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High strain rate behavior of mechanoluminescent material dispersed in a soft polymer matrix

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***Abstract*—** Mechanoluminescence (ML) is the emission of light from a solid material in response to mechanical stimuli [1]. Mechanoluminescent materials are classified based on the types of stress activation required for luminescence behaviour. In this paper, we propose the study of light emission characteristics of an elastico-mechanoluminescent (EML) material dispersed in a soft polymer matrix, under high-strain compressive loading for a qualitative and quantitative testing of onsite strain. We developed a strain sensor by creating a composite material through the combination of a polydimethylsiloxane (PDMS) matrix structure and strontium aluminate, europium, and dysprosium doped (SAOED) crystals. SAOED crystals possess a strong luminescence behavior, which has led to their proliferation as a viable optical sensor. Composite materials were tested using a modified Kolsky bar and high-speed camera. The light-emitting characteristics of the SAOED crystals in response to mechanical stimuli allows for the quantification of stress–strain experienced by the composite material. The light intensity, which is measured by a complementary metal–oxide–semiconductor (CMOS) sensor in a high-speed digital camera, provides a quantitative measure of the strain-rate. Light-emitting characteristics of the EML material and the strain behavior of the material were studied.

Keywords: mechanoluminescent crystals, high strain-rate, elastico-mechanoluminescence, strain sensor, SAOED

I. Introduction

Measurement of stress and strain can be carried out via non-contact or contact methods such as digital image correlation (DIC) [2] and piezoresistive sensing [3]. In recent years, there has been concerted effort to develop noncontact strain-sensing technology for real-time monitoring of structures such as electronic speckle pattern interferometry (EPSI). However, this process requires tedious data processing techniques for stress and strain characterization of a material [4]. Non-contact strain sensing for structural health monitoring (SHM) of mechanical, civil, and aerospace structures has garnered interest in recent years [5-6]. High-impact forces, which are currently detected by SHM, have posed a great threat to the reliability of aerospace structures for over 50 years [7]. This problem has led to advancement in sensor technologies that allow for the monitoring and immediate measurement of stress–strain on these structures. These advanced sensors pose a significant challenge, as only trained professionals can fully interpret the data acquired from these measurements. Therefore, there is a need for an easy-to-use qualitative and quantitative stress–strain sensor for SHM.

Material that possesses the unique characteristic of mechanoluminescence (ML) makes it suitable for qualitative and quantitative stress–strain measurements. ML material emits light in response to mechanical stimuli such as tension, pressure, bending, compression, etc. ML material can be grouped into three categories: elastico-ML (EML), plastico-ML (PML), and fracto-ML (FML). These categories correspond to luminescence induced by elastic deformation, plastic deformation, and fracture, respectively [1]. The stress-induced luminescence behavior of fracto-ML and plastico-ML materials pose a severe challenge, as light is emitted post yielding. Hence, EML has been widely adopted for strain-sensing purposes, as it allows for non-destructive testing. This mechanical behavior of EML has led to its widespread use in sensing applications, such as a uniaxial tensile test for full-field strain measurement [8]. The mechanical and luminescent properties of EML materials provide both qualitative and quantitative measurements of strain.

Recently, Ryu et al. [9] proposed an ML composite based on polydimethylsiloxane (PDMS) for the measurement of high strain rate. They reported the light characteristics of the PDMS–ML composite europium tetrakis (dibenzoylmethide)-triethylammonium (EuD_4TEA) crystals under high-strain compressive loading using a Kolsky bar and an image processing technique. EuD_4TEA crystals are reportedly one of the brightest ML materials [10], and hence are used as a viable optical sensor. However, EuD_4TEA crystals exhibit FML properties, which limit their application for non-destructive testing.

In this paper, we characterize the light-emitting properties of a PDMS-based EML composite for the direct visualization of stress and strain under high-strain compressive loading using a

Kolsky bar. The EML crystal used is strontium aluminate, europium, and dysprosium doped (SAOED), which possesses a green phosphor. The SAOED crystal is uniformly dispersed in a PDMS matrix. A Split-Hopkinson pressure bar or Kolsky bar is widely used to measure the stress–strain relation of material under high-impact load. Strain and strain rate of the sample are derived from the pulse data generated by strain gauges on the input and output bar, assuming homogeneous deformation of the sample. A complementary metal–oxide–semiconductor (CMOS) sensor in a high-speed digital camera is used to measure the light emitted from the composite material. Image processing of the acquired 24-bit RGB images from the high-speed camera is used to quantify the light emission characteristics of SAOED crystals in the polymer matrix.

We began this study by creating a composite material made of SAOED crystals uniformly dispersed in a PDMS matrix. The composite material was then subjected to high-strain compressive loading. The strain data acquired from the Kolsky bar and images produced by the high-speed camera were then processed to obtain a quantitative relationship between strain and light intensity.

II. EXPERIMENTAL METHODOLOGY

A. Materials

PDMS (Sylgard 184 kit) was acquired from Dow Corning Corp., and SAOED crystals were purchased from Sigma–Aldrich and used as received.

B. Composite Fabrication

The PDMS mixture was first made by mixing a 10:1 weight ratio of PDMS base to curing agent. Then a 1:1 weight ratio of PDMS mixture to SAOED crystals was mixed and stirred. The combined mixture of PDMS and SAOED crystals was then heated in a polyethylene terephthalate (PETE) container for ~40 min on a heated bed at 52 °C (Fig. 1). The initial heating of the combined mixture increases the viscosity of the PDMS mixture and prevents the sedimentation of the SAOED crystals. Dispersion of the EML crystal was verified using an inverted microscope (Fig. 2A). The mixture was then degassed in a desiccator to remove air bulbs and poured into a circular aluminum mold with an inner circular diameter of 15 mm and a height of 4 mm. The combined mixture of SAOED crystals and PDMS mixture was then cured over a heated bed at 100 °C (Fig. 1). Six composite samples were made for each test.

C. Experimental Setup

A high-speed CMOS sensor camera (Phantom V1611) was used to photograph the ML emission during loading, and a Split-Hopkinson pressure bar or Kolsky bar, supplied high-strain compressive loading. The high-speed camera, set with consistent exposure time, was positioned perpendicular to the Kolsky bar ~30 cm from the sample. The Kolsky bar consists of a striker, input bar, and output bar, with strain gauges attached on the input and output bars. Two strain gauges were placed on the input bar and output bar, which were located close to the centre of the bar. The strain gauges were positioned 180° from each other to negate bending waves when connected to a half-bridge circuit. Compressed nitrogen gas was used to drive the striker of the Kolsky bar. The pressure of the gas released is controlled by a valve on the compressed gas tank (Fig. 3). A hollow output bar

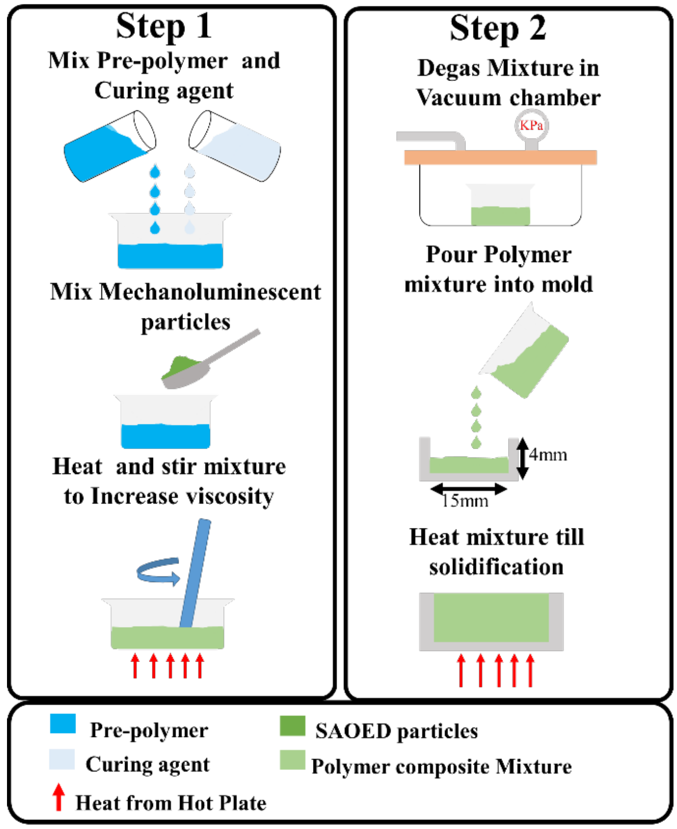

Figure 1. Fabrication process of strontium aluminate, europium, and dysprosium doped composite.

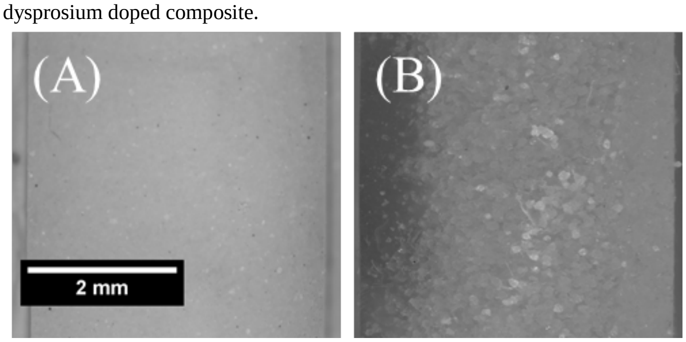

Figure 2. Mechanoluminescent crystals in polymer matrix. (A) Crystals suspended in the polymer matrix. (B) Initial result showing sedimentation of strontium aluminate, europium, and dysprosium doped (SAOED) crystals.

was used to increase load sensitivity [11]. National instrument USB-6341 was used for data acquisition from the strain gauges, and data acquisition occurred at 100 kHz. A relay was used to accurately synchronize the start time of the high-speed camera and the Kolsky bar (Fig. 3).

To begin testing, the PDMS–EML composite was consistently photo-excited by an 80 W LED lamp with a wavelength of 400–700 nm (white light) for ~2 min. This step ensured that the sample was fully saturated with the same photo-excitation power. An aging time of ~2 min immediately

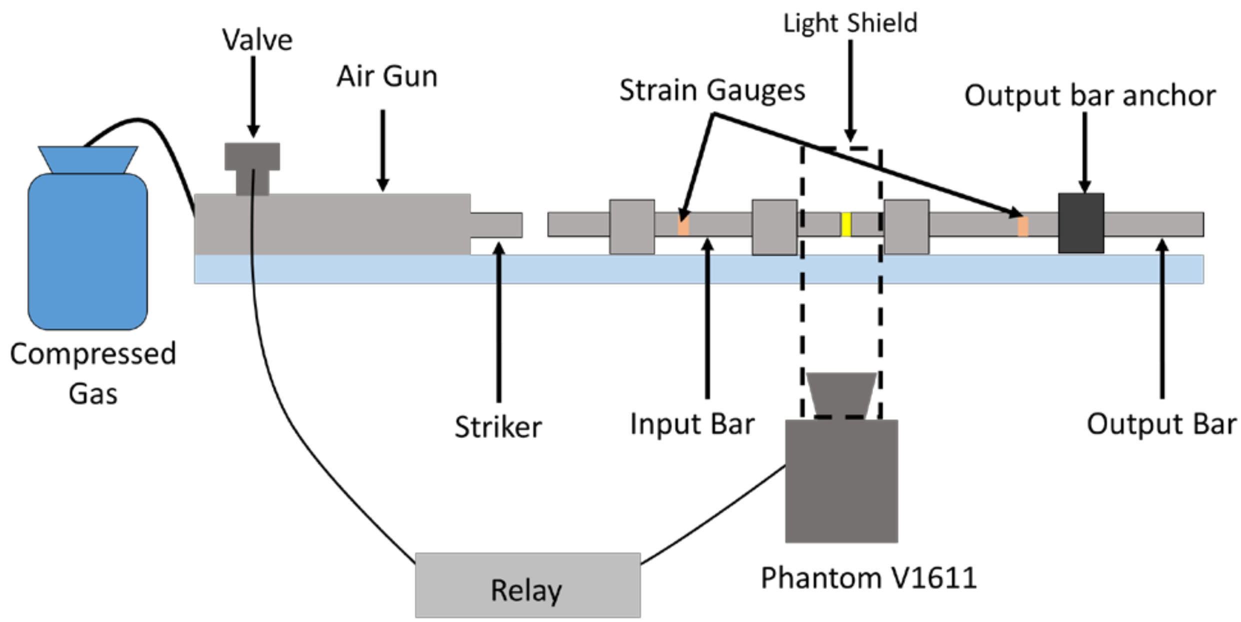

Figure 3. Experimental setup consisting of a Kolsky pressure bar and high-speed camera.

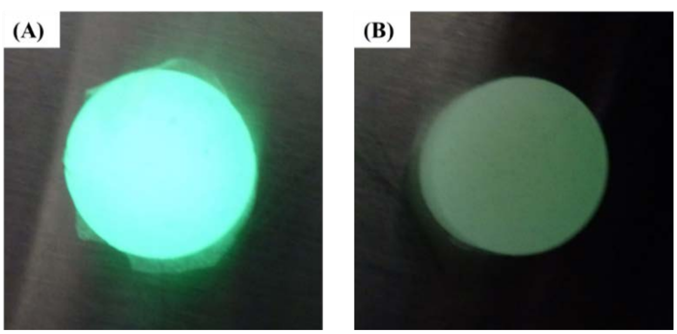

Figure 4. Photo-excitation of PDMS–EML composite. (A) Photo-excitation of PDMS–EML composite before aging. (B) Photo-luminescent stress-free decay of PDMS–EML composite.

followed this step, to minimize the effects of stress-free photo-luminescent decay to maximize ML sensitivity [8]. The PDMS–EML composite was aged in a dark environment before the loading was applied (Fig. 4).

III. RESULTS AND DISCUSSION

The light emission characteristics of the PDMS–EML composite were studied first, followed by derivation of strain from the pulse generated in the Kolsky bar. After aging the composite, the material was subjected to a high-impact compressive load from the Kolsky bar. The initial test was performed by controlling the shot pressure (520 kPa) from the air gun (Fig. 3). Image data acquired from the high-speed camera at a frame rate of 50,000 frames/s and data from the strain gauges which were acquired at higher frequency were synchronized with timestamps. Image processing techniques were then used to characterize the light emission characteristics of the PDMS–EML composite.

Image processing involved exporting the video file from the camera in 24-bit AVI (Audio Video Interleave) format, with a custom image resolution of 64 × 200. From the RGB data collected green pixel values were chosen, as SAOED crystals possess a green phosphor. The green pixel values of the images were extracted, and an arithmetic mean of the values was used to quantify the intensity of light emitted. Green pixels could attain a mean value of 255 for very bright green and 0 for dark green. A second-order, low-pass filter and normalization were applied to the mean green pixel data to understand the emitting characteristics of the PDMS–EML composite (Fig. 4). The filtered and normalized mean green pixel data (hereinafter mean green pixel intensity, MGPI) were then plotted with respect to time (Fig. 5).

Fig. 5 shows the luminescence behavior of the PDMS–EML composite during high-impact loading. The luminescence behavior displayed by the composite was similar to the pulse generated by the Kolsky bar.

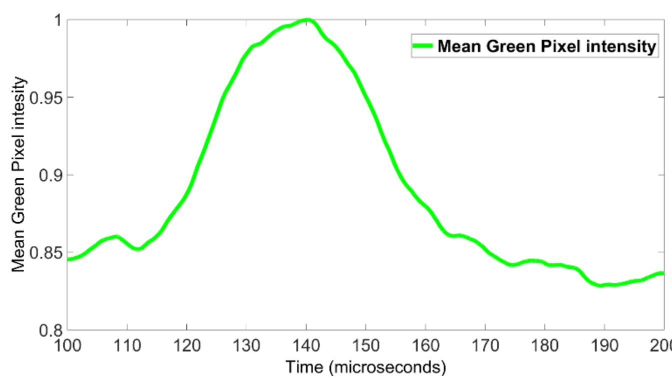

Figure 5. Quantification of light-emitting characteristics of SAOED crystals under compressive load.

The strain data were then correlated with the MGPI data with the aid of timestamps (Fig. 6). The luminescence behavior of the PDMS-EML composite does not provide a 1:1 correlation with the strain. However, has an instantaneous response to the applied strain.

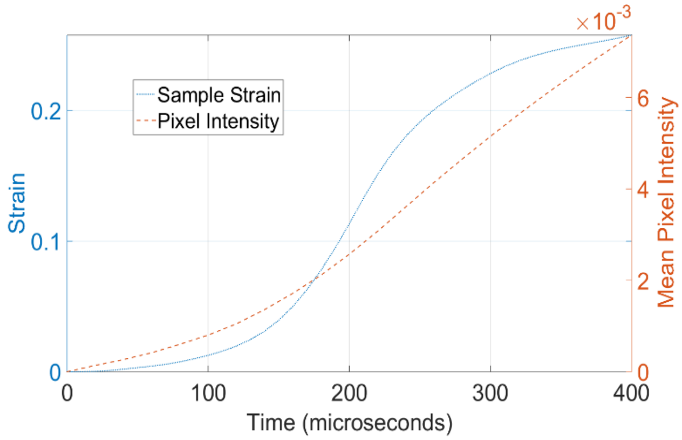

Figure 6. Strain and MGPI of PDMS–EML composite at a shot pressure of 520 kPa.

IV. Conclusion

In this paper, we studied the behavior of an EML material dispersed in a PDMS matrix under high-strain compressive loading. For this purpose, a PDMS–EML composite was created using a clear silicone elastomer and SAOED EML crystals. The crystal dispersion in the polymer matrix was also studied to verify its uniform distribution within the matrix. To carry out mechanical testing, a Split-Hopkinson pressure bar or Kolsky bar was used to produce a high-strain compressive load on the composite material. A CMOS sensor high-speed camera was used to collect images of the light-emitting characteristics of the PDMS–EML composite. Image and data processing techniques were used to quantify the light-emitting characteristics of SAOED crystals in a soft polymer matrix as well as the mechanical behavior under a high strain rate.

Preliminary results of the PDMS–EML composite show great promise. However, the transmittance of the load to the crystals is limited in a soft polymer matrix, as the strain transmittance is low. Hence, the magnitude of light intensity observed was limited.

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