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STIMULATION OF VISIBLE FRACTO-MECHANOLUMINESCENCE IN CRYSTALLINE SUGAR BY INFRARED LASER

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ABSTRACT

The present paper reports the stimulation of visible fracto-mechanoluminescence (FML) in crystalline sugar by infrared Nd3+:YAG laser. Laser pulse – induced shock waves as a source of mechanical stress can be used to stimulate FML. This method may offer adequate means to excite FML in crystals and solve the crucial problem of generation and detection timings of FML from crystals which is not efficiently possible by manual rubbing and other techniques. Temporal profile of the FML intensity facilitate to detect timing at which fracture of the crystal instigated and for how much time it continued after the application of laser – induced shock wave. As most of the fracto-mechanoluminescent organic materials are noncentric, piezoelectrification may be responsible for their FML. On the basis of the rate of creation of new surfaces by laser-induced shock wave, expressions are derived for the general kinetics of FML intensity, rise of FML intensity, time corresponding to the FML intensity versus time curve, peak FML intensity, total FML intensity and decay of FML intensity. Expressions explored for the characteristics of laser shock wave induced FML are able to explain satisfactorily the experimental results.

KEYWORDS: Fracto-mechanoluminescence, Piezoelectrification, Crystalline sugar, Infrared laser.

INTRODUCTION

Mechanoluminescence (ML) is a type of luminescence induced by any mechanical action on solids. Research on ML indicates that sugar crystal produces a glow of light when it is crushed or fractured in dark. Such phenomenon of light emission induced by fracture of solids is known as fracto- mechanoluminescence (FML) (Chandra, 1998, 2011). Although FML can be efficiently studied using deformation methods such as compressing, impulsive deformation, grinding, rubbing, etc., the control of FML intensity and the timing of the detection after the application of stress is difficult. Therefore, in terms of simplicity of measurement, it is highly desirable to use a new technique for excitation of FML. Attempts have been made by researchers to check the affordable feasibility of laser - induced shock wave as a source of mechanical energy which can stimulate light emission by fracture of materials (Hardy *et al.*; 1979, Tsuboi *et al.*, 2003, 2008). The FML intensity found to be 10^5 times greater than that obtained by the high-impact-velocity ML instrument. Thus, the laser - induced shock wave can induce quite intense FML compared with conventional methods. This paper reports the stimulation of visible FML from crystalline sugar and makes a comparison between experimental and theoretical results.

MECHANISM OF LASER SHOCK WAVE - INDUCED FML IN CRYSTALLINE SUGAR

When laser – induced shock wave propagate through a sugar crystal, fracture of the crystal takes place. Due to the movement of a crack in the crystal, new surfaces are created. (Tsuboi *et al.*, 2008). The piezoelectric constant and the stress needed to separate the surfaces of crystals are generally of the order of 10^{-12}–10^{-11} Coulomb per Newton (CN^{-1}) and 10^8 Nm^{-2}, respectively. Thus, the charge density ρ of the newly created surfaces is of the order of 10^{-4}–10^{-3} Coulomb m^{-2}. The electric field F between the oppositely charged surfaces will be, $F = \rho/\varepsilon_0$, where ε_0 is the permittivity of free space which is equal to $8.85\text{x}10^{-12}$ $C^2N^{-1}m^{-2}$. Thus, an electric field of the order of 10^7– $10^8 Vm^{-1}$

may be produced between the newly created oppositely charged surfaces. This field may cause the dielectric breakdown of the surrounding gases and in turn may give rise to the gaseous discharge FML. The field may also cause the dielectric breakdown of the crystals, and the recombination of free carriers may give rise to recombination luminescence. The capture of electrons in deep traps may also give rise to the light emission. Furthermore, the accelerated electrons moving from negatively charged surfaces towards the positively charged surface may excite cathodoluminescence (CL). Thus, it seems that the piezoelectricity that results from a noncentric crystal structure is the fundamental structural cause of FML (Chandra *et al.*, 2013).

MATHEMATICAL APPROACH TO THE LASER SHOCK WAVE - INDUCED FML IN CRYSTALLINE SUGAR

If g_0 is the initial rate of creation of new surfaces caused by laser fluxes falling per unit time and α is attrition coefficient for the decrease of the rate of generation of new surfaces, then we can write

$$\frac{dS}{dt} = g_0 - \alpha S$$

or,

$$S = \frac{g_0}{\alpha}[1 - \exp(-\alpha t)] \tag{1}$$

Differentiating Eq. (1), we get

$$\frac{dS}{dt} = g_0 \exp(-\alpha t) \tag{2}$$

If ρ is the surface charge density of charge produced due to the piezoelectrification of crystal, then the rate of decrease of surface charges with time can be written as

$$\frac{dQ}{dt} = \rho \frac{dS}{dt} = \rho g_0 \exp(-\alpha t) \tag{3}$$

If τ_q is the decay time for the decrease of surface charges, then the rate of change of surface charges is given by

$$\frac{dQ}{dt} = \rho g_0 \exp(-\alpha t) - \beta Q \tag{4}$$

where Q is the surface charges at any time t and $\beta=1/\tau_q$.
Integrating Eq. (4) and taking Q=0, at $t=t_c$, where t_c is the threshold time for FML emission, we get

$$Q = \frac{\rho g_0}{(\alpha - \beta)}[\exp\{-\beta(t - t_c)\} - \exp\{-\alpha(t - t_c)\}] \tag{5}$$

If η is the FML efficiency, then FML intensity can be expressed as

$$I = \eta\beta Q = \frac{\eta\beta\rho g_0}{(\alpha - \beta)}[\exp\{-\beta(t - t_c)\} - \exp\{-\alpha(t - t_c)\}] \tag{6}$$

Using Eq. (6), the rise of FML intensity I_r, the time t_m corresponding to the FML intensity versus time curve, intensity I_m corresponding to the peak of FML intensity versus time curve, total FML intensity I_T and the decay of FML intensity can be expressed as

$$I_r = \eta\beta\rho g_0 (t - t_c) \tag{7}$$

$$t_m = t_c + \frac{1}{(\alpha - \beta)} \ln(\frac{\alpha}{\beta}) \quad (8)$$

$$I_m = \eta \rho \beta g_0 \quad (9)$$

$$I_T = \eta \rho g_0 \quad (10)$$

$$I_d = I'_m \exp[-\beta(t - t_m)] \quad (11)$$

where I'_m *is the* extrapolated value of I_m.

EXPERIMENTAL SUPPORT TO THE PROPOSED THEORY

The output from a pulsed infrared Nd^{3+}:YAG laser was focused onto the shock-generating layer to induce ablation with accompanying shock wave generation (Tsuboi *et al.* , 2008).

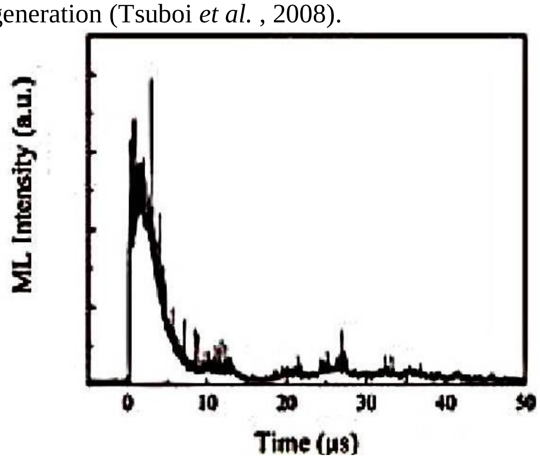

Fig.1. Temporal profile of laser shock wave-induced FML of crystalline sugar (after Tsuboi *et al.*, 2008).

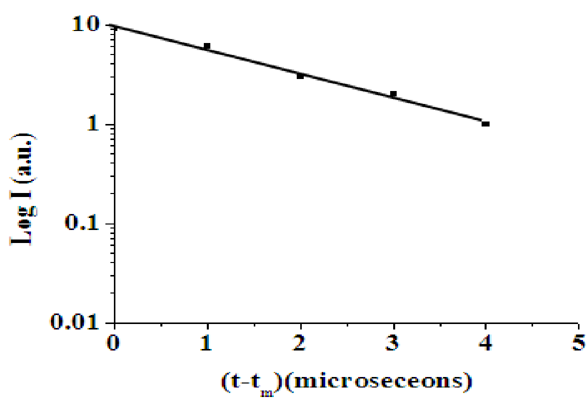

Fig.2 Semilog plot of FML intensity versus (t-t_m).

Fig. 1 illustrates the temporal profile of laser shock wave-induced FML of crystalline sugar (crystalline glucose).

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It is seen that initially the FML intensity increases with time, attains a peak value and then it decreases with time, initially at a fast rate and later on at a slow rate. Equation (7) supports this finding. Fig. 2 shows the semilog plot of FML intensity versus (t-t_m). It is seen that the FML intensity decreases at a fast rate. Such result is evident from Eq. (11).

CONCLUSIONS

Laser pulse – induced shock waves as a source of mechanical stress can be used to stimulate FML. Temporal profile of the FML intensity facilitate to detect timing at which fracture of the crystal instigated and for how much time it continued after the application of laser – induced shock wave. Expressions derived on the basis of the rate of creation of new surfaces by laser-induced shock wave, for the general kinetics of FML intensity, rise of FML intensity, time corresponding to the FML intensity versus time curve, peak FML intensity, total FML intensity and decay of FML intensity are able to explain satisfactorily the experimental results.

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