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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 SrAl2O4: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; Kreil 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 intuitive 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 SrAl₂O₄: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 SrAl₂O₄: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 SrCO₃, α-Al₂O₃ and Eu(NO₃)₃·2H₂O with a small amount of Ho₂O₃, calcining at 1300 °C for 4 h in a reducing atmosphere (H₂ + 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 mm³ 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.

Figure 1. ML image system.