

Infrared Nd:YAG Laser-Induced Visible Mechanoluminescence From Tungsten <u>V.D. Sonwane¹</u>, A.S. Gour² and B.P. Chandra³

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Abstract

The paper reports the infrared Nd:YAG laser induced visible mechanoluminescence (ML) from tungsten. When the front side of tungsten sample is irradiated with the infrared Nd:YAG laser pulses, the ML glow is produced in the back side of the sample. When a laser beam of specific power density hits the material sample of finite thickness, all the absorbed radiation eventually heats the material and consequently causes the rise in its temperature. On the basis of laser power density induced temperature, the expression is derived for the temperature induced thermal stress. Expression is derived for the correlation between the thermal stress and the laser power density which indicates that the temperature induced thermal stress is directly related to the incident laser power density. In the region of plastic deformation, the temperature induced thermal stress is related to the strain and consequently to the emitted ML intensity. As the incident laser power density increases, the intensity of ML glow signal also increases. Finally, expression is derived for the laser power dependence of the ML intensity, in which good agreement is found between the theoretical and experimental results. This study may give important information about the mechanism of ML in tungsten.

Keywords: Power density, radiation, thermal stress.

1. INTRODUCTION

The luminescence stimulated or induced by mechanical action on solids is termed as mechanoluminescence (ML). ML links mechanical, spectroscopic, electrical, structural and other properties of solids. Several ML excitation techniques have been proposed so far such as grinding, rubbing, cleaving, shaking, cutting, scratching, compressing, loading, crushing, impulsive deformation etc. [1]. Although ML can be efficiently studied using these methods, the control of ML 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 ML. We are interested to check the affordable feasibility of high energy laser pulses as a comparable stress inducing agent which many workers have earlier attempted. As the magnitude of laser pulses can be changed from low to high value and also the time duration can be varied from nanosecond to longer duration, the laser pulse - induced mechanical stress is more suitable for studying ML. Also the intensity of laser pulse - induced ML is much higher than that induced by manual crushing of the crystals. Thus, laser pulse - induced method have significant potential for providing wealth information of ML mechanism.

decreases, the ML intensity also decreases [3]. Temporal dependence of the ML intensity suggested that it is related to irradiative rising of mobile dislocations on the surface under elastic and thermal stresses resulting from the action of laser pulses. It has been shown that the ML intensity depends on the power density of the laser pulse. The increase of power density of laser pulse causes the growth of thermal stresses and when these stresses attains the critical value then density of defect flow in the irradiated sample increases. After that each subsequent laser pulse causes both the rising of some part of defects on the surface and the generation of new dislocations in the sample takes place [4]. In this paper, we studied the infrared Nd:YAG

Firstly, Hardy et al. [2] used pulse laser - induced mechanical stress for the excitation of ML. Subsequently,

laser pulse - induced ML has been studied for different

metals such as copper, gold, silver, platinum, tungsten,

molybdenum etc. [3-7]. It has been found that ML is

excited as soon as the laser pulse - induced mechanical

stresses at the sample become approximately equal to the

yield point of the sample material and the ML intensity

grows as long as the rate of stress rise increases, after which

it decreases. ML intensity correlates best with the stress

variation rate. The larger is stress variation rate, the higher

is the ML intensity, and when stress variation rate



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or.

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laser induced visible mechanoluminescence (ML) from tungsten.

2. THEORY

When a laser beam of power density P hits the material sample of finite thickness d, all the absorbed radiation eventually heats the material and consequently rises its temperature which can be expressed as [4]

$$T(t) = T_{i} + \frac{AP5t}{\pi [y_{\sigma} + \sqrt{2t}]^{2} d\rho c_{m}}$$
(1)

where, T_i is the initial temperature of the sample, A is the absorption coefficient, $S = \pi r_0^2$ is the irradiated area, t is the laser pulse deposition time, χ is the thermal diffusivity, ρ is the mass density and c_m is the specific heat of the sample.

The temperature change causes thermal expansion in material. In solid material an estimate of the amount of thermal expansion can be described by the material's thermal strain and defined as

$$\epsilon(t) = \alpha T(t) \tag{2}$$

where, α is the coefficient of thermal expansion.

Now, if the temperature deformation is not permitted to occur freely, an internal stress is created. This internal stress is termed as thermal stress and related to the thermal strain according to the Hooke's law as

where, E is the modulus of elasticity.

For a material of given thickness subjected to a stress, the inverse relationship, expressing the stress in terms of strain is given by

$$\sigma(t) = \frac{\varepsilon}{(1-v^2)} \varepsilon(t)$$

or,
$$\sigma(t) = \frac{\varepsilon}{\varepsilon} \alpha T(t)$$

where, v is the Poisson's ratio. (4)

In a material subjected to shearing, the shear stress τ is given by

$$\tau = G\gamma \tag{5}$$

where, γ is the shear strain and G is the shearing modulus or modulus of rigidity.

The modulus of rigidity G is related to the modulus of elasticity and Poisson's ratio as

$$E = 2G(1 + v)$$
(6)
Using Eqs. (4) and (6), we can write

$$\sigma(t) = \frac{2\theta}{(1-\nu)} aT(t)$$
(7)

By substituting the value of surface temperature T(t) from Eq. (1) into Eq. (7), we will obtain

$$\sigma(t) = \frac{2\sigma}{(1-\nu)} \alpha [T_i + \frac{APSt}{\pi [r_{\sigma} + \sqrt{2t}]^2 d\rho c_m}]$$
(8)

Equation (8) indicates that the temperature induced thermal stress is directly related to the incident laser power density.

In the plastic limit of deformation, the stress $\sigma(t)$ is related to the strain ε as

$$\sigma(t) = K \varepsilon^n$$

$$\varepsilon = \left[\frac{\sigma(t)}{R}\right]^m \tag{9}$$

where $\hat{\mathbb{R}}$ is proportional constant and $m = \frac{1}{2}$

Differentiating Eq. (9), we get

$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} = m \left[\frac{\sigma(t)}{R} \right]^{m-1}$$
For $m = 2$, Eq. (10) becomes
(10)

$$\vec{\varepsilon} = 2\left[\frac{\sigma(t)}{\hat{\kappa}}\right]$$
(11)

Now, as the rate of area swept by dislocations is related to the strain rate as $\vec{e} = \frac{dA}{dr}$, Eq. (11) can be expressed as

$$\frac{dA}{dt} = 2\left[\frac{\sigma(t)}{g}\right] \tag{12}$$

If $\boldsymbol{\eta}$ is the ML efficiency then the ML intensity can be expressed as

$$I = \eta \frac{dA}{dt} = 2\left[\frac{\sigma(t)}{\hat{K}}\right]$$
$$I = \eta \frac{dA}{dt} = 2\eta \frac{\sigma(t)}{\hat{K}}$$

r,
$$I = \eta \frac{dn}{dt} = \frac{d\eta}{g} \sigma(t)$$
 (13)
By substituting the value of thermal stress $\sigma(t)$ from

By substituting the value of thermal stress $\sigma(t)$ from Eq. (8) in Eq. (13), we obtain

$$I = \frac{2\eta}{\hat{\kappa}} \left[\frac{25}{(1-\kappa)} \alpha \left\{ T_{i} + \frac{AP5t}{\pi \left[F_{0} + \sqrt{2k} \right]^{2} d\rho E_{m}} \right\} \right]$$
(14)
Equation (14) indicates that the ML intensity is

Equation (14) indicates that the ML intensity is directly related to the incident laser power density.

3. EXPERIMENTAL SUPPORT TO THE PROPOSED THEORY

The front surface of tungsten sample of thickness upto 300 μ m was irradiated by infrared Nd:YAG laser of pulse length 1.4 ms and energy 3.5 joule and the ML glow was measured from the back surface of the sample using the photomultiplier tube installed at the distance of about 15 cm coaxially with the laser beam [4]. The laser pulse of specific power density and short energy deposition time incident on the surface of a metal sample and produces rapid heating, resulting in higher surface temperature. Fig. 1 shows the rise of temperature due to the incident laser power density.



Fig. 1 Rise of surface temperature of tungsten as a function of incident laser power density (after Banishev et al., ref.[4]).



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The considerable elevation of the material temperature in the beam action area induces thermal stresses which are possibly responsible for the excitation of ML. Fig. 2 shows the increase in thermal stress when the temperature of the sample increases. This finding supports Eq. (7).



Fig. 2 Increase in thermal stress due to rise in surface temperature of tungsten (after Banishev et al., ref.[4]).

Fig. 3 shows that the temperature induced thermal stress is directly related to the incident laser power density. Such result is in accordance with Eq. (8).



Fig. 3 Increase in thermal stress as a function of incident laser power density (after Banishev et al., ref.[4]).



Fig. 4 Dependence of ML intensity I on the $(P-P_{th})^2$.

The amplitude of ML intensity signal increases with the increase of laser power density. Eq. (14) indicates this finding. Fig.4 shows the dependence of ML intensity I on the $(P-P_{th})^{2}$, where P_{th} is the threshold laser power density.

4. CONCLUSION

When a laser beam of specific power density hits the material sample of finite thickness, all the absorbed radiation eventually heats the material and consequently causes the rise in its temperature. On the basis of laser power density induced temperature, the expression is derived for the temperature induced thermal stress. Expression is derived for the correlation between the thermal stress and the laser power density which indicates that the temperature induced thermal stress is directly related to the incident laser power density. In the region of plastic deformation, the temperature induced thermal stress is related to the strain and consequently to the emitted ML intensity. As the incident laser power density increases, the intensity of ML glow signal also increases. Finally, expression is derived for the laser power dependence of the ML intensity, in which good agreement is found between the theoretical and experimental results.

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