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Dislocation unpinning model of acoustic emission from alkali halide crystals

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Abstract. The present paper reports the dislocation unpinning model of acoustic emission (AE) from alkali halide crystals. Equations are derived for the strain dependence of the transient AE pulse rate, peak value of the AE pulse rate and the total number of AE pulse emitted. It is found that the AE pulse rate should be maximum for a particular strain of the crystals. The peak value of the AE pulse rate should depend on the volume and strain rate of the crystals, and also on the pinning time of dislocations. Since the pinning time of dislocations decreases with increasing strain rate, the AE pulse rate should be weakly dependent on the strain rate of the crystals. The total number of AE should increase linearly with deformation and then it should attain a saturation value for the large deformation. By measuring the strain dependence of the AE pulse rate at a fixed strain rate, the time constant τ_s for surface annihilation of dislocations and the pinning time τ_p of the dislocations can be determined. A good agreement is found between the theoretical and experimental results related to the AE from alkali halide crystals.

Keywords. Acoustic emission; dislocation; alkali halide crystals; plastic deformation.

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1. Introduction

Discrete acoustic wave packets are generated in solids during their mechanical deformation. This physical process of sound generation is known as acoustic emission (AE). The earliest use of AE analysis was made in the study of seismology. In recent years, the application of acoustic emission techniques to materials research, material evaluation, non-destructive testing and structural evaluation have increased rapidly. In addition, emission techniques have been proved successful for such uses as boiling and cavitation detection in fluid system. Much of the successful development work has been proposed for particular applications such as on-line acoustic emission monitoring of nuclear power reactors during the operation and acoustic emission monitoring of bridge structures.

Acoustic emission from single crystals of LiF and KCl under compression was first detected by Sedgwick [1]. The emission from LiF in the macroscopic elastic range was reported and it was shown that the number of events for emission for KCl was relatively low in comparison to that of LiF. James and Carpenter [2] have extensively studied acoustic emission from single crystals of LiF and NaCl. Acoustic emission was monitored during compression with a constant strain rate. Chandra [3] has studied the correlation between acoustic emission and mechanoluminescence in coloured alkali halide crystals. Recently the acoustic emission studies on stainless steels in the corrosive environment such as NaCl or $MgCl_2$ have become very useful and interesting [4–10].

The present paper reports the dislocation unpinning model of acoustic emission from alkali halide crystals and makes comparison between theoretical and experimental results.

2. Theory

The Burgers vector b is defined as the strain produced by the movement of a dislocation of unit length in a crystal of unit volume [1]. Therefore, for a strain ε, the number of dislocations produced in a crystal of unit volume will be ε/b. As a matter of fact, for a crystal of volume V deformed at a fixed strain rate $\dot{\varepsilon}$, the rate of generation g of dislocations is given by [2]

$$g = \frac{\dot{\varepsilon} V}{b}. \tag{1}$$

For a crystal of small dimension the annihilation of dislocations may take place at the surface and when the dislocation line makes 'image' at a free surface it becomes annihilated. The dislocations may also get annihilated due to other reasons. If α is the rate constant for the surface annihilation of dislocations, then we may write the following equation:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = g - \alpha N,$$

or

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{\dot{\varepsilon} V}{b} - \alpha N, \tag{2}$$

where N is the number of dislocations at any time t.

Integrating eq. (2) and taking $N = N_0$, the number of dislocations in undeformed crystals at $t = 0$, we get

$$N = \frac{\dot{\varepsilon} V}{b}[1 - \exp(\alpha t)] + N_0 \exp(-\alpha t). \tag{3}$$

Assuming the number of dislocation N_0 to be less as compared to the deformation generated dislocations, the second term in eq. (3) may be neglected and thus N may be expressed as

$$N = \frac{\dot{\varepsilon} V}{b}[1 - \exp(-\alpha t)]. \tag{4}$$

Differentiating eq. (4) with respect to time, the effective rate of generation g_e of the dislocations in crystal is given by

$$g_{\mathrm{e}} = \frac{\dot{\varepsilon} V}{b} \exp(-\alpha t). \tag{5}$$

When the dislocations are generated, they may get pinned after a pinning time τ_{p}. The rate of generation of mobile dislocations may be given by the difference between the rate of generation of dislocations and the rate of pinning of dislocations. Thus, we may write the following rate equation:

$$\frac{\mathrm{d}N_{\mathrm{m}}}{\mathrm{d}t} = g_{\mathrm{e}} - \frac{N_{\mathrm{m}}}{\tau_{\mathrm{p}}},$$

or

$$\frac{\mathrm{d}N_{\mathrm{m}}}{\mathrm{d}t} = \frac{\dot{\varepsilon} V}{b} \exp(-\alpha t) - \beta N_{\mathrm{m}}, \tag{6}$$

where $\beta = 1/\tau_{\mathrm{p}}$ is the rate constant for pinning of moving dislocations and N_{m} is the number of moving dislocations at any time t.

Integrating eq. (6) and taking $N_{\mathrm{m}} = 0$, at $t = 0$, and writing $t = \varepsilon/\dot{\varepsilon}$ we get

$$N_{\mathrm{m}} = \frac{\dot{\varepsilon} V}{b(\beta - \alpha)} \left[\exp\left(-\alpha \frac{\varepsilon}{\dot{\varepsilon}}\right) - \exp\left(-\beta \frac{\varepsilon}{\dot{\varepsilon}}\right)\right]. \tag{7}$$

Equation (7) shows that the density of mobile dislocations should be maximum at any particular value of the strain.

In various materials there are various deformation mechanisms which occur during different stages of the deformation. Clearly, there have to be many theories of deformation to deal with the various circumstances under which one (or more) of the mechanisms plays a major role in solids [11,12]. However, most of the mechanisms start with dislocation movement. Acoustic emission from a solid is associated with one (or more) of the deformation mechanisms during the stage of deformation. Therefore, it is possible to formulate a general theory which correlates acoustic emission with the deformation mechanism through the motion of dislocations.

Since a discrete acoustic emission is a sound pulse which is generated suddenly at certain stress, the motion of the dislocation associated with the acoustic emission must also be sudden and occur at a critical value of the applied stress or the corresponding value of strain [1,13]. This can happen in many ways. For instance, a Frank–Read source of length ℓ is bowed-out at a critical resolved shear stress $\tau = 2\mu b/\ell$, where μ is the shear modulus and b is the Burgers vector; or a dislocation pile-up of a critical size is suddenly released from its pinning points at a certain value of applied stress [2,14,15]. Therefore, regarding the emission due to deformation other than cracking it is postulated that the number of acoustic emission events in the strain range from ε to $\varepsilon + \mathrm{d}\varepsilon$ is proportional to the probability $p(\varepsilon)\,\mathrm{d}\varepsilon$ of the operation of mobile dislocations in the strain range [1].

For some cases, length of a dislocation is the factor controlling the operation of mobile dislocations. It is evident that the longer lengths of mobile dislocations will operate at lower values of stress than the shorter ones. Therefore, the probability of the operations of mobile dislocations as a function of stress or the corresponding value of strain may be expressed as a function of the inverse of the effective length $1/\ell$. This can be expressed by the following expression:

$$\frac{\mathrm{d}N(\varepsilon)}{\mathrm{d}\varepsilon} = \left(\frac{n_{\ell 1}}{\ell}\right) \exp\left(-\frac{\ell_0}{\ell}\right), \tag{8}$$

where ℓ_0 is the effective length of the mobile dislocation lines where $p(1/\ell)$ is maximum.

In the model presented above, ℓ is the effective length of the mobile dislocations, which can be subjected to movement at the critical stress. The distribution of the effective length ℓ is essentially equivalent to the distribution of the mobile dislocation density. The mobile dislocation density has a maximum value at a strain, when the most probable effective dislocation length ℓ_0 has attained its critical stress.

It has been shown that the probability of operation of dislocation density is directly proportional to mobile dislocation density [16,17]. Thus, if p is the probability of operation of dislocations, then the rate of breakaway of dislocation from pinning points may be expressed as

$$\frac{\mathrm{d}N_{\mathrm{d}}}{\mathrm{d}t} = pN_{\mathrm{m}}, \tag{9}$$

where $\mathrm{d}N_{\mathrm{d}}/\mathrm{d}t$ is the rate of breakaway of dislocations from Frank–Read source.

From eqs (7) and (9), we get

$$\frac{\mathrm{d}N_{\mathrm{d}}}{\mathrm{d}t} = p\frac{\dot{\varepsilon}V}{b(\beta-\alpha)}\left[\exp\left(-\alpha\frac{\varepsilon}{\dot{\varepsilon}}\right) - \left(-\beta\frac{\varepsilon}{\dot{\varepsilon}}\right)\right]. \tag{10}$$

It has been found that the AE pulse rate is directly proportional to the rate of breakaway of dislocation from pinning points. Thus, AE pulse rate $\mathrm{d}n/\mathrm{d}t$ may be expressed as

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \eta\frac{\mathrm{d}N_{\mathrm{d}}}{\mathrm{d}t} = \eta\frac{p\dot{\varepsilon}V}{b(\beta-\alpha)}\left[\exp\left(-\alpha\frac{\varepsilon}{\dot{\varepsilon}}\right) - \left(-\beta\frac{\varepsilon}{\dot{\varepsilon}}\right)\right], \tag{11}$$

where η is the correlating factor between the rate of acoustic emission and rate of breakaway of dislocations.

Equation (11) indicates that AE pulse rate is zero for $\varepsilon = 0$ as well as for $\varepsilon = \infty$. Thus, AE pulse rate should be maximum for a particular value of strain (ε).

Differentiating eq. (11) and equating it to zero, we get

$$\alpha \exp\left(-\alpha\frac{\varepsilon}{\dot{\varepsilon}}\right) = \beta\ \exp\left(-\beta\frac{\varepsilon}{\dot{\varepsilon}}\right). \tag{12}$$

From eq. (12), the strain ε_{m} at which AE pulse rate is maximum may be expressed as

$$\varepsilon_{\mathrm{m}} = \frac{\dot{\varepsilon}}{(\beta-\alpha)} \ln(\beta(\alpha)). \tag{13}$$

Equation (13) shows that ε_{m} should increase directly with the strain rate.

From eqs (11) and (12), we get

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \left[\left(\frac{\beta-\alpha}{\alpha}\right) \exp\left(-\frac{\beta\varepsilon_{\mathrm{m}}}{\dot{\varepsilon}}\right)\right]. \tag{14}$$

Now, substituting the value of ε_{m} from eq. (13) into eq. (14) we get

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{\mathrm{m}} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \left[\left(\frac{\beta-\alpha}{\alpha}\right) \exp\left(-\frac{\beta}{(\beta-\alpha)}\right) \ln\frac{\beta}{\alpha}\right]. \tag{15}$$

As $\beta \gg \alpha$, the value of exponential term in the above equation tends to 1. Thus, we get

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{\mathrm{m}} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \left(\frac{\beta-\alpha}{\alpha}\right) \frac{\alpha}{\beta},$$

or

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{\mathrm{m}} = \frac{\eta p\dot{\varepsilon}V}{b\beta},$$

or

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{\mathrm{m}} = \frac{\eta p\dot{\varepsilon}V}{b}\tau_{\mathrm{s}}. \tag{16}$$

Equation (16) indicates that the maximum value of AE pulse rate should depend on the volume V, strain rate $\dot{\varepsilon}$ of the crystal, and on the time constant $\tau_{\mathrm{s}} = 1/\beta$ for the surface annihilation of dislocations.

When α and β are of the same order, it becomes difficult to get values of α and β by using eq. (11) and also the comparison of the experimental and theoretical results becomes difficult. Therefore, some simplification of eq. (11) is needed for getting the values of α and β from the dependence of AE pulse rate on strain. For this purpose, let us write eq. (11) in the following way:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right) \left[1 - \exp\frac{[-(\beta-\alpha)\varepsilon]}{\dot{\varepsilon}}\right]$$

or

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \left[1 - 1 + \frac{(\beta-\alpha)\varepsilon}{\dot{\varepsilon}}\right] \exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right)$$

or

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)} \frac{(\beta-\alpha)\varepsilon}{\dot{\varepsilon}} \exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right)$$

or

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)}\exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right). \tag{20}$$

The right-hand side of eq. (17) is exactly the Gilman's equation for the strain dependence of mobile dislocation density.

Using the plot between $\ln[(\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ and ε, the value of α can be determined from its slope. Furthermore, using eq. (13) the value of β can be determined as the values of α and ε_{m} are known.

Now, integrating eq. (11), the total number of AE pulse produced during deformation of crystal may be expressed as

$$n_{\mathrm{T}} = \int \frac{\mathrm{d}n}{\mathrm{d}t}\mathrm{d}t = \frac{\eta p\dot{\varepsilon}V}{b(\beta-\alpha)}\int\left[\exp\left(-\alpha\frac{\varepsilon}{\dot{\varepsilon}}\right) - \exp\left(-\beta\frac{\varepsilon}{\dot{\varepsilon}}\right)\right]\mathrm{d}t$$

or

$$n_{\mathrm{T}} = \int \frac{\mathrm{d}n}{\mathrm{d}t}\mathrm{d}t = \frac{\eta pV\tau_{\mathrm{p}}\dot{\varepsilon}}{b\alpha}\left[1-\exp\left(-\frac{\beta\varepsilon}{\dot{\varepsilon}}\right)\right], \tag{18}$$

where $\tau_{\mathrm{p}} = 1/\beta$.

Equation (18) indicates that when a crystal will be deformed at a fixed strain rate, then the total number of AE pulse should increase linearly with deformation and later on it should attain a saturation value for large deformation of the crystal.

Using eq. (18) the saturation value of the total number of AE pulses may be expressed as

$$n_{\mathrm{s}} \approx \frac{\eta pV\tau_{\mathrm{p}}\dot{\varepsilon}}{b\alpha}. \tag{19}$$

It is evident from eq. (19) that the saturation value of the total AE pulse emitted should increase linearly with the volume V of the crystal, and also with $\tau_{\mathrm{p}} = (1/\beta)$, i.e., pinning time of the moving dislocations.

From eq. (16), we get

$$\frac{(\mathrm{d}n/\mathrm{d}t)}{\varepsilon} = \frac{\eta p\dot{\varepsilon}V}{b\alpha}\exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right). \tag{20}$$

Equation (20) indicates that the plot of $\ln[(\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ vs. ε should be a straight line with a negative slope, where the slope should be equal to $\alpha/\dot{\varepsilon}$. Thus, from the slope of the curve, the value of the rate constant for the surface annihilation of dislocations may be determined.

3. Experimental support to the proposed theory

Acoustic emission from single crystals of LiF and KCl under compression was first detected by Sedgwick [1], in which the AE emission from LiF in the macroscopic elastic range was reported. He also showed that the number of events for emission from KCl was relatively low in comparison to that of LiF. James and Carpenter

[2] have extensively studied acoustic emission from single crystals of LiF and NaCl. Single crystals of both LiF and NaCl were cleaved on (1 0 0) planes. The LiF samples were optically cleaved and were polished or in some cases etch pitched. The NaCl samples were polished in anhydrous methyl alcohol with 1% deionized water. Acoustic emission was monitored during compression with a constant strain rate. The frequency band of the monitoring sensor was ∼10 kHz.

Argen [18] has observed that the motion of dislocations in LiF, Cu, Zn, Fe, and Fe-3%, Si is in spurts, while dislocation motion in NaCl has been shown to be stepwise [19]. The acoustic emission detected from LiF and NaCl was of the so-called 'burst' type. Figures 1 and 2 show the acoustic emission data with the corresponding resolved shear stress–strain curves for annealed LiF and NaCl, respectively. As shown in the figures, the acoustic emission data are presented in terms of the number of events/s plotted as a function of strain. Since the tests were performed at a constant strain rate, the emission rate in terms of events/s is equivalent to the relative value of the rate of change of events with respect to strain. Both figures show that there is a maximum value of emission rate in each curve. The peak of the distribution of the emission rate for NaCl occurs near the yield point, but the peak for LiF occurs at a stress greater than the yield stress.

Figure 3 shows a plot between AE pulse rate and total strain for irradiated LiF crystals, reported by James and Carpenter [2]. The majority of pulses from the samples were in the 100–200 μV range referred to the pre-amplifier input. The rise time of a single pulse is approximately 20–30 μs for pulse from irradiated LiF. The irradiated sample was compressed at 1.595×10^{-4} s^{-1}. Some emission was also evident on unloading.

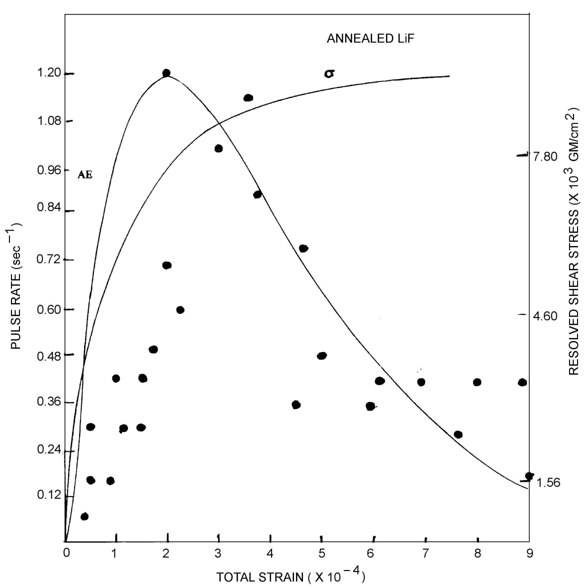

Figure 1. AE pulse rate and resolved shear stress (σ) vs. total strain for annealed LiF (after Ying *et al* [17]).

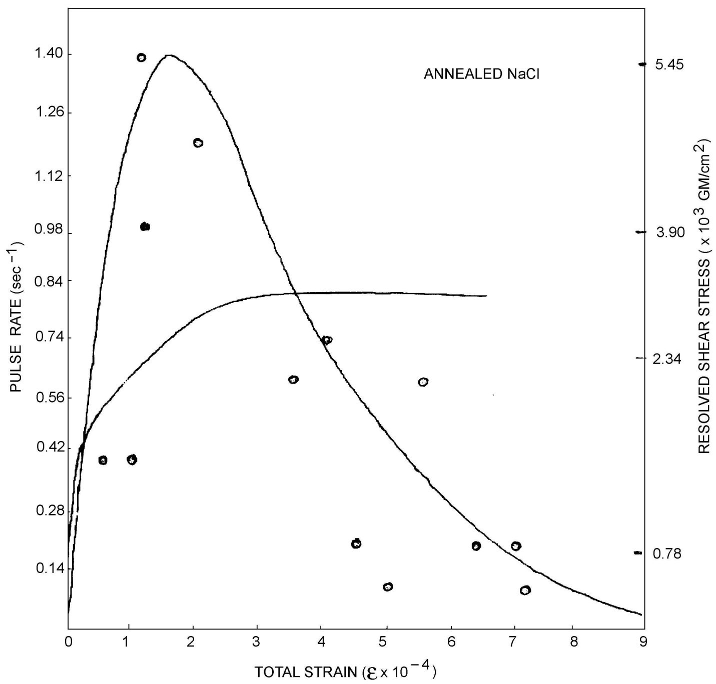

Figure 2. AE pulse rate and resolved shear stress (σ) vs. total strain for annealed NaCl (after Ying *et al* [17]).

Figures 4 to 6 show that the plot of $\ln[(\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ vs. ε is a straight line with a negative slope. This relation indicates that strain-dependence of AE pulse rate follows eq. (20). The value of α is estimated from the slope of figures 4–6 and they are shown in table 1 for annealed NaCl, LiF and irradiated LiF crystals, respectively.

The value of β is estimated using eq. (13). The values of β for annealed NaCl, LiF and irradiated LiF crystals are also shown in table 1.

Chandra [3] has studied the strain rate dependence of AE pulse rate of coloured alkali halide crystals, in which AE pulse rate was found to increase with increasing strain rate of crystals.

Table 1. Values of $\alpha, \beta, \tau_{\mathrm{s}}$ and τ_{p} for NaCl and LiF crystals.

Crystal	α (s^{-1})	β (s^{-1})	$\tau_{\mathrm{s}} = 1/\alpha$ (s)	$\tau_{\mathrm{p}} = 1/\beta$ (s)
NaCl annealed	1.022	0.940	0.978	1.063
LiF annealed	0.7960	0.543	1.256	1.841
LiF irradiated	0.1188	0.380	8.417	2.631

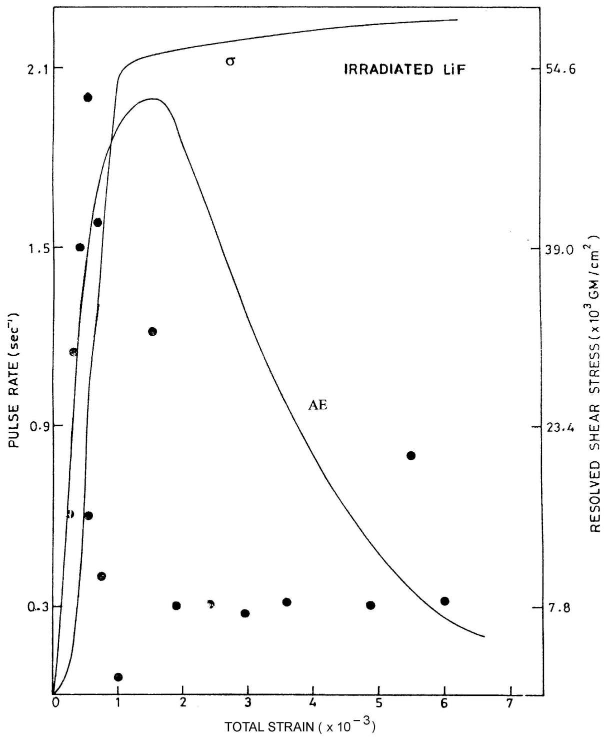

Figure 3. AE pulse rate and resolved shear stress (σ) vs. total strain for irradiated LiF (after James and Carpenter [2]).

Figures 1 to 3 show the comparison between the experimental and theoretical results. It is evident that except for the low strain region of annealed LIF there is a good agreement between the experimental and theoretical results. The low value of AE as compared to the theoretically predicted value may be due to the low value of η at low strain [17].

As far as we know limited studies have been made in the AE of alkali halide crystals. Therefore a detailed comparison between the theoretical and experimental results could not be made. In this regard the present theoretical investigation may be helpful for the further experimental investigation on AE.

4. Conclusions

The main conclusions drawn from the studies of the dislocation unpinning model of acoustic emission from alkali halide crystals are as given below:

(i) The strain dependence of the transient AE pulse rate can be expressed by the relation

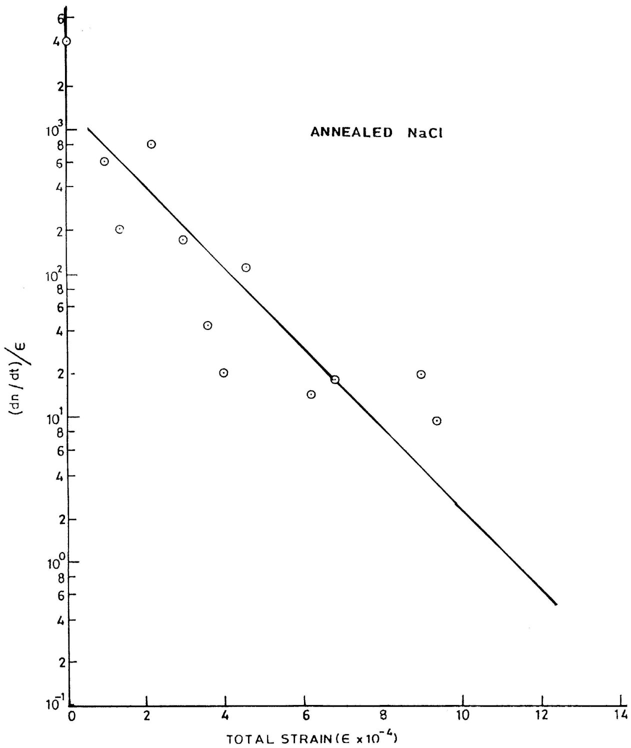

Figure 4. A plot of $\ln[(\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ vs. strain for annealed NaCl.

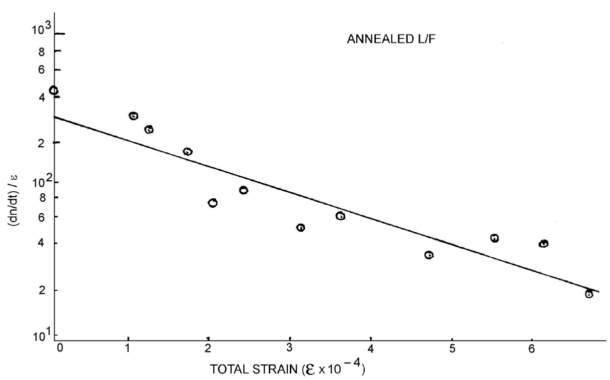

Figure 5. A plot of $\ln[(\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ vs. strain for annealed LiF.

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{\eta p V \varepsilon}{b} \exp\left(-\frac{\alpha\varepsilon}{\dot{\varepsilon}}\right) \tau_{\mathrm{s}}.$$

This equation shows that AE pulse rate should be maximum for a particular strain of the crystals.

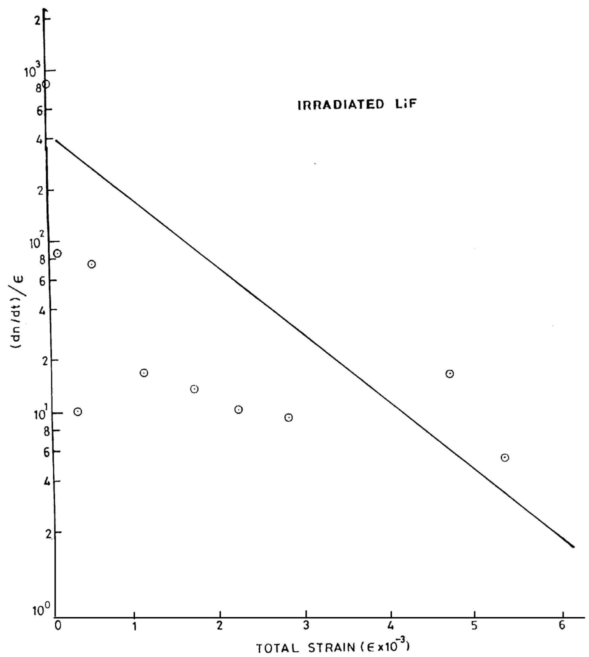

Figure 6. A plot of $\ln[\mathrm{d}n/\mathrm{d}t)/\varepsilon]$ vs. strain for irradiated LiF.

(ii) The peak value of the AE pulse rate can be expressed by the relation

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)_{\mathrm{m}} = \frac{\eta p \dot{\varepsilon} V}{b}\tau_{\mathrm{s}}.$$

(iii) The total number of the AE pulses emitted can be expressed by the relation

$$n_{\mathrm{T}} = \frac{npV\tau_{\mathrm{p}}}{b\alpha}\left[1 - \exp\left(-\frac{\beta\varepsilon}{\dot{\varepsilon}}\right)\right].$$

It is evident that the total number of AE pulse should increase linearly with deformation, and then it should attain a saturation value for the large deformation.

(iv) By measuring the strain dependence of the AE pulse rate at a fixed strain rate, the time constant τ_{s} for surface annihilation of dislocations and the pinning time τ_{p} of the dislocations can be determined.

(v) A good agreement is found between the experimental and theoretical results.

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