinsic point defects (vacancies and self-interstitials) and the split dislocation cores could be responsible for these different KPF mechanisms.

1. Introduction

In f.c.c. metals, the Bordoni peaks (B_1 and B_2) appearing in the low temperature range are generally considered as intrinsic dislocation relaxations, attributed to the kink pair formation (KPF) mechanism on the 60° dislocations and on the screw dislocations respectively [1–3]. However, this explanation has sometimes been controverted, because the Peierls stress which is deduced from the Bordoni relaxation is very much higher than the Peierls stress which is obtained from yield stress measurements. That is often referred to as the unsolved problem of the Peierls potential in f.c.c. metals.

2. Observation of the classical kink pair formation mechanism

In order to verify the KPF origin of the Bordoni relaxation, an original method of mechanical spectroscopy called the acoustic coupling technique (ACT), developed by Gremaud *et al.* [4], has been used. In this technique, attenuation α and velocity v of ultrasonic waves are measured in a sample simultaneously subjected to a low frequency stress σ. Closed curves $\Delta\alpha(\sigma)$ and $\Delta v/v(\sigma)$ are measured during each cycle of the applied stress σ. It has been shown that the shapes of these curves and their evolutions (as a function of time, temperature etc.) are characteristic for each mechanism controlling the dislocation motion. Therefore, the shapes of these curves have been called signatures of the dislocation motion mechanism activated by the low frequency stress.

Such signatures have been measured by Bujard *et al.* [5] in the temperature range of the Bordoni relaxation (Figs. 1(c) and 1(d)), in a single crystal of Al of high purity (better than 99.9999 at.%), after a thermomechanical treatment ensuring better conditions for observation of the Bordoni relaxation: a cold working at 4 K followed by an annealing at 220 K (the temperature of stage II of the electrical resistivity recovery). It has been shown by Bujard *et al.* [5, 6] that the temperature evolution of the shape of the signatures (called "Bordoni signatures") and the measurements, as a function of the temperature, of the area enclosed inside the signatures (which was found to be proportional to the damping on the low frequency Bordoni peak) are in very good agreement with those predicted for a KPF mechanism.

3. Observation of a lubricated kink pair formation mechanism

In the kink picture of the dislocations in f.c.c. metals, the Bordoni relaxation is due to the KPF mechanism, and, as a consequence, at temperatures lower than the Bordoni relaxation, only migration of pre-existing geometrical kinks is possible. According to different models of the ultrasonic attenuation, the signatures in this temperature range should be almost flat, and this is precisely what was measured in the Al samples cold worked at 4 K and annealed at 220 K.

However, just after the cold working at 4 K, without annealing at 220 K, new kinds of signatures have been observed by Bujard *et al.* [5, 6], in a much lower temperature range than that of the Bordoni relaxation (Figs. 2(c) and 2(d)). It was observed that the shape of these signatures (called "flip–flop signatures") presents some similarities with the signatures observed for the Bordoni relaxation. This observation leads Bujard

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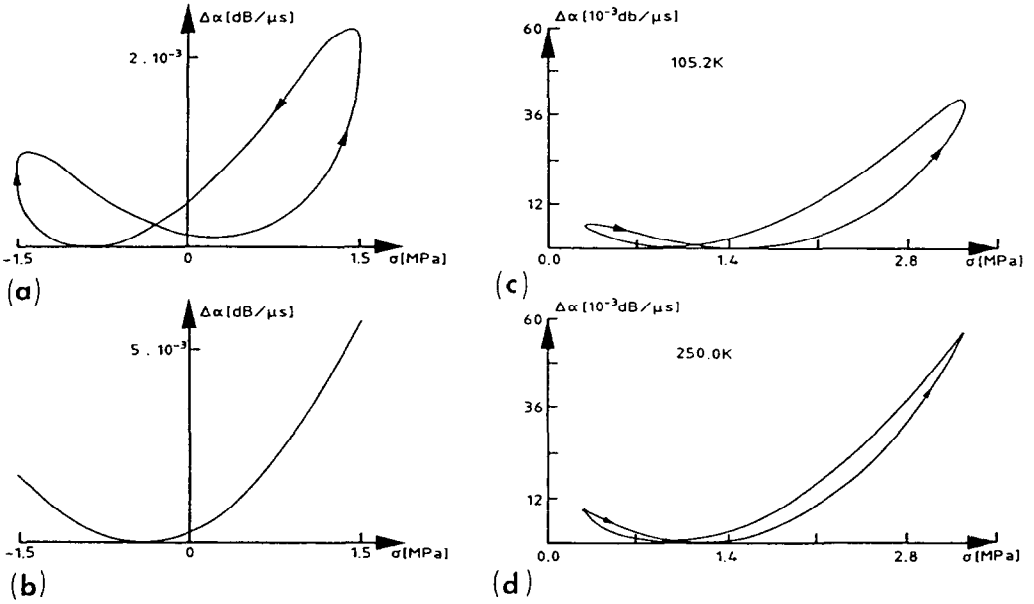

Fig. 1. Computer-simulated signatures at (a) 100 K and (b) 250 K with a KPF model using parameters measured in Al (KPF activation energy of 0.2 eV) and (c), (d) signatures measured in very pure Al single crystal in the temperature range of the Bordoni relaxation, after cold working at 4 K and annealing at 220 K.

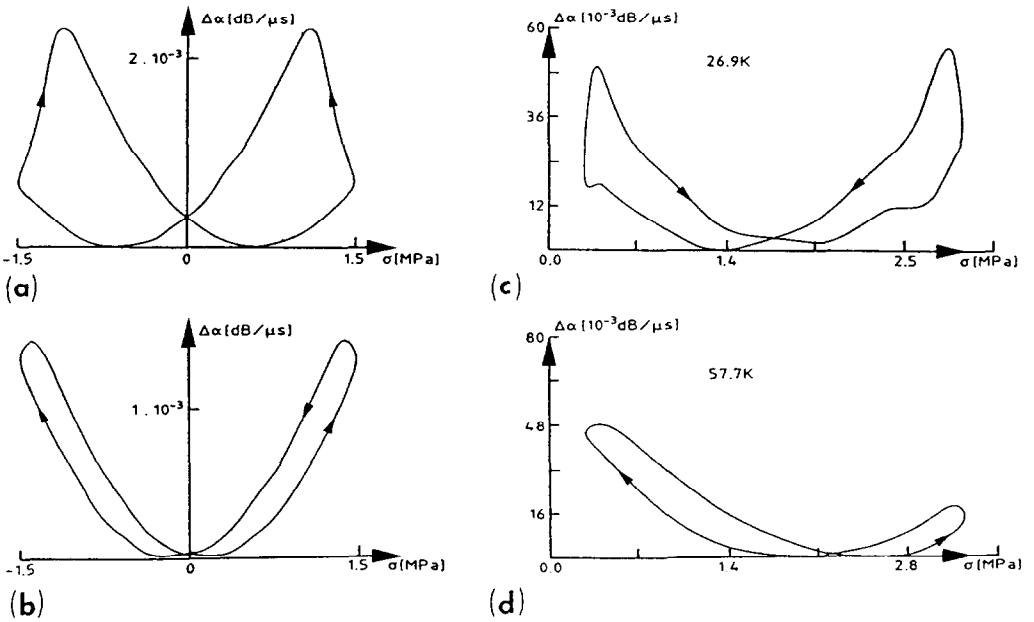

Fig. 2. Computer-simulated signatures at (a) 25 K and (b) 50 K with the same KPF model, using exactly the same parameters, but with a lower KPF activation energy of 0.02 eV and signatures (c), (d) measured in the same very pure Al single crystal largely below the Bordoni relaxation temperature, just after cold working at 4 K.

et al. [3, 6] to conclude that the new signatures have the same origin as the signatures observed during the Bordoni relaxation: the KPF mechanism. However, this KPF mechanism, which occurs at very low temperatures, has to be different from the classical mechanism responsible for the Bordoni peak. The idea of a short-circuit mechanism of the KPF was introduced as an explanation of this effect, which was called the "lubrication mechanism" of the KPF.

In order to confirm and obtain a better understanding of this lubrication process, low frequency damping and modulus defect measurements were performed by Lauzier *et al.* [7, 8] with very pure Al samples, after cold working and after electron irradiations. These detailed

measurements showed that a significant softening is induced by cold working or by electron irradiation at temperatures lower than the Bordoni relaxation temperature, which proved that a lubrication mechanism really exists in f.c.c. metals. Moreover, these measurements allowed origin to be assigned to this lubrication process: an interaction of the dislocations with vacancy-type intrinsic point defects, created during the cold working or by the electron irradiation, and leading to a short-circuit mechanism of KPF.

More recently, Quenet [9] has undertaken, on the basis of an original KPF model developed by Gremaud, a precise numerical simulation of the signatures which have to be observed in the presence of a KPF mechanism. By introducing the KPF activation energy of 0.2 eV measured on the Bordoni peak in Al, the signatures obtained by simulation (Figs. 1(a) and 1(b)) are very similar to those experimentally measured at the same temperatures for the Bordoni relaxation (Figs. 1(c) and 1(d)). Moreover, using exactly the same parameters of simulation, but only decreasing the KPF activation energy to 0.02 eV, the simulated signatures at very low temperatures (Figs. 2(a) and 2(b)) become very similar to those measured just after cold working (Figs. 2(c) and 2(d)). These simulations strongly support the interpretation of the Bordoni relaxation by the KPF model and the existence of a short-circuit mechanism of the KPF just after cold working.

4. The role of intrinsic point defects in the kink pair formation mechanism

In her recent thesis [9], Quenet analyses, at the microscopic scale of the core structure, the interactions of intrinsic point defects (vacancies and self-interstitials) with 60° and screw split dislocations in f.c.c. metals, and their influence on the KPF mechanism. She concludes that three different microscopic KPF mechanisms could occur in f.c.c. metals [10]:

(1) The first is an intrinsic KPF mechanism without point defects (with an activation energy of 0.2 eV and an activation volume of about 20 b^3 in aluminium).

(2) The second is a vacancy-assisted KPF mechanism (with an activation energy of 0.02 eV and an activation volume of about 20 b^3 in aluminium).

(3) The third is a non-conservative KPF mechanism with formation of vacancies (with an activation energy somewhat higher than 0.2 eV, but also an activation volume higher than 20 b^3 in aluminium).

5. Conclusion

This new picture of several kinds of KPF mechanisms in f.c.c metals could explain the following.

(1) A discrepancy exists between the Peierls stress deduced from Bordoni damping peaks (associated with the first KPF mechanism) and from yield stress measurements (controlled by the third KPF mechanism).

(2) Very high concentrations of vacancies (in comparison with the absence of interstitials) are generally observed by Mössbauer spectroscopy [11] or by perturbed γ–γ angular correlation measurements [12] after plastic deformation (controlled by the third KPF mechanism) of f.c.c. metals.

(3) Very low temperature softening is observed after cold working or after irradiation in pure aluminium and the flip–flop signatures are observed under the same conditions by the ACT; these are both due to the second KPF mechanism, presenting an activation energy (0.02 eV) which is strongly decreased by the interaction with the vacancy-type intrinsic point defects, in comparison with the activation energy of the pure intrinsic KPF mechanism (0.2 eV).

(4) D_0 and D_1 peaks (probably associated with the second KPF mechanism) have been observed by Kosugi and Kino at very low temperatures in very pure Al samples [13].

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