Sensors and Actuators A 230 (2015) 83–93

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Modelling of fracto-mechanoluminescence damage sensor for structures

B.P. Chandra[a,*,1], V.K. Chandra[b], Piyush Jha[c]

[a] School of Studies in Physics and Astrophysics, Pt. Ravishankar Shukla University, Raipur 492010, C.G. India
[b] Department of Electrical and Electronics Engineering, Chhatrapati Shivaji Institute of Technology, Shivaji Nagar, Kolihapuri, Durg 491001, C.G., India
[c] Department of Applied Physics, Raipur Institute of Technology, Chhatauna, Mandir Hasuad, Raipur 492101, C.G., India

ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form 4 April 2015
Accepted 8 April 2015
Available online 21 April 2015

Keywords:
Mechanoluminescence
Triboluminescence
Sensor
Phosphors
Damage

ABSTRACT

The present paper reports the modelling of fracto-mechanoluminescence damage sensor which is useful for real-time and remotely monitoring of both the magnitude and location of damage of the structure without the use of electrodes. In this technique, the intense fracto-mechanoluminescent material of several micron size is mixed in liquid resin and then coated on the surface of structure whereby the occurrence and strength of the damage is given by the intensity of the resulting mechanoluminescence (ML) light. Monitoring of the position of damage is achieved by identifying the colour of ML light emitted as the ML particles coated in different locations emit ML light of different colours. The modelling of fracto-mechanoluminescence damage sensor is based on the fact that the total ML intensity depends on the total area of the newly created surfaces (damage). For a projectile having large contact area such as a cylinder, below the characteristic impact velocity v_c, at which the sample is compressed to $1/e$ of its thickness, both the peak ML intensity I_m and the total ML intensity I_T increase linearly with the impact velocity; however, above v_c, both I_m and I_T tend to attain saturation value. In the case of impact of a projectile having small contact area such as a ball, below v_c, both I_m and I_T increase quadratically with the impact velocity; however, above v_c, both I_m and I_T tend to attain saturation value. In the case of a projectile having large contact area the total volume of the sample is compressed and only the rate of creation of new surfaces increases with the impact velocity; however, in the case of a projectile having small contact area, in addition to the increase of strain rate with impact velocity, the effective volume compressed by the impact also increases linearly with the impact velocity, and therefore, the rate of creation of new surfaces increases quadratically with the impact velocity. A good agreement is found between the experimental and theoretical results.

1. Introduction

In the recent past, the fracto-mechanoluminescence phenomenon has attracted the attention of a large number of researchers all over the world because of its potential application for damage sensor of structures [1–6]. In fact, mechanoluminescence (ML) is the phenomenon of cold light emission from a solid as a response to a mechanical stimulus given to it. The cold light emissions induced by elastic deformation, plastic deformation, and fracture of solids are known as elastico mechanoluminescence (EML), plastico mechanoluminescence (PML), and fracto mechanoluminescence (FML), respectively [7,8]. Whereas nearly 50% of all inorganic salts and organic molecular solids exhibit ML during their fracture, only a limited number of solids show ML during their elastic deformation and plastic deformation. The elastico ML of $SrAl_2O_4$:Eu, CaZnOS:Mn^{2+}, $BaTiO_3$–$CaTiO_3$:Pr^{3+}, etc. and fracto ML of europium dibenzoylmethide triethylammonium(EuD_4TEA), ditriphenylphosphine oxide manganese bromide, freshly grown impure saccharin, etc. is so intense that it can be seen in day light with naked eye.

Currently the techniques being used for damage detection and monitoring of civil, aerospace, and military structures are: acoustic based methods (acoustic emission and ultrasonic testing) [9–12]; electro-imaging methods such as thermography, ultrasonic pulse velocity (UPV), and ground penetrating radar (GPR) [13–24]; radiography such as X-ray, gamma-ray, and neutron ray [25]; and fibre optics methods [25–27]. These techniques have major drawbacks that they do not provide in situ (excluding fibre optic methods) and

---

[*] Corresponding author. Tel.: +91 771 2263650.
E-mail addresses: bpchandra4@yahoo.co.in, bpchandra4@rediffmail.com (B.P. Chandra).
[1] Emeritus Professor.

http://dx.doi.org/10.1016/j.sna.2015.04.005

distributed sensing [10,26,27]. Because of these drawbacks real-time monitoring of the structural states is not possible. Moreover, the associated cost resulting from the downtime required for periodic nondestructive inspections can be very high for civil structures like bridges and aerospace structures like aircrafts. There is also the prohibitive cost arising due to fatal accidents when such structures fail without warning. Fracto-mechanoluminescence sensor systems are able to overcome the above mentioned challenges because they have the potential for wireless, in situ, and distributed sensing that can enable real-time continuous monitoring. A fracto-ML damage sensor system comprising highly efficient fracto-mechanoluminescent materials could allow simple, real-time monitoring of both the magnitude and location of damage with minimal parasitic influence to the host structure [1–6].

The mechanoluminescent materials which emit intense light when they are fractured have been developed by Bourhill and his co-workers as real-time optical damage sensors [1–4]. In this technique, the intense fracto-mechanoluminescent material of several micron size is mixed in liquid resin and then coated on the surface of structure by curing at a suitable temperature whereby the occurrence and severity of the damage is given by the intensity of the resulting mechanoluminescent light. Monitoring of the position of damage is achieved either by designing an array of sensors, with each sensor in the array comprising a different mechanoluminescent material and, thus, mechanoluminescencing over a discrete wavelength range or by designing an array of mechanoluminescent sensors with each and every sensor having the same type of mechanoluminescent material whereby a wavelength-shifting is produced using a range of conventional fluorescent dyes in which the ML from the doped resin pumps the dye, which then emits at a different wavelength. Such an arrangement allows location monitoring simply by detecting the wavelength of the emitted light. Each sensor in the array can be fibre-optically connected to a central detector capable of measuring in real-time both the intensity (for damage occurring severity) and wavelength (for damage location) of the emitted light. Furthermore, the use of only one detection unit reduces complexity and helps to reduce parasitic weight. In such sensors, no light is emitted until the crystalline mechanoluminescent material has actually fractured, therefore, no false alarms are generated. Scientists have succeeded in doping composite structures for aircraft with fine mechanoluminescent crystals. When an impact cracks the doped resin, it sends a tiny flash of light analogous to a pain signal along the fibres to a detector. Thus, the intensity of light directly gives the magnitude of the damage and the wavelength of the light emitted indicates the location of damage.

Although fracto-mechanoluminescence damage sensor for structures is very important and useful, the systematic correlation between the signal and source, i.e., between the damage (ML intensity) and impact stress or impact velocity is not known till now. In the present paper the modelling of fracto-mechanoluminescence damage sensor for structures is performed and the systematic correlation between the damage (ML intensity) and impact velocity is explored, in which a good agreement is found between the theoretical and experimental results. The present study may be helpful in the development and refinement of fracto-mechanoluminescence damage sensor. In the past, using the fracture mechanics an attempt has been made to correlate the ML intensity and impact velocity, where the derivation is lengthy, involves many assumptions, and correlates the ML intensity indirectly with the impact velocity [28]. In this paper, using a new theory based on successive fragmentation of crystallites, a correlation is developed between the damage and the impact velocity, which is comparatively short and directly correlates the ML intensity with the impact velocity. Furthermore, the present paper explains the basic principle involved in damage sensor.

2. Significance of present study

In our previous paper, we have studied the real-time sensing of the amplitude and duration of impact stress using elastico-mechanoluminescence (EML) of the films of ZnS:Mn and $SrAl_2O_4$:Eu [29], in which the impact of a small ball from a low height onto the ML film was used for the EML excitation. The impact stress was in the elastic region, in which the fracture of ML particles did not take place. It was shown that the impact stress can be sensed by measuring the EML intensity, and the pulse duration of the impact stress can be monitored by measuring the value of time corresponding to the peak of the EML intensity versus time curve. The present study is related to the fracto ML, i.e., the ML induced by fracture of solids, in which applied pressure is high and the damage or newly created surface area is related to the total ML intensity. Therefore, the ML measurement in this case can be used for the monitoring of damage. Thus the present study is completely different from the previous one. Using the theory based on successive fragmentation of crystallites, a correlation is developed between the damage and the impact velocity for the first time. The modelling of fracto-mechanoluminescence damage sensor for structures is performed. Furthermore, new concepts are provided with regard to large and small contact area between the impacted load (or ball) and the ML particles and comparison between the related ML response is made.

3. Mechanisms of fracto ML of crystals

The fracto ML can be understood on the basis of the Langevin model for the creation of charged surfaces during the movement of a crack in a piezoelectric crystal [30]. When a crack moves in a piezoelectric crystal, one of the newly created surfaces gets positively charged and the other surface gets negatively charged in which a strong electric field is generated between the two walls of a crack. The piezoelectric constant is generally of the order of 10^{-12}–10^{-11} Coulomb per Newton ($C\,N^{-1}$) and the stress needed to separate the surfaces of crystals is of the order of $Y/100$ (where Y is the Young's modulus of elasticity of the crystal), which comes out to be order of $10^8\,N\,m^{-2}$. 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, equal to $8.85\times10^{-12}\,C^2\,N^{-1}\,m^{-2}$. Thus, an electric field of the order of 10^7–$10^8\,V\,m^{-1}$ may be generated 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 ML. The field may also cause the dielectric breakdown of the crystals, and the recombination of free charge carriers may give rise to recombination luminescence. Furthermore, the accelerated electrons moving from negatively charged surface towards the positively charged surface may excite cathodoluminescence (CL).

It has been found that, in addition to the piezoelectric crystals, a large number of non-piezoelectric crystals also exhibit ML [31]. Thus, it seems that the charging of newly created surfaces also takes place due to the movement of charged dislocations, barodiffusion of defects in crystals, local piezoelectric field caused by impurities and defects, creation of non-centrosymmetric structure by the stress required for fracture, local piezoelectric field caused by the large strain at fracture, fracturing of centrosymmetric ionic crystals in a direction which actually generates charged surfaces, the presence other phases in solvated materials, presence of non-centrosymmetric phase due to disorder in materials, charging of the sites (like oxygen, halogen, etc.) of different electro-negativity in neutral polar molecules, etc.