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# Effect of Ultrasonic Wave – Induced Oscillatory Mechanical Stress on Plastico Mechanoluminescence of X- ray irradiated Alkali Halide Crystals

**V.D. Sonwane[1*], A.S. Gour[1], P. Jha[2] and B.P. Chandra[1]**
[1]School of Studies in Physics and Astrophysics, Pt. Ravishankar Shukla University, Raipur, Chhattisgarh 492010, India.
[2]Department of Applied Physics, Raipur Institute of Technology, Raipur, Chhattisgarh 492101, India

**Abstract**

*In this paper, we report the effect of ultrasonic wave - induced oscillatory mechanical stress on plastico mechanoluminescence (PML) of X – ray irradiated alkali halide crystals. The dislocations move over a large distance abruptly because the oscillatory stress exerted on dislocations increases for a moment which is not observed in the case of static stress. As the oscillating dislocations sweep a large area per unit time, the PML intensity from X – ray irradiated alkali halide crystals increases with increased amplitude of oscillating mechanical stress. Expressions are derived for the general kinetics of PML intensity, rise of PML intensity, saturation value of PML intensity and decay of PML intensity, in which a good agreement is found between the theoretical and experimental results.*

***Keywords:*** *Ultrasonic wave; Plastico-mechanoluminescence; Alkali halide crystals; Oscillatory stress.*

***PACS Code:***

## 1. INTRODUCTION

Mechanoluminescence (ML) is a type of luminescence induced by any mechanical action on solids. The cold light emissions induced by elastic deformation, plastic deformation, and fracture of solids are called elastico ML (EML), plastico ML (EML), and fracto ML (FML), respectively [1,2]. Attempts have been made by researchers to check the affordable feasibility of ultrasonic wave as a source of mechanical energy [3-5]. Ultrasonic waves are a form of mechanical energy and can induce motion of dislocations at high frequency when propagating through the materials. Therefore, the ultrasonic technique is a possible candidate to induce PML as it occurs due to the mechanical interaction between the moving dislocations and F-centres. In general, the techniques such as loading, compressing, stretching, etc. are used as sources of static mechanical stress to induce PML in X – ray irradiated alkali halide crystals. In contrast, the ultrasonic wave induces oscillatory mechanical stress. The dislocations move over a large distance abruptly because the oscillatory stress exerted on dislocations increases for a moment which is not observed in the case of static stress. As the oscillating dislocations sweep a large area per unit time, the PML intensity from X – ray irradiated alkali halide crystals increases with increased amplitude of oscillating mechanical stress. This paper reports the effect of ultrasonic wave - induced oscillatory mechanical stress on PML of X –ray irradiated alkali halide crystals and makes a comparison between experimental and theoretical results.

## 2. MECHANISM OF THE PML OF X – RAY IRRADIATED ALKALI HALIDE CRYSTALS

The plastico PML in X – ray irradiated alkali halide crystals takes place in the following steps [6]:
(i) The plastic deformation causes movement of dislocations.
(ii)The moving dislocations capture electrons from the interacting F-centres lying in the expansion region of dislocations.
(iii) The captured electrons from F-centres move with the dislocations and they also drift along the axes of dislocations.
(iv) The recombination of dislocation-captured electrons with the holes lying in the dislocation donor band gives rise to the light emission characteristic of the hole centres.

## 3. PML INDUCED BY SIMULTANEOUS APPLICATION OF STATIC AND ULTRASONIC OSCILLATORY STRESS



* Corresponding author: Tel: +91 9755856657; Email: vdsonwane@gmail.com
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### 3.1 THEORETICAL APPROACH TO THE PML INDUCED BY SIMULTANEOUS APPLICATION OF STATIC AND ULTRASONIC OSCILLATORY STRESS

When X – ray irradiated alkali halide crystal plastically deformed by the simultaneous application of ultrasonic oscillation over compression, movement of dislocations occurs.

If $G_d$ is the rate of generation of mobile dislocations caused by the deformation of a crystal at a fixed strain rate and $\tau_p$ is the pinning time of dislocations, then we can write the following equation [7].

$$\frac{dN_m}{dt} = G_d - \frac{N_m}{\tau_p} = G_d - \phi N_m \tag{1}$$

where $\phi = 1/\tau_p$.

Integrating Eq.(1) and taking $N_m = 0$, at $t = 0$, we get

$$N_m = \frac{G_d}{\phi}\left[1 - \exp(-\phi t)\right] \tag{2}$$

If $v_d$ is the velocity of dislocations, then the rate of sweeping the area by the moving dislocations can be expressed as

$$\frac{dS}{dt} = N_m v_d = \frac{G_d v_d}{\phi}\left[1 - \exp(-\phi t)\right] \tag{3}$$

where S is the surface area swept out by the dislocation at any time t.

As $G_d v_d / \phi = G_d \tau_p v_d$, and the density of moving dislocations in equilibrium is, $N_d = G_d\ \tau_p$, taking the strain rate $\dot{\varepsilon} = N_d v_d b$, Eq (3) can be written as

$$\frac{dS}{dt} = \frac{\dot{\varepsilon}}{b}\left[1 - \exp(-\phi t)\right] \tag{4}$$

where b is the Burgers vector.

If η is the ML efficiency, $n_F$ the density of F-centres, $r_F$ is the radius of interaction of F-centres and $p_F$ the probability of capture of interacting F-centre electrons by moving dislocations, then the ML intensity can be expressed as

$$I = \eta\frac{dS}{dt} = \frac{\eta\dot{\varepsilon}}{b} p_F r_F n_F \left[1 - \exp(-\phi t)\right] \tag{5}$$

For $\phi t \ll 1$, Eq.(5) can be written as

$$I_r = \frac{\eta\dot{\varepsilon}}{b} p_F r_F n_F \phi t \tag{6}$$

Equation (6) indicates that initially the PML intensity should increase linearly with time. For $\phi t \gg 1$, from Eq.(5), the saturation value of ML intensity can be expressed as

$$I_s = \frac{\eta\dot{\varepsilon}}{b} p_F r_F n_F \tag{7}$$

Equation (7) indicates that the saturation value of the PML intensity should increase linearly with the strain rate and also with the density of F-centres in the crystals.

As $p_F = p_F^0 \exp(-E_a/kT)$, then the temperature dependence of PML can be expressed as

$$I_s = \frac{\eta\dot{\varepsilon}}{b} p_{Fo} r_F n_F \exp\left(-\frac{E_a}{kT}\right) \tag{8}$$

where $p^0_F$ is constant, $E_a$ the activation energy of the material, , k the Boltzmann's constant, T the absolute temperature.

In the case of plastic deformation, the fast and slow decay of the PML intensity can be given by the following equations

$$I_{df} = I_0 \exp\left[-\phi(t - t_c)\right] \tag{9}$$

and, $$I_{ds} = I'_o \exp\left[-\chi(t - t'_c)\right] \tag{10}$$

where $I_0$ is the value of $I_{df}$ at $t = t_c$, and $I'_0$ is the value of $I_{ds}$, at $t = t'_c$.

### 3.2 EXPERIMENTAL OBSERVATION OF PML INDUCED BY SIMULTANEOUS APPLICATION OF STATIC AND ULTRASONIC OSCILLATORY STRESS

Nakamura et al. [3] investigated the influence of ultrasonic wave – induced oscillatory mechanical stress on the luminescence of X – ray irradiated KCl: $Ca^{2+}$ crystals during plastic deformation. Fig. 1 shows a schematic diagram of apparatus used for measurement of PML induced by simultaneous application of static and oscillatory stress. In this apparatus an Instron 4465 testing machine was used to induce static stress and ultrasonic oscillatory stress with frequency 20 kHz was applied to the sample during plastic deformation. PML was observed by using a photomultiplier (Hamamatsu R928).

Equations (6), (7), (9) and (10) are important for the dependence of PML on the different parameters such as strain rate, time, the density of F-centres, radius of interaction of F-centres and probability of capture of interacting F-centre electrons by moving dislocations.

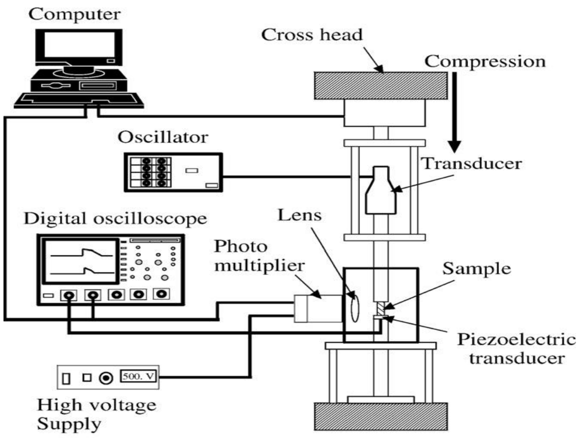


**Fig.1. Schematic diagram of PML observing system (after Nakamura et al. [3])**

Simultaneous application of compression and superposition of ultrasonic oscillations over compression forced dislocations to move over a large distance abruptly. These oscillating dislocations must sweep a larger area per unit time i.e. enhances the rate of sweeping area [3]. When the dislocation moves during the deformation of crystal, then mechanical energy of the crystal decreases and this change is followed by reduction in stress in the stress-strain curve of the crystal. Such fact is shown in Fig.2.

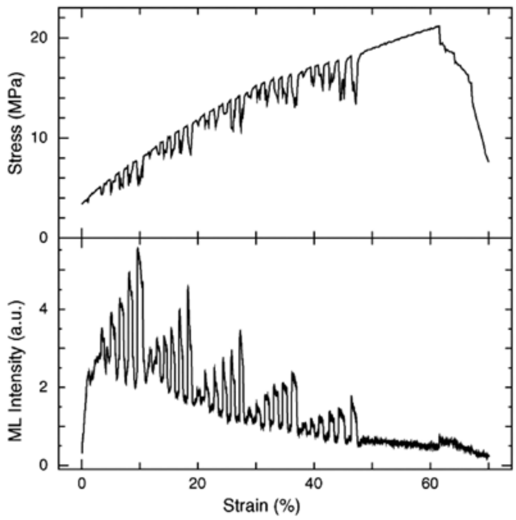


**Fig.2. Relation of stress and PML with strain under superposition of oscillation during plastic deformation for X – ray irradiated KCl: $Ca^{2+}$ crystals (after Nakamura et al. [3])**

Fig.2. illustrates variance of stress and PML intensity with strain under superposition of oscillation during plastic deformation for X – ray irradiated KCl: $Ca^{2+}$ crystals. It is seen that initially the PML intensity increases with time and strain rate. Eq.(6) supports this finding. It is also observed that PML intensity attains saturation value. This result follows Eq.(7). The fast and slow decay of PML intensity is in accord with Equations (9) and (10), respectively.

## 4. CONCLUSIONS

When X – ray irradiated alkali halide crystal is plastically deformed by the simultaneous application of ultrasonic oscillation over compression, movement of dislocations occurs. The dislocations move over a large distance abruptly because the oscillatory stress exerted on dislocations increases for a moment which is not observed in the case of static stress. As the oscillating dislocations sweep a large area per unit time, the PML intensity from X – ray irradiated alkali halide crystals increases with increased amplitude of oscillating mechanical stress. Expressions are derived for the general kinetics of PML intensity, rise of PML intensity, saturation value of PML intensity and decay of PML intensity, in which a good agreement is found between the theoretical and experimental results.

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