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Understanding the probability of crack generation in crystals using mechanoluminescence

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Abstract

As there is one-to-one correspondence between the source and signal, i.e. between the number of cracks and the number of fracto-mechanoluminescence (ML) pulses, FML can be used to study the fracture of solids. It is found that the probability p of crack-formation during deformation of a crystal is the product of strain rate coefficient α of the probability of fracture and the strain rate $\dot{\varepsilon}$. *For low value of* $\alpha\dot{\varepsilon}$, *the number of cracks or the number of ML pulses should increase linearly with the strain of crystals; however, for higher values of* $\alpha\dot{\varepsilon}$ *the number of ML pulses should increase exponentially with the strain of crystals. In the strain caused by impact exponential increase of cracks with strain should occur. In the present investigation, a good agreement is found between the theoretical and experimental results.*

1. INTRODUCTION

Mechanoluminescence (ML) is a type of luminescence induced by any mechanical action on solids [1,2]. The ML can be excited by compressing, stretching, bending, or impulsive deformation of solids. The present paper reports the understanding of the probability of crack generation using ML and makes the comparison between the theoretical and experimental results, in which a good agreement is found.

2. THEORY

In the experiment related to the ML produced during fracture of solids, a crystal is compressed at a fixed strain rate using a material testing machine. During the compression fracture of the crystal takes place and the number of cracks produced increases with the increasing compression of the crystal. The moment a crack is produced, ML pulse is generated. Thus, there is one-to-one correspondence between the number of ML pulses and the number of cracks produced during the deformation of crystal.

The number of cracks N produced during compression $d\varepsilon$ of a crystal can be expressed as If dN is the number of crystallites formed due to the deformation of a crystal from strain ε to (ε +dε) , then we can write the following equation

$$dN = M d\varepsilon \qquad \ldots(1)$$

where M is the multiplication factor which when multiplied with the strain gives the number of crystallites formed.

Considering that, in this case, the multiplication factor M depends on the number N of the previously existing crystallites at the strain ε, Eq. (15) can be written as

$$dN = \alpha N d\varepsilon$$

$$\text{or, } \frac{dN}{dt} = \alpha\dot{\varepsilon}N = \frac{N}{\tau} \qquad \ldots(2)$$

where M = α N, in which α is a constant, τ =1/ $\alpha\dot{\varepsilon}$, is the characteristic time and p= $\alpha\dot{\varepsilon}$ =1/τ ,is the probability of crack-formation during deformation of a crystal. In other words, α is the probability of crack-formation at unit strain rate or strain rate coefficient for the probability of fracture..

Integration of Eq. (2) gives

$$\log N = \alpha\dot{\varepsilon}t + C_2 \qquad \ldots(3)$$

where C_2 is the constant of integration.

For just below the fracture time t_f, at which $\varepsilon = \varepsilon_f$, at which fracture starts, N =1, and therefore, Eq.(3) gives, $C_2 = -\alpha\dot{\varepsilon} t_f$. Thus, from Eq. (3), we get

$$N = \exp[\alpha\dot{\varepsilon}(t - t_f)] = \exp[\alpha(\varepsilon - \varepsilon_f) \qquad \ldots(4)$$

For N number of crystallites, the number of cracks N_c created in the crystal is given by

$$N_c = (N - 1) = \exp[\alpha(\varepsilon - \varepsilon_f)] - 1 \quad \ldots(5)$$

As the movement of each crack produces one ML pulse, the number of ML pulses N_p is given by

$$N_p = N_c = [\exp\alpha(\varepsilon - \varepsilon_f)] - 1 \qquad \ldots(6)$$

It is evident from Eq.(6) that, after the fracture strain ε_f, the number of ML pulses should increase exponentially with $(\varepsilon - \varepsilon_f)$.
Equation (6) can be written as

$$\log(N_p + 1) = \alpha(\varepsilon - \varepsilon_f) \qquad \ldots(7)$$

As d[log(Np +1)]/dε = α, the slope of log(Np +1)] versus ε plot gives the value of α, and thus the probability $\alpha\dot{\varepsilon}$ of crack-formation during the deformation of the crystals at the strain rate $\dot{\varepsilon}$ can be determined.

Now, two conditions arise: (i) $\alpha(\varepsilon - \varepsilon_f) << 1$, and (ii) $\alpha(\varepsilon - \varepsilon_f) >> 1$.

Condition I: $\alpha(\varepsilon - \varepsilon_f) << 1$

In this case, Eq. (6) can be expressed as

$$N_p = \alpha(\varepsilon - \varepsilon_f) \qquad \ldots.(8)$$

It is evident from Eq.(8) that, after the fracture strain ε_f, the number of ML pulses should increase linearly with $(\varepsilon - \varepsilon_f)$. This is similar to the case of static loading discussed previously.

Condition II: $\alpha(\varepsilon - \varepsilon_f) >> 1$

In this case, after neglecting 1, Eq. (6) can be expressed as

$$Np = [\exp[\alpha(\varepsilon - \varepsilon_f)] \qquad \ldots.(9)$$

It is evident from Eq.(9) that, in this case, the number of ML pulses should increase exponentially with $(\varepsilon - \varepsilon_f)$. The semilog plot of Np versus $(\varepsilon - \varepsilon_f)$ should be a straight line with a positive slope, in which the slope should be equal to α.

3. EXPERIMENTAL SUPPORT

Fig. 1 shows the stress-strain and ML-strain curves produced during slow deformation of $\dot{\varepsilon}$ copper sulphate pentahydrate crystal. It is seen that the ML pulses are produced concurrently with the steps occurring in the stress-strain curve of the crystal. As the step in the stress-strain curve is caused due to the movement of a crack in the crystal, it is clear that the ML pulses in copper sulphate pentahydrate crystal is caused by the movement of cracks in the crystal. It is evident from Fig. 1 that, at slow deformation the number of cracks increases linearly with the deformation or strain of the crystal. It seems that, at the low strain rate, the probability of crack formation, p=α$\dot{\varepsilon}$, is low, as $\dot{\varepsilon}$ = 10^{-4}, and α=100. Therefore, in this case, the cracks are produced due to the increasing stress caused by the increasing strain because the increasing stress separates the cleavage planes of higher and higher strength in the crystal.

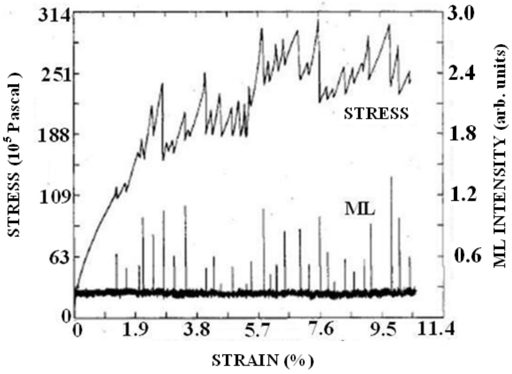

Fig. 1 Mechanoluminescence vs strain curve and stress vs strain curve of a single crystal of copper sulphate pentahydrate of size 11 x 7 x 4 mm^3 mm^3 (rate of compression = 1.69 x 10^{-3} mm s^{-1}).

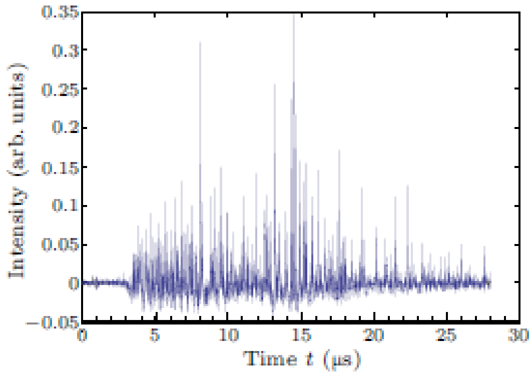

Fig. 2. Sequence of light impulses versus time. The impulses appear from the fracture of sugar particles.

time. The impulses appear from the fracture of sugar particles [3].

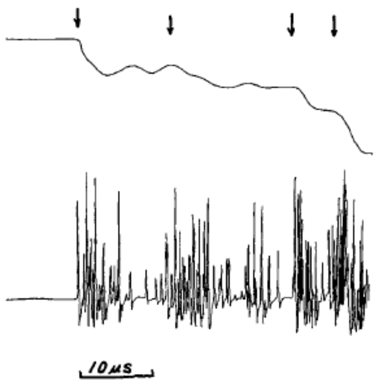

Fig.3 An example of record which shows a correlation between the load change (upper trace) and the ML activity (lower trace. Arrows indicate indicate times when the load begins to drop irregularly and the ML activity is stimulated [4] .

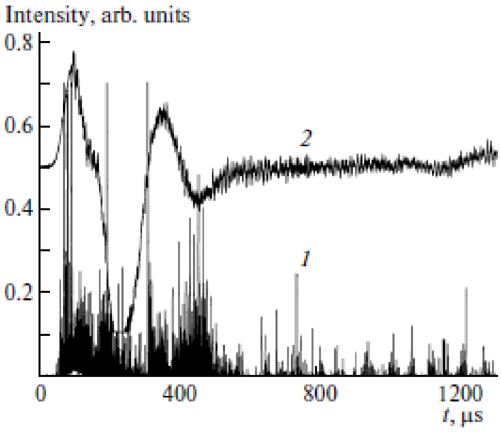

Fig.4 Time variation of the impact-initiated (i) Fracto ML intensity and (2) AE intensities [5].

Fig. 2 shows the ML pulses produced due to the cleavage of a sugar crystal [3]. In the case of cleavage the strain rate is fast and it is nearly a constant foe the duration of fracture of crystal. It is evident from Fig.2 that the rate of emission of ML pulses caused by the microcracks is nearly a constant. Such result is expected from the present investigation.

Fig.3 shows the ML pulses and the change in force produced during the cleavage of sugar crystals [4]. It is evident that the ML pulses are created when there is change in the magnitude of force.

Fig.4 shows the time variation of the impact-initiated fracto ML intensity and acoustic emission (AE) intensities [5] of a quartz crystal. It is seen that the ML emission occurs in nearly four to five series of bursts, in which the first series is produced by the impact stress; however, the other series bursts due to the reflection of stress wave from the walls of the crystals. Since the amplitude of stress wave decreases with increasing number of reflection, the ML intensity of the successive series decreases with increasing time after the impact.

It seems that, at the high strain rate, the probability of crack formation, $p=\alpha\dot{\varepsilon}$, is high, as $\dot{\varepsilon} = 10^3$, and α=100. Therefore, in this case, the cracks are produced due to the increasing probability of the crack formation, whereby the number of cracks increases exponentially with the strain of the crystals. Thus, there is a good agreement between the theoretical and experimental results.

4. CONCLUSION

The important conclusions drawn from the present investigation are as given below:

(i) Because of the is one-to-one correspondence between the source and signal, i.e. between the number of cracks and the number of fracto-mechanoluminescence (ML) pulses, FML can be used to study the fracture of solids.

(ii) The probability p of crack-formation during deformation of a crystal is the product of strain rate coefficient α of the probability of fracture and the strain rate $\dot{\varepsilon}$.

(iii) For low value of $\alpha\dot{\varepsilon}$, the number of cracks or the number of ML pulses should increase linearly with the strain of crystals; however, for higher values of $\alpha\dot{\varepsilon}$ the number of ML pulses should increase exponentially with the strain of crystals.

(iv) In the strain caused by impact exponential increase of cracks with strain should occur.

(v) In the present investigation, a good agreement is found between the theoretical and experimental results.

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