Mechanoluminescence technique for real-time monitoring of cracks produced during application of loads on crystals

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When a load is applied on to a crystal, then the fracto mechanoluminescence (ML) emission takes place in the form of light pulses. The number of ML pulses and the time duration $t_c$ for the appearance of ML increase with increasing value of the load and the average ML intensity from a single ML pulse decreases with increasing value of the load. For a given value of the applied pressure, the total number $N_T$ of ML pulses, the total ML intensity $I_T$ and the time duration $t_c$ of ML emission increase with increasing size of the crystals. As the total ML intensity is directly related to the area of newly created surfaces, the pressure dependence of the total ML intensity indicates that initially the total area of newly created surfaces increases with increasing value of the applied load and later on it tends to attain a saturation value for higher values of the applied load. As the strain rate is maximum at a particular time after the application of load on to a crystal, the rate of the emission of ML pulses is maximum at a particular time after the application of load on to the crystals. The dependence of $N_T$, $I_T$, and $t_c$ on the applied pressure $P_0$ follows the following expressions, respectively

$$N_T = M_o V^y [1 - \exp(-\delta_c (P_0 - P_f))]$$

$$I_T = D b M_o V [1 - \exp(-\delta_c (P_0 - P_f))]$$

and,

$$t_c = \frac{1}{\alpha} \ln \left( \frac{P_0}{P_f} \right)$$

where $V$ is volume of crystal, $y$ is an exponent, $\delta_c = 1/P_c$, $P_c$ is the critical pressure, $P_f$ is the fracture stress, $M_o$, $D$, $b$, and $\alpha$ are constants. A good agreement is found between the theoretical and experimental results.

The mechanoluminescence (ML) induced by fracture of solids is known as fracto ML. Initially, fracture was used as a tool to induce ML, but now a days, it is used to study the fracture of solids. The fracto ML provides a self-indicating method of monitoring the microscopic and macroscopic processes occurring during fracture of solids and gives important information related to the initiation, propagation and interaction of cracks in solids in microsecond and nanosecond scales. Rapid photographic methods and CCD cameras have been used effectively to photograph the active areas of the crystals by their own light arising due to ML. The ML technique makes possible the real-time monitorings of crack-growth in solids, severity and location of damages, and the stress distribution near the tip of crack in solids. The fracto ML also provides the online monitoring of grinding process in milling machines. Consequently, the ML technique is attracting the interest of many workers for fracture studies. Moreover, the emission of intense light during the earthquakes and mine-failure has also created the curiosity for the studies of ML produced during fracture of solids.

More often, fracture occurs during the applications of loads on solids. In the past, only few studies have been made on the ML produced during the application of loads of solids. Therefore, it will be interesting to study the fracto ML of solids induced by the application of loads. The present paper reports the theory of ML produced due to the fracture produced during the application of loads on crystals and makes a comparison between the theoretical and experimental results. It is shown that the ML provides a tool for the real-time monitoring of cracks produced during the application of loads on crystals.

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Theoretical

In the fracto ML induced by the application of a load or a pressure step on a crystal, a load is placed on to a crystal and the ML is produced during the fracture of the crystal. Let \( dN \) be the number of cracks produced during change of strain from \( \varepsilon \) to \( (\varepsilon + \Delta \varepsilon) \), then we can write

\[
dN = M \, d\varepsilon
\]

where, \( M \) is the correlation factor between the number of cracks and strain of the crystals. Here, the number of cracks means the number of cleavage planes along which the separation of surfaces is taking place or, in other words, number of crack means number of crack nuclei.

When a crystal is compressed by the application of a load, the number of defects in the crystal increases with strain\(^{16}\). Because of the increase in the number of defects, the probability of nucleation of cracks in a crystal increases and consequently, the correlation factor increases with the strain of the crystal. Moreover, the correlation factor also increases with the volume \( V \) of the crystal because of the availability of more number cleavage planes of the crystal. Thus, \( dN \) may be expressed as

\[
dN = M_o \, V^y \, \varepsilon^z \, d\varepsilon
\]

where \( M = M_o \, V^y \, \varepsilon^z \), \( M_o \) is a constant and \( y \) and \( z \) are exponents.

It has been found that \( z \) depends on the value of strain of the crystals. For low strain, \( z = 0 \), and for high strain \( z = 2 \). When a load is applied on to a crystal, initially the pressure \( P \) increases with time \( t \) and then it attains a maximum value \( P_o \). If \( \tau \) is the time-constant for the rise of pressure \( P \) with time \( t \) and \( P_o \) is the final value of pressure, then \( P \) can be expressed as

\[
P = P_o \left[ 1 - \exp(-t/\tau) \right] = P_o \left[ 1 - \exp(-\xi \, t) \right]
\]

where \( \xi = 1/\tau \), is the rate constant for the rise of pressure.

It has been found\(^{21-23} \) that the dependence of the pressure \( P \) or stress on strain \( \varepsilon \) in the fracture region follows the relation

\[
P = Ke^n
\]

or,

\[
\varepsilon = \left( \frac{P}{K} \right)^{1/n} = \left( \frac{P_o}{K} \right)^{m}
\]

where \( K \) is a factor related to the strength coefficient of the crystal, \( n \) is the work hardening exponent, and \( m = 1/n \).

From Eqs (3) and (4), we get

\[
\varepsilon = \left( \frac{P_o}{K} \right)^m \left[ 1 - \exp(-\xi \, t) \right]^m \quad \ldots (5)
\]

Taking \( z = 0 \), and integrating Eq. (2), for \( N = 0 \), at \( \varepsilon = 0 \), we get

\[
N = M_o \, V^y \, \varepsilon = M_o \, V^y \, \frac{P_o^m}{K^m} \left[ 1 - \exp(-\xi \, t) \right]^m \quad \ldots (6)
\]

The total number \( N_T \) of cracks emitted from \( t = 0 \), to \( t = \infty \), is given by

\[
N_T = \frac{M_o \, V^y \, P_o^m}{K^m} \left[ 1 - \exp(-\xi \, t) \right]^m = \frac{M_o \, V^y \, P_o^m}{K^m} \quad \ldots (7)
\]

Pressure dependence of total number of ML pulses

From Eq. (5), the maximum strain \( \varepsilon_m \) of a crystal for the pressure of amplitude \( P_o \) is given by

\[
\varepsilon_m = \frac{P_o^m}{K^m} \quad \ldots (8)
\]

As \( K \) is pressure dependent, the estimation of \( \varepsilon_m \) may be made in the following way. The comparison of the crystal attains a saturation value due to the work hardening which can be raised with great difficulty by raising the value of external stress. If \( P_c \) is the critical amplitude of the pressure at which the initial thickness \( H \) reduces to \( H/e \), then we may write

\[
-\frac{dH'}{dP_o} = \frac{H'}{P_c} \quad \ldots (9)
\]

where \( H' \) is the thickness of the crystal at any pressure \( P_o \).

For \( H' = H \), the original thickness of the crystal, at \( P_o = 0 \), the integration of Eq. (9) gives

\[
H' = H \exp\left( -P_c/P_c \right) \quad \ldots (10)
\]

Thus, the pressure dependence of the total compression of the crystal may be given by

\[
x_m = (H-H') = H \left[ 1 - \exp(-\delta_e P_o) \right] \quad \ldots (11)
\]

where, \( \delta_e = 1/P_c \).
From Eq. (11), the maximum strain $\varepsilon_m$ for the pressure $P_o$ can be written as

$$\varepsilon_m = x_m/H = [1 - \exp(-\delta_c P_o)] \quad \ldots (12)$$

From Eqs. (8) and (12), we get

$$\frac{P_o^m}{K^m} = [1 - \exp(-\delta_c P_o)] \quad \ldots (13)$$

Thus, from Eqs. (7) and (13), we get

$$N_T = M_o V^\gamma [1 - \exp(-\delta_c (P_o - P_f))] \quad \ldots (14)$$

As $M_o = 0$, below $P_o = P_f$ that is, for the minimum pressure required to fracture a crystal, it will be appropriate to express the pressure dependence of $N_T$ as

$$N_T = M_o V^\gamma [1 - \exp(-\delta_c (P_o - P_f))] \quad \ldots (15)$$

**Pressure dependence of total ML intensity**

The average surface area produced during the fracture of a crystal depends on volume of crystal. If $bV^{y'}$ is the surface area produced during the movement of single crack, where $b$ is a proportionality constant and $y'$ is an exponent, then the total surface area created during the creation of $N$ crystallites may be expressed as

$$S = bM_o V^{(y+y')} [1 - \exp(-\delta_c (P_o - P_f))] \quad \ldots (16)$$

As the total ML intensity $I_T$ is proportional to the total area of newly created $S$, we can write

$$I_T = DbM_o V^{(y+y')} [1 - \exp(-\delta_c (P_o - P_f))] \quad \ldots (17)$$

where, $D$ is the proportionality constant.

As the total ML intensity increases linearly with the volume of crystals, $(y+y')$ may be taken as 1, and thus, Eq. (17) may be expressed as

$$I_T = DbM_o V [1 - \exp(-\delta_c (P_o - P_f))] \quad \ldots (18)$$

For low pressure, $\delta_c (P_o - P_f) \ll 1$, and therefore, Eq. (18) can be written as

$$I_T = DbM_o V \delta_c (P_o - P_f) \quad \ldots (19)$$

It is evident from Eq. (19) that the ML should appear beyond a particular pressure $P_f$ and then the total ML intensity should initially increase linearly with the applied pressure.

**Time duration for appearance of ML**

With increasing time of deformation, the total cross-sectional area of the fractured crystallites increases and therefore, for a given value of the applied load, the value of pressure decreases. If $\alpha$ is the rate constant for the decrease of pressure due to increasing cross-sectional area with time, then we may write

$$P = P_o \exp(-\alpha t) \quad \ldots (20)$$

If $t_c$ is the time at which $P_o$ becomes equal to $P_f$, below which the fracture of crystallites does not take place, then the time $t_c$ up to which fracture will take place and the ML will appear, may be expressed as

$$t_c = \frac{1}{\alpha} \ln \left( \frac{P_o}{P_f} \right) \quad \ldots (21)$$

It is evident from Eq. (21) that $t_c$ should increase with increasing value of $P_o$.

**Rate of appearance of ML pulses**

From Eq. (2), for $z = 0$, we get

$$\frac{dN}{dt} = M_o V^\gamma \frac{d\varepsilon}{dt} \quad \ldots (22)$$

From Eq. (5), the strain rate can be expressed as

$$\frac{d\varepsilon}{dt} = \left( \frac{P_o}{K} \right)^m m \xi [I - \exp(-\xi t)]^{-1} \exp(-\xi t) \ldots (23)$$

Substituting the value of $\frac{d\varepsilon}{dt}$ from Eq. (23) in Eq. (22), we get

$$\frac{dN}{dt} = M_o V^\gamma \left( \frac{P_o}{K} \right)^m m \xi [I - \exp(-\xi t)]^{-1} \exp(-\xi t) \ldots (24)$$

It is evident from Eq. (24) that $\frac{dN}{dt} = 0$, at $t = 0$ and $t = \infty$. Therefore, $\frac{dN}{dt}$ should be maximum for a particular value of time after the application of a load on the crystal.
Experimental validation of theory

Figure 1 (a,b) shows the time dependence of the ML emission produced during the application of loads on sugar crystals. It is seen that the number of ML pulses increases with increasing value of the load applied on the crystal. It is also clear that the average intensity of ML from a single ML pulse decreases slightly with increasing value of the applied load. It is found from the time dependence of the number of ML pulses for higher load that the rate of the appearance of ML pulses is more in between $t = 0$, and $t = t_c$. This is in accord with Eq. (24).

Figure 2 shows that the time duration $t_m$ of the ML emission increases with increasing value of the applied load and the average value of the ML intensity from a single ML pulse decreases with increasing values of the applied load.

Figure 3 shows the plot between total number of cracks of total number of ML pulses and load. It is seen that the total number of ML pulses increases with increasing value of the load.

Figure 4 illustrates the dependence of total ML intensity on the value of load applied on the crystal. It is seen that initially the total ML intensity increases linearly with the applied load. It is also seen that the total ML intensity for a given value of applied load is higher for larger size of the crystals.

Figure 5 shows the dependence of total ML intensity on the pressure applied on the crystals. It is seen that the total ML intensity initially increases and then it tends to attain a saturation value for higher value of applied pressure. It is evident that for a given pressure, the total ML intensity is higher for larger size of the crystals.

Figure 6 shows the dependence of total ML intensity on the volume of the crystals. It is seen that for a given pressure, the total ML intensity increases linearly with the volume of the crystals.
In the present investigation, a uniaxial pressure was applied on the crystal along its $b$ crystallographic axis by placing a load with almost zero velocity using the technique reported elsewhere\cite{24}. The ML intensity was measured using a photomultiplier tube whose output was connected to a storage oscilloscope. For the present investigation, commercial single crystals of sugar were used. As the ML emission during fracture of sugar crystals is due to the gas discharge, non-luminescent impurity does not affect significantly the intensity ML. It was checked that the sugar crystals used do not show photoluminescence, hence, there were no photoluminescent impurities.

Thus, there is a good agreement between the theoretical and experimental results.

Conclusions

The following conclusions are drawn from this study:

When a load is applied on to a sugar crystal, then the ML emission takes place in the form of light pulses.

The total number of ML pulses and the time duration for the appearance of ML increase with increasing value of the load, however, the average ML intensity from a single ML pulse decreases with increasing value of the load.

With increasing size of the crystals, the number of ML pulses increases and also the time duration of ML increases. The total ML intensity increase with increasing size of the crystals.

As the total ML intensity is directly related with the area of newly created surfaces, the pressure...
dependence of the total ML intensity indicates that initially the total area of newly created surfaces increases with increasing value of the applied load and later on it tends to attain a saturation value for higher values of the applied load.

For a given pressure, the total ML intensity increases linearly with the volume or mass of the crystals.

The pressure dependence of the total number $N_T$ of ML pulses, total ML intensity $I_T$, and the time duration $t_c$ for the appearance of ML can be expressed by the following expressions, respectively

$$N_T = M_0 V \left[ 1 - \exp\left( -\delta_c (P_o - P_f) \right) \right]$$

$$I_T = D b M_0 V \left[ 1 - \exp\left( -\delta_c (P_o - P_f) \right) \right]$$

and

$$t_c = \frac{1}{\alpha} \ln \left( \frac{P_o}{P_f} \right)$$

References