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Dynamic Visualization of Stress Distribution on Metal by Mechanoluminescence Images

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Abstract : We have successfully demonstrated that the stress distribution of a metal material can be directly displayed by coating the surface of test objects with an upgraded strong mechanoluminescence (ML) material of $SrAl_2O_4$:Eu (SAO). In this paper an aluminum plate with the SAO sensing film was applied to experimental analysis of stress concentrations. And the comparison with a numerical analysis showed that the ML intensity of SAO sensing film correlates linearly with stress on metal surface and the observed real-time ML images quantitatively reflect stress concentration. This novel visualisation technique can be applied to view stress concentration in various fields such as modelling, manufacturing and demonstration of industrial products as well as to point out danger areas in structural objects such as pipelines and bridges.

Keywords : Visualization, Mechanoluminescence, Stress distribution.

1. Introduction

As seen from the collapse of the Mississippi River Bridge in Minneapolis (01/08/2007) and the bursts of a steam pipe in midtown Manhattan (18/07/2007), measurement of stress distribution is of great importance for structural objects in order to improve their reliability and safety. Several typical techniques are conventionally employed for the detection of stress, such as electric resistance strain gauges and piezoelectric sensors, but they are not suitable for analyzing the distribution of stress because of the limitations of sensor size and measurement point. Other intricate methods utilizing optical signals, such as experimental stress analysis utilizing photoelastic and photoplastic effects, X-ray diffraction methods, optical fiber networks embedded in composites, thermography based on thermoelastic analysis, and electronic speckle pattern interferometry (Toyooka et al., 1995; Matsuda et al., 2007), liquid-crystal coating (Nakano et al., 2006), have been in use for remote detection. However, currently, these methods are still complex and not suitable for real-time health monitoring of structures. Therefore, a simple technique for real-time visualizing the stress distribution is needed.

Mechanoluminescence (ML) is a light emission induced by mechanical deformation during applied stress. In general, ML can be divided into fractoluminescence and deformation luminescence (DL), which corresponds to luminescence induced by fracture and mechanical deformation of solid, respectively (Hayashiuchi et al., 1990; Krell et al., 1982,; Walton, 1977). Reversible luminescence in the elastic region suggests possible uses of the DL phenomena in direct view of stress distribution. An exciting evolution has been achieved in ML material, which enable us to directly display stress distribution (Wang et al., 2005; Xu et al., 1999 and 2004). For the detection of stress on an area, it is a much simpler and intuitional way than other intricate methods utilizing optical signals. Until now, application of ML to a stress sensing technique for a test object such as a metal has not been reported yet because the strain of metal is too small to display. Metal plays an important role in various structural objects such as aircrafts and bridges. Here we show that the stress distribution of a metal material can be directly displayed by coating the surface of test objects with an upgraded strong ML film of $SrAl_2O_4$: Eu (SAO).

2. Experimental Process

In order to realize the visualization of stress distribution on a metal material in which deformation is generally small, ML intensity was enhanced by one order of magnitude than that reported previously in the $SrAl_2O_4$:Eu system (Xu et al., 2004) by co-doping Ho. The sample was prepared by mixing a high purity (> 99.9 %) ultra fine powder (< 0.2 μm) of $SrCO_3$, α-Al_2O_3 and $Eu(NO_3)_3{\cdot}2H_2O$ with a small amount of Ho_2O_3, calcining at 1300 °C for 4 h in a reducing atmosphere (H_2 + Ar). Furthermore, a resultful ML paste and method of preparing a uniform film of the SAO coating for screen-printing the specimen was developed. The resulting ML sensing film adhered to the metal substrate tightly enough to deform identically with the underlying metal without any peeling. The luminescence of the present SAO film was extremely high and enabled the monitoring of stress distribution of a metal under various stress conditions in real time using a high-speed camera.

As shown in Fig. 1, we set up a ML image system consisting of three parts: (1) a material test machine to apply a mechanical load (MTS 810, MTS Corp.), (2) a high-speed camera to capture ML images and (3) a computer to set up system software and record real-time ML images (FocusScope SV200-i, Photron Corp.).

Figure 2 shows the relationship between the stress and ML intensity, which was measured by this ML image system and an aluminum specimen (225 × 25 × 3 mm^3 without circular holes) coated with the present SAO sensing film. It can be observed that the ML intensity is almost linearly proportional to stress and it was used as the calibration curve for the following quantitative analysis (40 MPa ~ 170 MPa region). Such a relationship was found for both compressive and tensile tests. The ML-stress relationship showed good reproducibility around room temperature in our measurement conditions (temperature 25 ± 5 °C, relative humidity 40 ± 20 %). The investigation for wide temperature region (−15 °C ~ 80 °C) is under way.

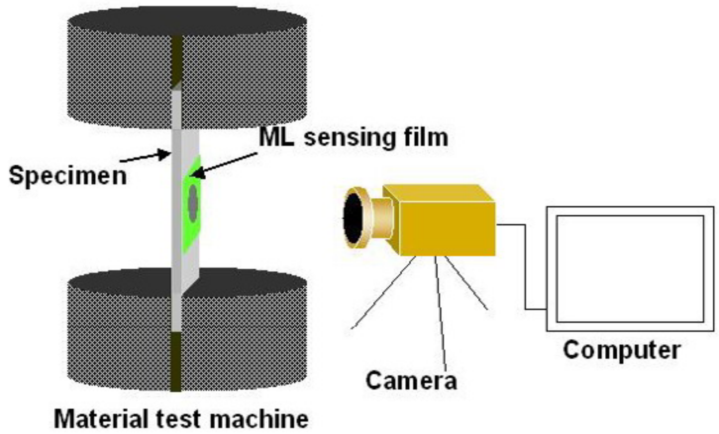

Fig. 1. ML image system.

Considerable research has been carried out on the stress concentrations produced by circular holes, and specific results have been obtained utilizing theoretical calculations and experimental measurements (Howland, 1930). In order to demonstrate the capability of detecting stress distribution using this novel visualization technique, an aluminum plate (JIS A5052, Young's modulus 68 GPa) with dimensions of 225 mm by 25 mm by 3 mm was prepared as a tensile experimental specimen and a hole of 10 mm diameter was bored in the center. Figure 3(a) shows a typical coated specimen used in the tensile test. The coated specimen was set on the material test machine. A tensile load was applied with a triangular wave up to 5 kN at a rate of 5 kN/s. Simultaneously, the ML images were recorded at a frame rate of 250 fps using the high-speed camera. Experiments were carried out in a dark room at room temperature (25 ± 5 °C). We repeated the acquisition of ML images several times under the same experimental conditions and confirmed the same images could be obtained.

A finite element method (FEM) calculation for stress distribution was performed using the commercially available finite element package ANSYS 10.0. In this numerical analysis, we simulated a quarter of the axial symmetry of the specimen, as shown in Fig. 3(b), with the following boundary conditions: symmetry conditions at edges AE and BC, and an applied uniaxial tension at edge CD.

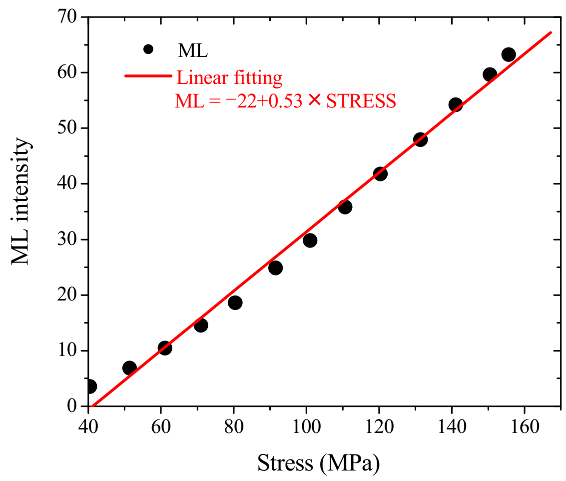

Fig. 2. Calibration curve between tensile stress and ML intensity.

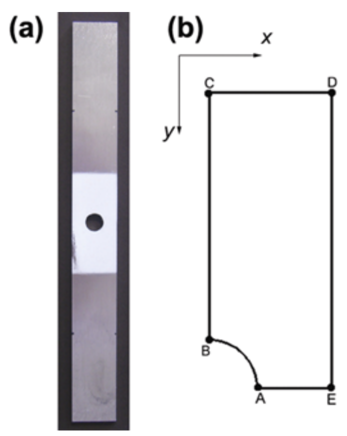

Fig. 3. A typical coated specimen used in the tensile test (a) and the FEM model (b).

3. Results and Discussion

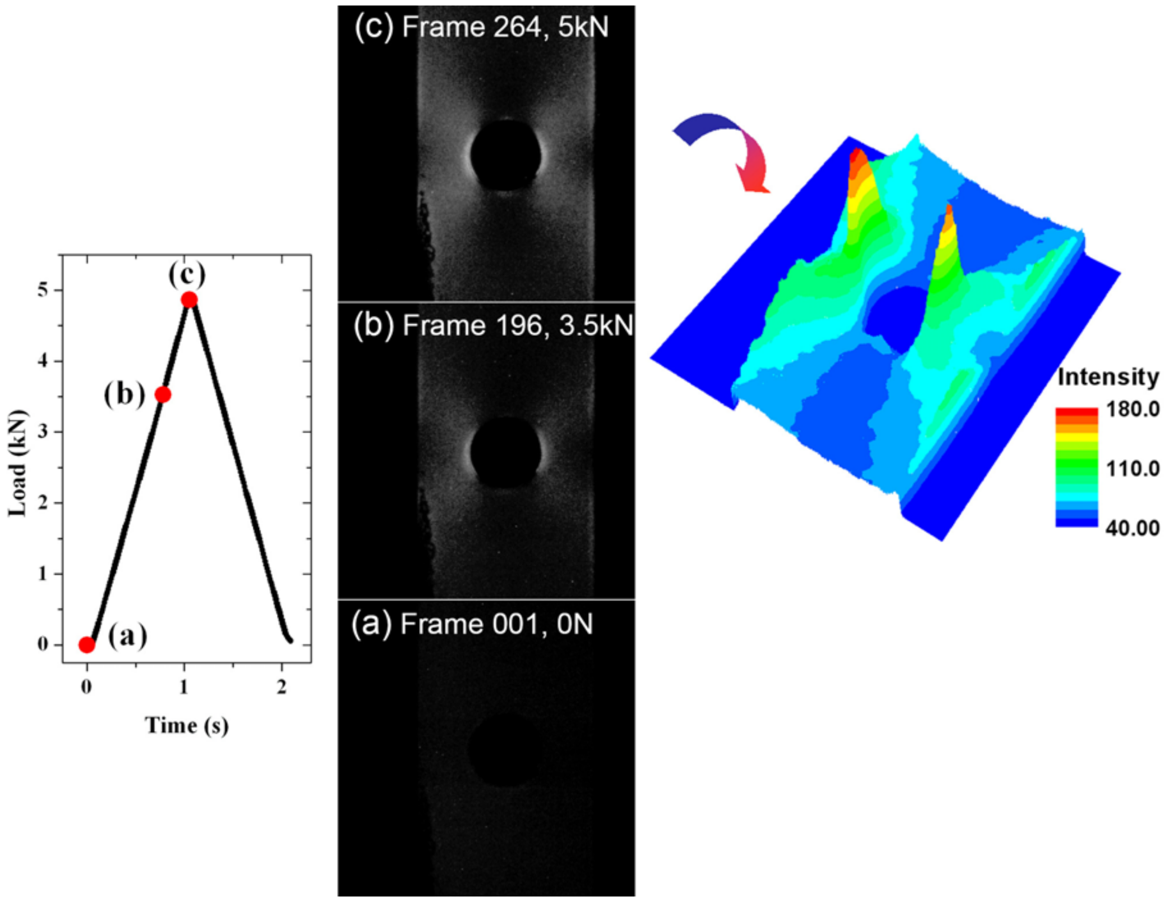

Fig. 4. Real-time ML images. Sequences of ML images were recorded by a high-speed camera during the tensile load cycle as shown in the left plot, reflecting real-time images of stress concentration. The three-dimensional analysis diagram (right) shows ML image (c), in which colors correspond ML intensity.

Figure 4 shows typical ML images during one tensile load cycle, where images (a) to (c) correspond to each load point as indicated in the left plot in Fig. 4. It can be clearly seen that ML images with a characteristic pattern gradually appear with increasing tensile load. In particular, a strong ML can be observed around the hole, implying that a large stress concentration is generated around the hole. In order to examine the observed ML distribution quantitatively, we took the example of Fig. 4(b), an ML image at 3.5 kN load. First, the ML distribution was corrected by subtracting the background distribution (Fig. 4(a)) at 0 N. Second, the corrected ML image was compared with the stress distribution calculated by FEM. Figure 5 illustrates the distributions of the ML intensity and the stress along AE in one plot. These results indicate that the ML intensity of the SAO sensing film correlates linearly with the stress on the metal surface. The corrected ML image is displayed in pseudo-color, as shown in Fig. 6(a), wherein the ML intensity is transformed into stress according to the calibration curve between stress and ML intensity (Fig. 2).

The stress distribution calculated by FEM is shown in Fig. 6(b) and is in complete agreement with the observed ML image (Fig. 6(a)). According to the numerical analysis, when the specimen is pulled along the y direction in Fig. 6(b), maximum stress is generated at point A, which is the intersection of the minimum section part and the edge of the hole. Further, along the edge of the hole, the stress is observed to decrease gradually until point F, at which minimum stress is generated, before increasing slightly until point B again, which is the compressive stress. In addition, the stress along A-E rapidly decreases.

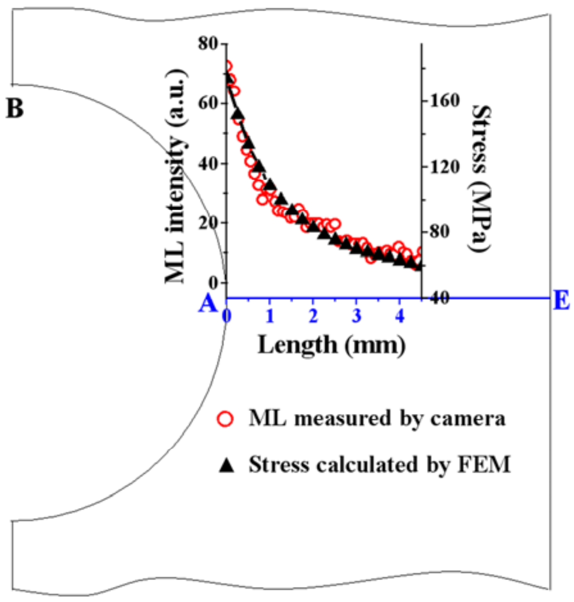

Fig. 5. Comparison between the ML intensity and the stress on the minimum section AE. The ML intensity at 3.5 kN load is shown and agrees with the stress calculated by FEM.

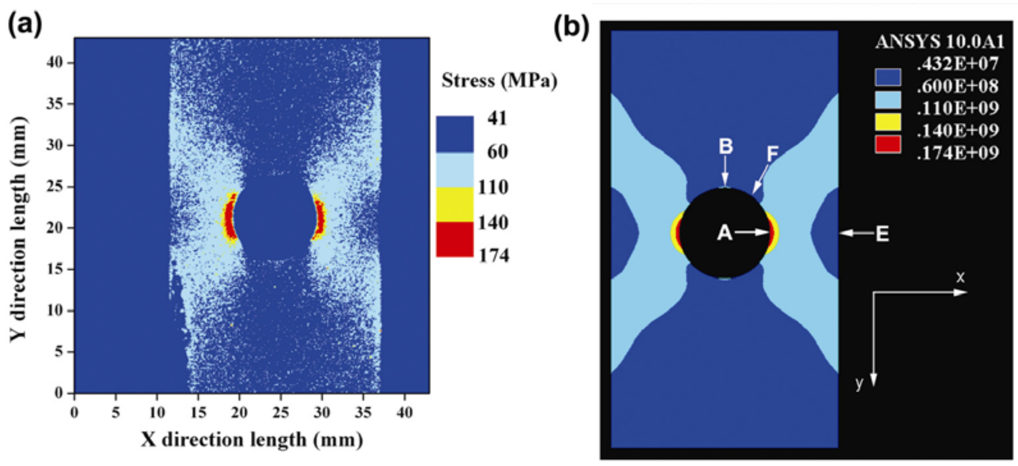

Fig. 6. Comparison between the ML image and the result of FEM calculation. (a) The ML image of 3.5 kN is transformed into stress according to the calibration curve between stress and ML intensity (Fig. 2). (b) The stress distribution calculated by FEM is shown when the specimen is pulled along the y direction by 3.5 kN load.

The observed ML images clearly show these characteristics of the stress changes in the specimen. Such a good correlation between the ML image and the stress distribution indicates that the extent of the stress concentration can be quantitatively visualized in real time using this technique. Moreover, as if viewing a live display of stress distribution, we could see the stress distribution directly from the emission intensity with the naked eyes, which is more convenient than with other methods using optical signals such as photoelasticity that require interference pattern analysis.

4. Conclusion

In this paper we demonstrated that the stress distribution of a metal substrate could be directly displayed by coating the surface of test objects with a strong ML film. Utilising this novel technique, a real-time system for monitoring stress dangers (abnormality) can be developed, and then the system can be tied up by a network to establish a comprehensive safety monitoring system to detect danger signs in structural objects such as tunnels and bridges.

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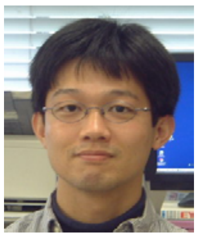

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