A Review on Mechanoluminescent Materials in Structural Health Monitoring

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Abstract

Structural Health Monitoring (SHM) is a diagnostic approach used to assess modern structures, which involve monitoring a structure to detect changes in its structural state. Smart materials play a crucial role in the development of functionality. These materials can sense the surroundings and detect the changes thereof and respond to external stimuli. The application of smart materials allows a better understanding of the structure's conditions, leads to cost-effective infrastructure management, and improves structure lifespan and public safety. This paper presents an innovative smart material using Mechanoluminescence (ML) material as a smart sensor to detect damage in structures that emits light when subjected to external mechanical action. ML materials have great potential in applications to stress sensing techniques, damage sensors, and safety management monitoring systems. The characteristics and potential applications of ML in the field of structural health monitoring are discussed. The research achievements of various well known mechanoluminescent materials for a better understanding of ML phenomena are also reviewed. At present, the development of ML material has been initiated by many researchers as a diagnostic method, and it has to be applied to real social infrastructure.

Keywords: *- Structural Health Monitoring, smart material, Mechanoluminescence material, sensor*

INTRODUCTION

Structural Health Monitoring refers to monitoring that aims to gain knowledge or information about the integrity of in-service structures on a continuous real-time basis. SHM refers to a series of connected sensors to collect and analyse data at every moment during the structure's service life. By implementing the SHM systems, it takes a step forward towards proactive maintenance systems. Thus the goal of the SHM system is to identify and figure out any damage or deterioration state that might occur over the service life.

SHM systems can help identify structural defects in the early stages when repair and rehabilitation will be more cost-effective and efficient. This system was designed to obtain, organise data and to detect damage diagnosis easily. It is a network that provides ease of installation, low cost, flexibility, and applicability. Depending on the type of structure, its environment, and different aspect of structural and durability performance, a series or pair of sensors or smart materials can be used in SHM systems. Sensors or smart materials are fundamental to temperature and humidity, advanced vibration monitoring, or acoustic emission systems.

Another aspect of the SHM system, which is complex for many owners and maintenance managers, is the type of sensors or smart materials that is to be required. Selecting sensors or smart materials is an important task that requires solid structural, material, and environmental engineering. Recent advancements in sensing technology (i.e. MEMS, Acoustic sensors, fibre optics) and latest developments in the Internet of Things (IoT), mobile networks (5G), and wireless connectivity (Wi-Fi, Bluetooth 5) are creating a good platform for the inspection and evaluation of structural systems.

Smart materials are designed materials that achieve unique favourable properties that can be altered by external stimuli such as stress, moisture, temperature, light, or chemical compounds. The conventional or standard materials like bricks, cement, mortar, concrete, steel, etc., shall withstand the alterations. If the functions of sensing and actuation are combined, then the resulting new materials can be called smart materials [1].

Mechanoluminescence (ML) materials are smart materials that can induce luminescence to any mechanical action on solids. Recently, the use of ML has motivated a potential interest in the field of structural health monitoring. The need for the structural health monitoring sensor system is that it should be in-situ, provides real-time continuous evaluation and sensing capabilities. The ML sensors can predict the occurrence of structural failure and detect the location of the defects in the structure. Several applications in structural health monitoring utilising ML material for damage detection, stress sensing, and surface crack detection have been proposed.

In this review work, the characteristics and potential applications of mechanoluminescence material are discussed. Different well-known ML materials studied by many researchers in the field of structural health monitoring are also presented.

MECHANOLUMINESCENT MATERIALS

Sir Francis Bacon created the first discovery of Mechanoluminescence (ML) materials or related phenomenon in the 17th century (1605) [2]–[4], which he recorded in his book, Advancement of Learning, that complex sugar being easily scratch with a knife would produce a sparkling light. Mechanoluminescence has been known for over 400 years, but the mechanism of the ML has not been understood fully [3]. In general, luminescence is a response to mechanical stimuli termed Mechanoluminescence.

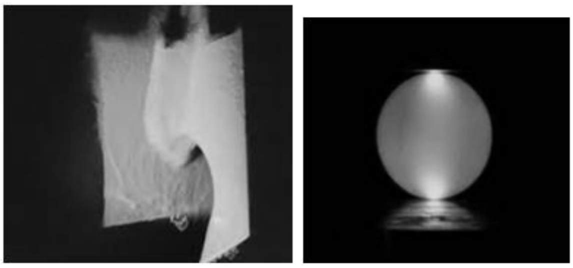

Figure 1 Mechanoluminescence Material

CLASSIFICATION OF ML MATERIAL

There are two types of the physical process which induces ML in solids:

1. Deformation-ML (DML)
2. Tribo-ML (TML)

Deformation-ML depends on the material under deformation, and it is not dependent on the material used to produce the deformation. Tribo-ML depends upon the nature of the material which is under deformation as well as on the material which is used to produce it.

DML is subdivided into three types:[2], [5]

1. Elastico-mechanoluminescence (EML)- light emission induced by elastic deformation.
2. Plastico-mechanoluminescence (PML)- light emission induced by plastic deformation.
3. Fracto- mechanoluminescence (FML)- light emission induced by fracture of solids

TML is subdivided into three types: [2], [5]

1. Electrically Induced ML- light emission induced due to the electric field.
2. Chemically Induced ML- light emission induced due to the chemical reaction.
3. Thermally Induced ML- light emission induced to the black body when crystals are cut with sharp material.

Till 1950, the reports were available on fracto-ML only, but the method of FML was not helpful in the advancement of non-destructive sensors. In this relation, all attempts were made for the development of non-destructive mechanoluminescent materials. EML is a non-destructive mechanoluminescence that is reproducible

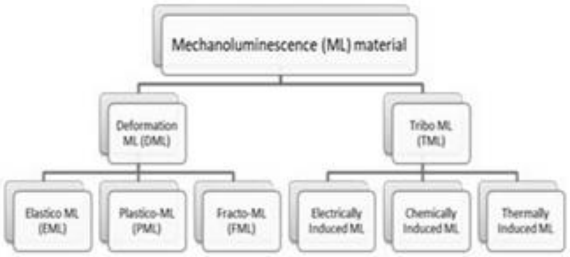

Figure 2 Schematic diagram for types of Mechanoluminescence [6]

Characteristics of ML Material

As reported by Chandra et al. (1998), Mechanoluminescence has [2]:

1. Deformation Characteristic
2. Temporal Characteristic
3. Thermal Characteristic
4. Spectral Characteristic

Apart from this, the characteristics of ML material are as follows:

- It has great potential for damage sensing when subjected to force. [7]
- The defects invisible with the naked eye and microscopic cracks in small parts can be detected. [7],[8]
- It can provide a high-resolution representation of the corresponding strain/stress distribution. [7]
- It has the ability of luminescence to convert mechanical energy to optical radiation. [9],[10]
- It is possible to visualise stress distribution or strain measurements by other sources such as piezoelectricity, magnetic restriction, and ultrasound radiation. [8],[11]

- ML material can emit light when subjected to mechanical loads. [11]

Mechanoluminescence Measurement Devices

Two types of devices are generally needed for the ML measurements; one for deforming the samples and the other for the spectral measurements.

1. The techniques used for deforming the crystals in ML measurements are: (1) compression (2) bending (3) stretching (4) loading (5) piston impact or impulsive (6) needle impact (7) cleaving and cutting (8) laser (9) shaking (10) air-blast (11) scratching (12) grinding and milling (13) tribo or rubbing. [2]
2. ML intensity can be measured using a photomultiplier tube, semiconductor diodes, photodiodes, charge-coupled device (CCD) cameras, high-speed cameras or portable spectrometers. [2], [4], [12]

APPLICATION OF ML MATERIAL

1. Some of the applications which can be applied for real-world applications are illustrated below: [8], [11], [13]–[15].
2. It provides a self-indicting method for detecting fracture of solids and microscopic processes during deformation [2].
3. The ML sensing materials have the potential for their use in stress sensors [12], [13], [16], ML signals which are recorded, provides a direct measure of torque.
4. ML has potential application in damage sensors, impact sensors [7].
5. When a tensile force is applied, the ML can convert the ML intensity values to stress distributions [11].
6. ML imaging techniques are used to detect active cracks and invisible defects [17].
7. ML has a far faster imaging technique for visualising the crack propagation in solids than conventional crack monitoring techniques [17], [18], as well as the stress near the tips of cracks [12], [18].
8. ML sensor has been applied to buildings, bridges [17], high-pressure vessels [19] and welding points of pipelines [20]

Well-known ML Materials

Different ML sensing materials such as ZnS:Mn, ZnS:Cu, Sr2MgSi2O7:Eu(SMSE), SrCaMgSi2O7:Eu(SCMSE), SrAl2O4:Ce, SrBaMgSi2O7:Eu (SBMSE), SrCaMgSi2 O7:Eu, SrAl2O4:Eu,Dy (SAOED), Ca2Al2SiO7:Ce, SrAl2O4:Eu (SAOE), ZnS:Mn,Cu, and so on- have been developed as potential ML sensors [8], [12], [13]. These materials can be used in possible substantial and substitutive methods for applications in structural health monitoring. They show bright ML emissions and can be used for sensing applications.

The ML material based on strontium aluminate and zinc sulphide has gained more attention due to its intensely bright emission. Table 1 shows the comparisons between the well-known ML materials.

Table 1- Comparison between the well-known ML materials [8], [12], [21]

Crystals	Wavelength peak of ML light emission	ML intensity
$SrMgAl_6O_{11}$:Eu	512	Very high
$Sr_2MgSi_2O_7$:Eu	460	High
$SrCaMgSi_2O_7$:Eu	490	High
$SrBaMgSi_2O_7$:Eu	440	Moderate
$SrAl_2O_4$:Eu, Dy	520	High
$SrAl_2O_4$:Eu	520	High
ZnS	450	Moderate
ZnS: Mn	580	High
ZnS: Cu	556	High

SrAl2O4:Eu, Dy (SAOED) has been considered one of the most promising materials but now ZnS: Mn, Cu was substituted by SAOED as they exhibit the brightest luminescent emission. Fontenot et al. (2012) tested some selected luminescent materials in a low-cost and straightforward apparatus to determine the relative brightness of each luminescent material. It was found that ZnS: Mn, Cu was the brightest inorganic material of the materials tested among others during this research [22].

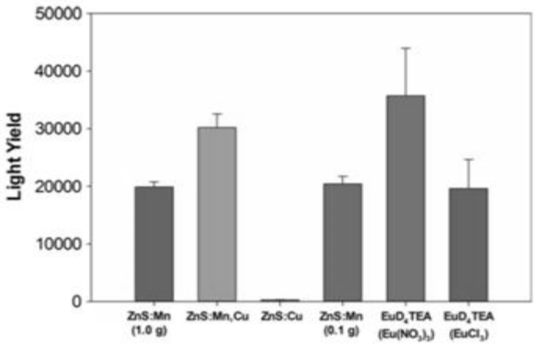

Figure 3 Bar chart showing ML emission for a selection of materials [22]

Some of the well-known ML materials are described below:

1. $SrAl_2O_4$:Eu

$SrAl_2O_4$:Eu (SAOE) is considered the most efficient and promising ML sensing material for SHM applications. It emits light when it is subjected to mechanical action. The loading rate dependence of $SrAl_2O_4$:Eu and the light intensity under stationary loadings are the most important characteristics of SAOE to be used for SHM purposes. In 1999, Xu et al. researched the ML materials, and SAOE were developed as a high luminescent material. It enables the visualisation of light with the naked eye in daylight. Sohn et al. have also reported that $SrAl_2O_4$:Eu has the brightest luminescent with Eu of 0.01 mol, and they used them for detecting crack at the tip. The emission peak intensity of SAOE is equal to wavelength 520 nm, and it can be acted as a light source [12]–[14]. Wang et al. performed a test using SAOE; and detected crack and evaluated stress concentration and stress intensity factors [7]. On the susceptibility of small-strain range, Yoshida et al. succeeded in increasing the sensitivity of $SrAl_2O_4$: Eu. The study demonstrated that the ML intensity of $SrAl_2O_4$: Eu is more than 100 mcd/m2 when strained at 1000 µst [23]. Terasaki et al. used $SrAl_2O_4$: Eu as an ML sheet sensor to an old bridge to visualise active crack and invisible progressing micro-crack [17].

2. ZnS: Cu

ZnS: Cu has the potential of stress sensing by itself as well as it is a UV source, and it emits green light. Sik et al. used ZnS: Cu as a non-contacting torque sensor in the study. They showed that when loading was applied, there was rapid decay in PL and less in ML. They found out that the luminescent material was able to sense mechanical stress [16]. Joeng et al. studied the ML spectrum of ZnS: Cu. They reported that it showed the brightness of 120 cd/m2 and durability of over 100000 repeated mechanical actions. It is also determined that the spectrum shifts differentially in contact with mechanical stress. This study found out that the ML emission peaked at 510 nm wavelengths at low-stress rate stimuli, and the spectrum shifted to 3 nm wavelengths at high-stress rate stimuli. They also have identified that the blue emission of the composite film has a wavelength of 456 nm with a decrease in green emission at high-stress rate stimuli. [24]

3. ZnS: Mn

ZnS: Mn is one of the brightest ML materials, and it emits orange light. Therefore, it is the main candidate for structural health monitoring. It is not expensive and has a large emission yield, and it can be used as an active element for stress sensing [3]. At first, Otawale et al. conducted a study on the ML-based sensor, ZnS: Mn phosphors, for the structural health monitoring in concrete structures. He reported that the dispersion of ZnS: Mn is critical as their density is high. It showed that the increase in ZnS: Mn concentration decreases the tensile strength [25]. Chandra et al. reported using ZnS: Mn as real-time sensing of the amplitude and duration of impact stress [26]. Ali et al. noticed that increasing the doping concentration of Mn in ZnS shows a decrease in energy band and optical bandgap [27]. The response of ML increases as the concentration of ZnS: Mn increases in the system. The studies also prove that it can be used for structural health monitoring applications. [25]

4. ZnS:Mn, Cu

ZnS: Mn, Cu is the most prominent ML material that SAOED substituted as they exhibit the brightest luminescent emission. The doped materials with different luminescent materials emit distinct colours, and co-doping enhances the ML intensity. Therefore, co-doping Mn and Cu with ZnS increase the intensity of ML. If the ML material is coated on the solid surface, it acts as a small sensor when a load is applied to the specimen. Selma m. et al. reported that the emission peak showed a longer wavelength in ZnS: Mn, Cu than other ML materials. The peak position remains the same after increasing the concentration of co-doped Mn and Cu [21]. Many researchers have used ZnS: Mn, Cu as ML material due to its intense EML emission visible in naked daylight. ZnS: Mn, Cu offers long life, consistent and reliable performance in structural health applications.

5. EuD$_4$TEA

EuD$_4$TEA (europium-doped dibenzoy lmethidetriethy lammonium) is a triboluminescent synthesised material that can be applied to visualise stress near the tip of the crack, sensors for the detection of cracks inside concrete beams and earthquake detection. It can also be used as an ML light source in the determination of ultrasonic power and laser. Fontenot et al. reported that EuD$_4$TEA emits ML when struck; it produces light upon crystalline material. It was found that EuD_4TEA has more emission yield than other materials [3]. The intensity of ML material depends on the ligand molecule's flexibility, and EuD_4TEA has excellent flexibility compared to other inorganic luminescent materials. The ligand molecules can quickly move in all directions when stress is applied to ML material; this helps the electrons transit to higher energy levels. When PVP (polyvinylpyrrolidone) is added to EuD_4TEA, the PL and ML intensities are higher than the material without PVP [28]. The FML of EuD_4TEA is so intense that the ML material can be seen with naked eyes. [25]

CONCLUSION

Many researchers and journals have shown that SHM practice has now become a well-established subject during the past decades. As a result, in the present paper, the topic of Mechanoluminescence sensing in SHM practice was widely discussed and reviewed, particularly the applications in civil engineering structures. First, the concept of SHM was explained. Then the background theory associated with the ML sensing material; its types, characteristics, ML measuring devices and applications were described and elaborated. It is understood that the ML material has wide applications in the field of civil engineering. Despite the promising application of Mechanoluminescence material, the research field is still facing difficulties in understanding the mechanism of ML. The development of ML material is necessary for research and practical applications. To enhance the resolution of ML sensing, further analysis has to be carried out to use this technique in civil engineering.

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