Non-contact measurement of acoustic emission in materials by laser interferometry

M. Enoki\textsuperscript{a,}* , M. Watanabe\textsuperscript{a}, P. Chivavibul\textsuperscript{a}, T. Kishi\textsuperscript{b}

\textsuperscript{a}Department of Materials Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
\textsuperscript{b}National Institute of Advanced Interdisciplinary Research, 1-1-4 Higashi, Tsukuba Science City 305-8562, Japan

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Abstract

The non-contact measuring system of acoustic emission (AE) by laser interferometry was developed to detect AE signals and analyze microfracture quantitatively during materials testing. The capability of this system was estimated by comparison between simulated AE signals due to glass capillary breaking and calculations using the finite element method. The system could measure AE signals during practical tensile tests of carbon fiber reinforced plastics. This technique was also applied to the thermal cycle test of ceramic/metal coatings, and AE signals during cooling were successfully detected and analyzed by a deconvolution method to evaluate quantitatively the microfracture process. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The acoustic emission (AE) method, which detects an elastic wave due to microfracture in materials, is an extremely useful technique to monitor damage in structural components and understand the fracture behavior of materials, and it has been applied to various research fields. However, some disadvantages can be pointed out in the conventional AE method. It is very difficult to use it at elevated temperatures because the Pb(Zr\textsubscript{1-x}Ti\textsubscript{x})O\textsubscript{3} (PZT) transducer in the conventional technique must be directly attached to the surface of specimen using a couplant between the transducer and specimen, such as a chemical adhesive. It is not easy to analyze quantitatively the detected AE signal because in general most AE transducers are of resonant type with non-flat frequency characteristics and the detected AE signal is not a displacement or velocity at the surface of the specimen. A transducer has some size and the detected signal is an average value over the sensitive area of the transducer. Also, the detected waveform is strongly affected by the geometry of the specimen due to the reflection of the wave at the surface of the specimen. A waveguide has been used for AE measurements at elevated temperatures, but quantitative AE analysis becomes difficult because of these reflections. Non-contact measurement is desirable in order to extend the application of the AE method [1,2].

In recent years the laser based ultrasonic (LBU) method has been developed to characterize material properties and to detect flaws in materials, which consists of two techniques, the generation of ultrasonic waves by laser and the detection of surface motion by laser interferometry [3–9]. Fig. 1 shows a schematic of the difference between LBU and AE. Much effort has been made to improve the capability of LBU in order to replace conventional ultrasonic testing, which uses a PZT transducer to generate and receive waveforms, and water as the medium of sound. The detection of surface motion by laser interferometry has many advantages. Non-contact measurement is practicable and a medium of ultrasonic sound is not needed. The frequency characteristic of laser interferometry is very wide and it is possible to detect various ranges of signals. A displacement or velocity at the surface can be directly measured. A point contact measurement is practicable because a laser beam can be focused at a very small spot (of the order of microns). However, there are some disadvantages of laser interferometry. In most laser interferometers a reflective surface is required for sufficient sensitivity and it is very difficult to get an adequate signal to noise ratio. Handling or setting-up a laser interferometer is not very easy because the focusing point is very limited in most interferometers. These factors
result in low sensitivity compared with conventional PZT transducers.

Some other factors become severe problems in the detection of AE signals which are not problems in measurement by PZT transducers. For example, machines that are used in mechanical tests may induce some vibration, which becomes a noise to the AE signal and reduces the sensitivity of the laser interferometer due to the out-of-focus. In the LBU method it is possible to gain enough sensitivity by repeating the laser incidence with high amplitude for generation of ultrasonic waves and by averaging the received signal of the laser interferometer. However, AE is a transient phenomenon and not repeatable, and in general the AE signal is rather smaller than ultrasound generated by incident laser. These reasons lead to few reports of AE measurement by laser interferometry during practical mechanical testing. In this paper, we investigate the possibility of laser interferometry for actual AE measurement and estimate the capability of the technique for understanding fracture mechanisms in advanced materials.

2. Detection of simulated AE waveform

Most AE transducers for monitoring microfracture in materials have a frequency range from ~100 kHz to ~1 MHz. To simulate these AE signals some sources were proposed such as pencil lead breaking and glass capillary breaking, which were used to calibrate the AE system. Before application of the laser AE system to mechanical testing, the laser interferometer used in the experiment was calibrated by comparing the detected signal and the theoretical waveform.

2.1. Experimental procedure

A heterodyne type laser interferometer with He–Ne laser was used to measure the surface velocity of the specimen, and it can detect changes of surface displacement up to 0.3 µm/s. A schematic of the set-up is shown in Fig. 2. An Al block 400 × 400 × 17 mm after mirror polishing was used as the medium of elastic wave propagation, and a simulated AE signal was generated using a glass capillary with external diameter 1.5 mm and length 50 mm. A glass capillary was fractured at the center of the surface on the Al block by a steel indenter and a simulated AE waveform through the Al block was detected at the opposite side of the Al block using the laser interferometer. The output from the laser interferometer was transferred to the AE analyzer (DCM 140, JT Tohsi Inc.) and saved in a computer. The distance between the epicenter and the measuring point, x, was varied: x = 0, 25 and 50 mm. A low pass filter (LPF) of 1 MHz, trigger level of 0.005 m/s, sampling period of 50 ns and indenter speed of 0.5 mm/min were selected for the measuring conditions.

2.2. Simulation of wave propagation

Wave propagation behavior was calculated by the finite element method (FEM), and the code of LS-DYNA.
Livermore Software Technology), which can analyze three-dimensional wave motion, was used. As the simulated AE by glass capillary was a well-known step-like function, the input function with rising time of 1 μs and force of 5 N shown in Fig. 3 was used for FEM calculation. Fig. 4 shows the comparison between the detected surface velocity by laser interferometry and the calculated one by FEM. The shapes of these waveforms are in good agreement, and this laser interferometer obviously can measure the absolute surface velocity of the specimen and it is quite expected to detect actual AE signals during mechanical testing. This consistency brings about a quantitative inverse analysis of the detected AE waveform to estimate information about the microfracture, such as microcracking size. The small difference seems to come from the fact that the assumed rising time and the time function of the input are not exactly the same in the case of glass capillary fracture.

3. Non-contact measurement during tensile test

The possibility of AE measurement by laser interferometry was demonstrated in the previous section, as the surface velocity of elastic wave propagation through an Al block due to breaking a glass capillary was detected quantitatively by the laser interferometer. This technique was applied to a material testing in order to extract the capability of problems in AE measurement by laser interferometry during mechanical testing.

3.1. Experimental procedure

The material used in tensile test was a ±45° cross ply carbon fiber reinforced plastic (CFRP) and the geometry of the specimen was 100 × 12 × 2.5 mm. Notches were introduced to both the sides of specimens in order to restrict the area where microfractures are generated. As it was difficult to improve the reflectivity by polishing the surface of the specimens, a reflective tape was attached to the surface to increase the stability for receiving reflected laser. PZT AE transducers with resonant frequency 300 kHz (A304, Fuji Ceramics) were also attached to the specimens. The detection of the AE signal was triggered by the PZT transducer, and both signals from PZT transducer and laser interferometer were recorded by the AE waveform analyzer. A schematic of this AE measurement using both laser interferometer and PZT transducer is shown in Fig. 5. Waveforms from laser interferometer that have twice the amplitude of the noise level were recognized as detected AE signals. A high pass filter (HPF) of 100 Hz and an LPF of 200 kHz were set for the measurement by the laser interferometer in order to reduce both mechanical and electrical noise, and a preamp of 52 dB was used for the measurement of PZT transducer.

3.2. Results and discussion

Fig. 6 shows an example of waveforms from both the laser interferometer and the PZT transducer for the same AE event, where the vertical axis means the velocity of the surface and the preamp input voltage, respectively. This result clearly demonstrates that it is possible to detect AE signals during mechanical testing by laser interferometry. The waveform by laser interferometry has a lower frequency component than that by the PZT transducer, and the shape of the waveform by laser interferometry is also quite different from that by the PZT transducer, because the LPF was used for laser interferometry and the absolute surface velocity was measured by laser interferometry. The detected signal by laser interferometry included continuous noise and it was difficult to find the rising point of the waveform. Fig. 7 shows the cumulative number of AE events by both the laser interferometer and the PZT transducer versus the tensile stress applied to the specimen. AE events started to increase at the stress of 85 MPa and the laser interferometer could trace the tendency of increasing AE events observed by the PZT transducer. However, the total number of events detected by the laser interferometer was about 30% of that by the PZT transducer. It was difficult to detect AE events with small amplitude generated during the initial stage of the tensile test by laser interferometry because of the low signal to noise ratio of the laser interferometer, but AE events with large amplitude at the nearly final stage of
the test could be clearly detected. However, the counted number of AE events by the laser interferometer was not consistent with that by the PZT transducer at even the final stage of the test because the degradation of the specimen with the increase of stress could reduce the reflectivity of the laser.

The laser interferometer could measure AE signals continuously during the tensile test. Nevertheless there were some limitations such as sensitivity and stability. It was expected that this technique could be applied to mechanical testing at elevated temperatures. Reflective tape cannot be used in the high temperature environment because the adhesive of the tape cannot withstand it, and also oxidation at the surface of the specimen may cause reduction in reflectivity at elevated temperatures. However, by surface treatment of the specimen, selection of practicable experiments, removal of noise by data processing, and selection of a different laser interferometer that is not interfered by noise, the capability to measure AE at elevated temperatures using laser interferometry will be improved.

4. Non-contact measurement during thermal cycle test

Thermal barrier coatings, which consist of a bond layer of MCaAlY and a top coat of Y2O3-stabilized ZrO2, have been developed to increase the temperature of use of the components of gas turbines and jet engines [10]. The dissimilar interface of these materials causes cracking in the ceramic layer and delamination near the interface due to thermal and residual stresses. In order to improve the integrity of these coatings the evaluation of damages due to thermal shock and thermal cycles becomes a very important problem. However, it is very difficult to monitor in situ fracture behavior of coatings at elevated temperatures due to the temperature difference of over 1000°C. The AE method is one of the very useful tools to analyze microfracture behavior before unstable fracture [11]. The AE measurement by laser interferometry described in the previous section especially is a promising technique to evaluate the fracture process in coatings at elevated temperatures. Waveguides have been used to measure AE signals during thermal cycles in order to avoid the heated zone and prevent damage to the
PZT transducer from high temperatures. However, as mentioned before, the waveform of the AE is strongly affected by the transfer function of the waveguide, and it is very difficult to analyze the quantitative characteristics of each microfracture in terms of location, size and fracture mode. Laser interferometry is expected to evaluate quantitatively the parameters of microfracture, because it can measure the absolute value of the surface velocity or displacement, and non-contact measurement that can avoid the effect of a complicated transfer function is practicable at elevated temperatures. As this technique of AE measurement has not been applied to the thermal cycle test in ceramic coatings, in this paper we tried to measure AE signals from coatings at elevated temperatures and evaluate the fracture behavior in these materials.

4.1. Experimental procedure

The coated specimen used in the experiments consists of a matrix of SUS304 stainless plate of 15 × 15 × 5 mm, NiCrAlY alloy as the bond coat and Al₂O₃ as the top coat. After one side of the matrix was blasted, NiCrAlY of
0.1 mm thickness and Al₂O₃ of 0.5 mm thickness were coated in air by the plasma spray technique. Fig. 8 shows the schematic of the experimental set-up for detection of AE during the thermal cycle test using laser interferometry. The coated surface of the samples was heated by an infrared image furnace with spot diameter of 10 mm. A heterodyne laser interferometer with He–Ne laser (AT3500, Graphtec Corp.) was used to detect AE signals at the side opposite to the coated surface of the specimen. The output from the laser interferometer was recorded by an AE analyzer (DCM 140, JT Tohsi) and the frequency filter was set to an HPF of 200 Hz and an LPF of 300 kHz. Various maximum temperatures of 900, 1000, 1100 and 1200°C were selected, and the coated surface was heated at a heating rate of 10°C/s and the temperature was kept at the maximum temperature for 10 s before air cooling. This heat cycle was repeated until complete fracture of the specimen. Some samples were observed for delamination at the interface by scanning acoustic microscopy (SAM) and scanning electron microscopy (SEM).

4.2. Results

Fig. 9 shows the result of the detected AE behavior and temperature history at the center of the coated surface, where each symbol means the generation of AE and the order of cycles. AE signals were detected only during the cooling period and the final delamination occurred within four cycles. A specimen held at 1200°C was fractured after one cycle, but more than two or three cycles were needed for the final fracture of other specimens. A temperature difference over 500°C caused microfracture before the final fracture, but the relationship between the maximum temperature and the number of cycles to final fracture was not clear because of the scatter of the material properties of the coatings. Fig. 10 shows the SEM image of cross section of a specimen after one cycle at 1200°C. No vertical crack was observed in the ceramic layer and delamination was observed in the Al₂O₃ layer near the interface between the ceramic layer and the bond coat. It was concluded that all the detected AE signals were due to these horizontal delaminations. Fig. 11 shows the result of SAM observation in the specimen held at 1100°C, specimen after each thermal cycle was scanned from the matrix side using a 25 MHz ultrasonic probe. Delamination with about 1 mm diameter was observed at the center of the specimen after the first cycle, and the second thermal cycle caused the growth of the delamination that was induced during the first cycle as well as new delamination. Delamination was propagated to the end of the specimen and the ceramic layer was completely debonded from the bond coat after the fourth cycle. This observation and the AE behavior demonstrated that the fracture process of this coating due to the thermal cycle involved delamination, arrest of this delamination, and coalescence of delaminations, and finally the cracks reached the end of the specimen. The AE events during each cycle were identified to be discrete microcracks with sub-millimeter dimensions.

The frequency characteristics of each AE waveform were investigated by fast Fourier transform (FFT), and examples of detected waveforms and power spectra after FFT are shown in Fig. 12. The detected waveforms were classified into two groups, high frequency group (type A) and low frequency group (type B). Fig. 12(c) and (d) is the frequency characteristics by FFT corresponding to type A (Fig. 12(a)) and type B (Fig. 12(b)), respectively. Type A had sharp peaks in the power spectrum at about 180 and 280 kHz, which is completely different from type B. Fig. 13 shows...
the number of type A and type B AE events of each thermal cycle during the test with the maximum temperature of 1000°C. The number of type A events decreased with the cycle number, while type B events were mainly generated at the second and third cycle. In general the frequency characteristics are affected by the geometry and properties of the media, rising time of the source function, fracture mode and the location of the source, so it is necessary to quantitatively analyze microfracture sources by the AE source characterization technique [12]. However, the results of Figs. 13 and 11 clearly demonstrates that a type A event corresponds to the initiation of microcracks near the center of the specimen and a type B event seems to be due to delamination near the interface accompanied by coalescence and propagation of cracks.

4.3. AE source characterization

The detection of AE by laser interferometry has an advantage in quantitative evaluation of AE sources by inverse analysis over conventional AE methods using PZT transducers, because laser interferometry gives the absolute value of the displacement or velocity while it is necessary to consider the transfer function of the PZT transducer in the conventional method. The exact location is required to evaluate Green’s function of the media and analyze the AE source quantitatively, but type A waveforms were generated from the center of the specimen. A six-channel measurement of AE is necessary for the evaluation of the fracture mode because the source function tensor of the microfracture has six independent components. However, microfracture of this coating system can be analyzed by the one-channel measurement because symmetric thermal residual stresses at the center of the specimen cause a tensile type (mode I) fracture and the direction of the microcrack surface is restricted to the perpendicular to the interface (Fig. 10).

Assume that the media is homogeneous and that the AE source is small compared with the wavelength of the elastic wave and the distance between the AE source and the detected point. Based on this point source approximation,
a displacement due to the microfracture, \( u_f(t) \), can be formulated by

\[
u_f(t) = G_{ij,k}(t)^* D_{jk}(t)
\]

where \( D_{jk}(t) \) is the source function moment tensor for the microcrack, \( G_{ij,k}(t) \) is the Green’s function of \( i \)-direction due to the dipole with \( j \)- and \( k \)-directions, and \( * \) means a convolution integral in time. By assuming mode I fracture perpendicular to the interface, the moment tensor components can be represented as

\[
(D_{jk}(t)) = \begin{pmatrix}
\lambda & 0 & 0 \\
0 & \lambda & 0 \\
0 & 0 & \lambda + 2\mu
\end{pmatrix} f(t)
\]

where \( \lambda \) and \( \mu \) are Lamé’s parameters, \( f(t) \) is a time function of source function. Thus the vertical displacement due to the mode I microcrack can be represented by

\[
u_3(t) = \left( \lambda G_{31,1} + \lambda G_{32,2} + (\lambda + 2\mu) G_{33,3} \right)^* f(t).
\]

By deconvolution of known \( G_{ij,k}(t) \) and \( u_f(t) \), \( f(t) \) can be evaluated and the intensity of moment due to microcrack \( D_0 \) can be obtained from the first peak of \( f(t) \).

The Green’s function of the coating system consisting of two layers was calculated by FEM (LS-DYNA3D), where material properties in Table 1 and a mesh of one fourth of the area of the whole specimen were used for the calculation. The bond coat of NiCrAlY was neglected due to the computing limitations. The ramp function with raising time of 1 \( \mu \)s and moment of 1 Nm was input near the interface in the ceramic layer and the response at the epicenter of the metal was calculated in order to estimate the components of \( G_{ij,k}(t) \). Deconvolution of Eq. (3) gives a source function of microfracture, and an example is shown in Fig. 14.

From the first peak of source function \( D_0 \), the following equation was used to estimate the radius of the microcrack, \( a \),

\[
a = \left( \frac{3(1 - 2\nu)D_0}{16(1 - \nu^2)\sigma_0} \right)^{1/3}
\]

where \( \sigma_0 \) is the strength for microfracture, and \( \nu \) is the Poisson’s ratio [13]. Fig. 15(a) shows the distribution of microcrack radius for the temperature difference between the maximum and microcracking temperatures. The relationship between crack generation time and temperature difference was also shown in Fig. 15(b). Microcrack radius is distributed from 100 to 600 \( \mu \)m, which is in good agreement with the observed result by SAM. It could demonstrate that the AE measurement by laser interferometry estimates the size and generation temperature of microfracture, even for the thermal cycle test at elevated temperatures. Further measurement for location of each microfracture using a multi-channel system will improve the accuracy of estimation of size and give more information of the microfracture such as fracture mode and direction of microfracture. The sensitivity of the laser interferometer is still a problem and smaller microfractures that could not be detected by the laser interferometer might be generated during a thermal cycle. However, the outline of the fracture process in coatings during thermal cycles could be viewed by AE measurement using laser interferometry. Oxidation at the reflective surface of the laser beam may become a severe problem for long term tests at high temperatures. These problems may be solved by progress in laser interferometry itself.

5. Concluding remarks

It was demonstrated by comparing the calculated wave motion using FEM that laser interferometry could detect the absolute velocity of surface due to the glass capillary breaking signal used to simulate AE signals, that is, this non-contact AE measurement system is applicable to practical AE measurement during mechanical tests. The AE behavior of CFRP during tensile tests was successfully measured by this laser interferometer, though the sensitivity is lower than a conventional PZT transducer. Non-contact AE measurement by a laser interferometer was applied to the thermal cycle test in the ceramic/metal coating system and the detected waveforms were analyzed by FFT and the deconvolution method. FFT results could conjecture the change of fracture types and deconvolution could estimate the distribution of microfractures. AE measurement by laser interferometry still involves several problems such as sensitivity and difficulty in set-up, but it is a promising technique to detect and analyze AE signals in various environments where the conventional method cannot be applied.

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Table 1

| Material properties used in the FEM calculation | Matrix (SUS304) | Top coat (Al₂O₃) |
|-----------------------------------------------|-----------------|-----------------|
| Young’s modulus (GPa)                         | 185             | 30              |
| Poisson’s ratio                               | 0.295           | 0.25            |
| Density (Mg/m³)                               | 7.8             | 1.57            |

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Fig. 14. Evaluated source function of microfracture by the deconvolution method.
Fig. 15. (a) Distribution of microcrack radius for the temperature difference between the maximum and microcracking temperatures. (b) The relationship between crack generation time and temperature difference.

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