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Research Article

Study on X-Ray-Induced Defects as Barriers for Dislocation Motion by Strain-Rate Cycling Tests Combined with Ultrasonic Oscillation

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Abstract

Strain-rate cycling tests were carried out under superposition of ultrasonic oscillation during plastic deformation at 77 to 293 K for two kinds of specimens: non-irradiated and X-ray-irradiated NaBr single crystals. This method is considered to give the effective stress τ_p, when a dislocation begins to overcome the defects induced by the radiation in the NaBr crystal with the help of thermal activation. The relative curve of τ_p and temperature is fitted to the Barnett model within the temperature by numerical calculation with the parameters: τ_p value (1.99 MPa) at 0 K and T_c (369 K) for the crystal. T_c is the critical temperature at which τ_p is zero (i.e., dislocation overcomes the radiation-induced defects only with the help of thermal activation and the defects no longer act as obstacles for dislocation motion).

Keywords: Dislocation; X-ray irradiation; Effective stress; Plastic deformation; Strain rates

Introduction

The solution hardening due to the additives are caused by the mobile dislocations obstructed by the point defects around them in the crystal at low temperature. The dislocation-additive ions interaction affects the hardening of crystal. It is well known that alkali halide crystals are hardened by X-ray irradiation [1-4] and the yield stress becomes large with the irradiation dose [5]. However, the interaction between dislocation and the defect is not clearly established yet.

The results on the movement of dislocation breaking-away from impediments such as the additives [6,7] with the oscillatory stress have been obtained by the strain-rate cycling tests combined with ultrasonic oscillation. Useful information on the interaction between mobile dislocation and additive ions has been reported so far by the method during plastic deformation of alkali halide crystals [6-8]. The X-irradiation-induced defect and dislocation interaction is reported here by the method with the irradiated NaBr single crystals.

Experimental Procedure

NaBr single crystalline ingot was cleaved to the size of 5×5×15 mm^3 and the specimens were subjected to the heat treatment: annealing at 973 K for 20 h and were gradually cooled to room temperature at the rate of 40 K/h for the purpose of reducing dislocation density as much as possible. The specimens were further exposed to X-ray (W-target, 30 kV, 20 mA) for 3 h on each of the pair wide surfaces at room temperature by Shimadzu XD-610. Namely, the total exposure time is 6 h.

The experimental apparatus is schematically illustrated in Figure 1. The specimens fixed on a piezoelectric transducer were compressed by a testing machine (Shimadzu DSS-500) and the ultrasonic oscillatory stress was intermittently superimposed by the resonator composed of a vibrator and a horn with the resonant frequency of 20 kHz. The strain of the specimen seems to be homogeneous, since the wavelength (166.5 mm [9]) for NaBr is approximately 11 times as long as the length of specimen.

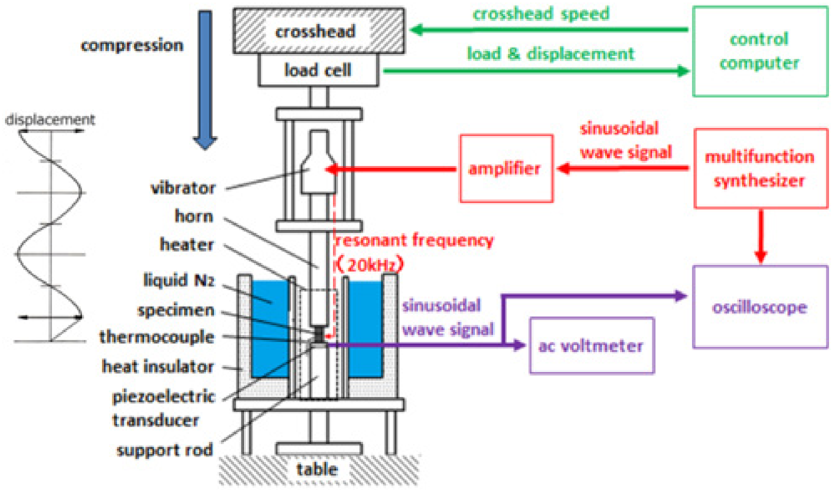

Figure 1: Experimental apparatus: schematic block diagram of apparatus system.

When the strain-rate cycling tests combined with ultrasonic oscillation were carried out, the variation of applied stress τ_a is illustrated in Figure 2. Stress change ($\Delta\tau$) is caused by applying or removing ultrasonic oscillation during plastic deformation of the specimen. As the strain-rate cycling between two strain rates (1.1×10^{-5} and 5.5×10^{-5} s^{-1}) was conducted at 77 to 293 K in the middle of the application of ultrasonic oscillation, the stress change is denoted by $\Delta\tau'$ as illustrated in the figure. The strain-rate sensitivity λ of flow stress was derived from the $\Delta\tau'$ value $\left(i.e., \lambda = \Delta\tau'/\Delta\ln\dot{\varepsilon} = \Delta\tau'/\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)\right)$.

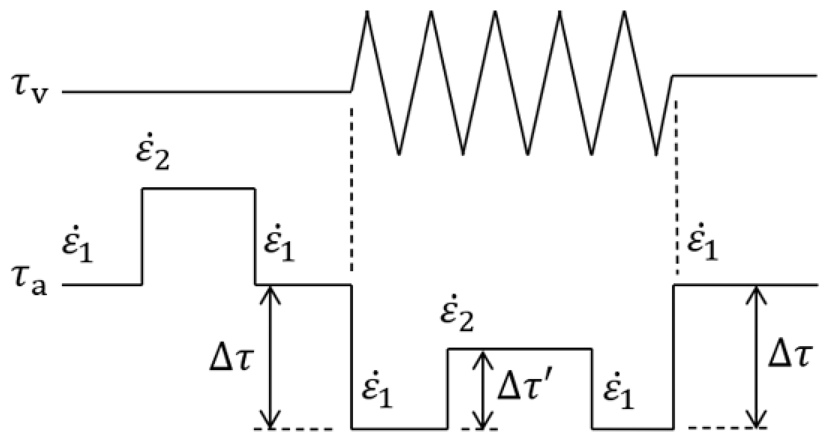

Figure 2: Variation of applied shear stress, τ_a ,when the strain-rate cycling between the strain rates, $\dot{\varepsilon}_1$ (1.1×10^{-5} s^{-1}) and $\dot{\varepsilon}_2$ (5.5×10^{-5} s^{-1}) are carried out under superposition of ultrasonic oscillatory shear stress, τ_v .

Results and Discussion

With regard to non-irradiated NaBr single crystal at 193 K, the values of $\Delta\tau$ and λ at strains 10, 12, and 14 % are plotted in Figure 3 as the relative curve of $\Delta\tau$ versus λ at a given strain. Only one bending point is on each curve. As for the X-ray-irradiated NaBr single crystal, the relative curves of $\Delta\tau$ versus λ at 173 and 213 K are shown in Figure 4 (a) and (b). The relative curves have stair like shape. That is to say, the first plateau place ranges below the first bending point, τ_p, within low $\Delta\tau$ and second one extends from the second bending point within high $\Delta\tau$. λ decreases with $\Delta\tau$ between the two bending points.

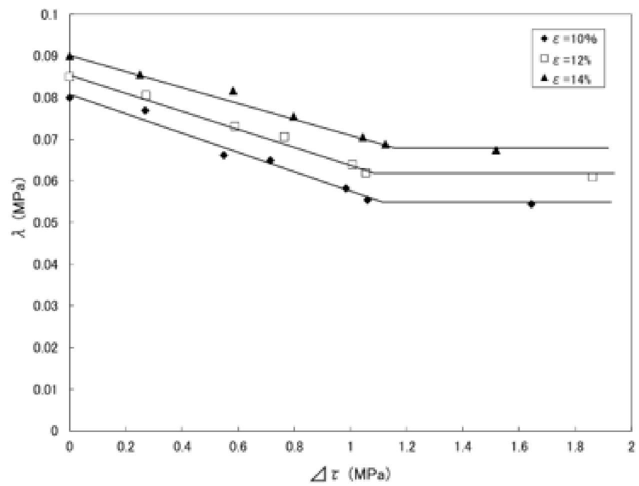

Figure 3: Stress decrement $(\Delta\tau)$ vs. λ for non-irradiated NaBr single crystal at 193 K.

The shape of $\Delta\tau$ versus λ is similar to the case of NaBr:Li$^+$ (0.5 mol%) single crystals at low temperature, which was described in the previous paper [10]. It has been reported that the length of dislocation segment increases and λ decreases when the ultrasonic oscillatory stress is applied to KCl:Br$^-$ (0.5, 1, 2 mol%) or I$^-$ (0.2, 0.5, 1 mol%) single crystals during plastic deformation at room temperature [11]. λ relates to the average length of dislocation segment pinned by obstacles. In addition, the value of τ_p (see Figure 4 (a)) depends on temperature and on type and concentration of dopants in alkali halide doped with monovalent or divalent ions [12,13]. Therefore, τ_p has been considered the effective stress due to the obstacles, when a dislocation begins to overcome the weak obstacles such as dopants which lie on the dislocation with the help of thermal activation during plastic deformation [6-8].

Although τ_p is not observed on the relation between $\Delta\tau$ and λ for the non-irradiated NaBr crystal at 193 K, τ_p becomes to appear on the relative curve at near the temperature by irradiating the crystal with the X-ray, as can be seen in Figure 4 (a) and (b). The weak obstacles for dislocation motion are considered the X-ray induced defects here. Accordingly, the appearance of τ_p in Figure 4 (a) and (b) represents the effective stress due to the defects induced by the X-irradiation.

None were added to NaBr, but a small amount of various impurities seems to contain in it. This may lead to the phenomenon that the bending point appears on $\Delta\tau$ versus λ curve in Figure 3 for the non-irradiated crystal.

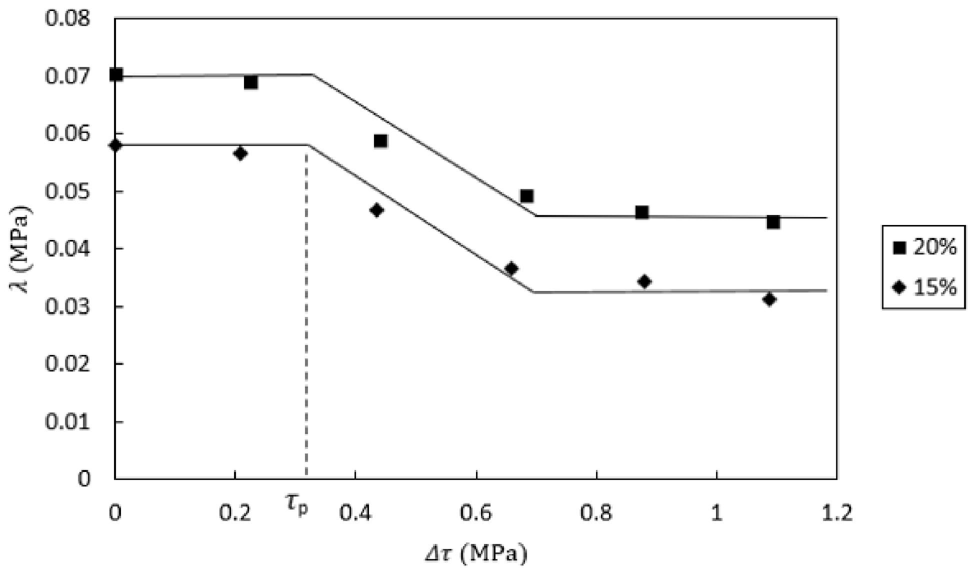

Figure 4 (a): Stress decrement $(\Delta\tau)$ vs. λ for X-ray-irradiated NaBr single crystal at 173 K.

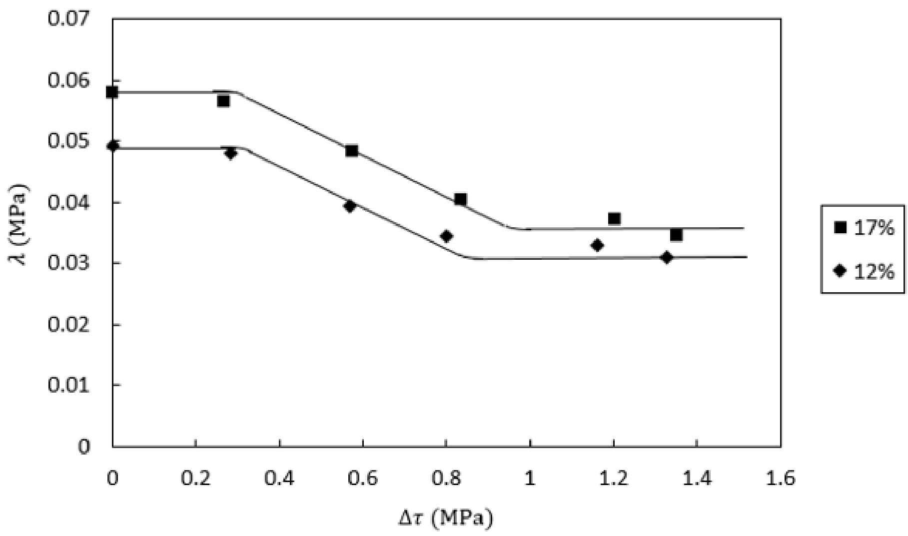

Figure 4 (b): Stress decrement ($\Delta\tau$) vs. λ for X-ray-irradiated NaBr single crystal at 213 K.

Figure 5 shows the τ_p-temperature relationship for the specimens and reflects the interaction between dislocation and the X-ray-induced defects. The plots (open circles) in the figure represent τ_p for the irradiated NaBr crystals at 77 to 293 K. τ_p decreases with the temperature and approaches to zero at the critical temperature T_c at which dislocation overcomes the radiation-induced defects only with the help of thermal activation and the defects no longer act as obstacles for dislocation motion. The force-distance curve between dislocation and tetragonal defect was reported by Barnett and Nix [15]. Assuming that the interaction between dislocation and the radiation-induced defect can be approximated by the Barnett model, the solid curve in Figure 5 was obtained by numerical calculation with the parameters: T_c (369 K) and τ_{p0} (1.99 MPa). The solid curve agrees with the open circles (i.e., τ_p for the specimen) in Figure 5. τ_{p0} is the value of τ_p at absolute zero.

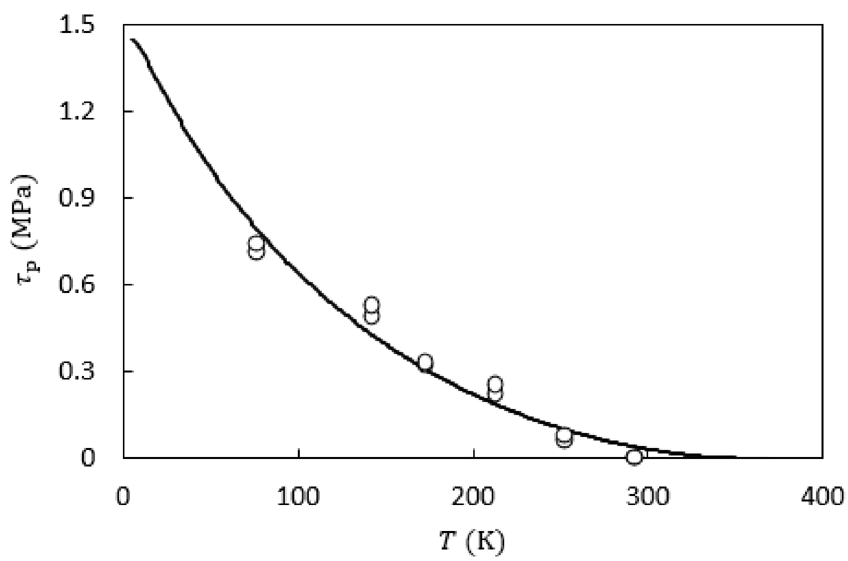

Figure 5: Dependence of τ_p on temperature for X-ray-irradiated NaBr single crystal. The solid curve is given by numerical calculation [14].

Conclusion

Non-irradiated and X-ray-irradiated NaBr single crystals were deformed by compression; during the tests strain-rate cycling was conducted under superposition of ultrasonic oscillation. The data were analyzed in terms of λ versus $\Delta\tau$ due to oscillation. As a result, τ_p is referred to the effective stress due to the X-ray-induced defects and τ_p versus T curve reflects the interaction between dislocation and the defects induced by the X-irradiation. Furthermore, the values of τ_{p0} (1.99 MPa) and T_c (369 K) were estimated for the irradiated ionic crystal. The combination method of strain-rate cycling tests and ultrasonic oscillation gives useful information on dislocation-the point defects interaction in the irradiated NaBr crystal, as the case for ionic crystals doped with monovalent or divalent ions.

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Conflict of Interest

No conflict of interest.

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