THE FORTY-EIGHTH HONDA MEMORIAL LECTURE

Nondestructive Evaluation and Smart Materials*

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Evaluation of microcracking behavior, among other nondestructive evaluations, is important for understanding the fracture of materials and improving their fracture resistance. This paper deals with the principle of the inverse problem analysis of acoustic emission (AE), the method of analyzing the moment tensor of microcracks developed by the author *et al.*, and examples of the method's application. The paper goes on to introduce the concept of the smart materials and structural systems that perform nondestructive evaluation on their own and function to repair and restore defects. The paper also overviews the present state of research and development.

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1. Preface

In understanding the mechanism of fracture and its relationship to the development of high-toughness materials, it is important to make quantitative evaluation of microcracks that occur in materials before ultimate fracture. This paper describes a method to derive moment tensor (Eigen strain in micromechanics) by the inverse problem analysis of acoustic emission (AE) which was developed by the author *et al.*, and examples of its application to microcrack evaluation. As a continuation of the discussion, this paper also touches upon the present state of nondestructive evaluation and application to structural composite materials and smart (intelligent) materials which have a characteristic of repair and restoration of anomalous parts (such as defects).

2. Nondestructive Evaluation

2.1 Understanding of fracture¹⁾

Brittle fracture in ceramics arises from fine defects. Macroscopically speaking, brittle fracture often results from the formation and coalescence of micron-sized microcracks, as shown in Fig. 1. For metals, such formation and coalescence occur in the plastic zone as a result of dislocation-activity and stress concentration,²⁾ while for ceramics, they occur in the process zone. For composite materials,³⁾ microfracture occurs in the matrix and reinforcement and at the interface between them, causing complex coalescence with accompanying delamination and, eventually, ultimate fracture. To understand such fracture behaviors, it is necessary to establish a method to detect microcracks which are undetectable by the existing technologies.

Microscopically, fracture can be classified into shear and tensile separation. When a macrocrack propagates, microcracks coalesce three-dimensionally in front of the macrocrack,⁴⁾ and fracture resistance (toughness) varies depending

Fig. 1 Occurrence of microcrack and propagation of macrocrack in fracture toughness test.

on whether the coalescence process is of shear type or tensile type. In effect, it is necessary to classify both microscopic and macroscopic fractures into shear and tensile types, and the formation speed of microcracks can serve as an evaluation parameter of ductility and brittleness.⁵⁾

For macroscopic understanding of fractures, it is necessary to define the propagation of the main crack associated with the material structure. As the main crack often propagates non-uniformly, it is necessary to define the length corresponding to the non-uniform propagation of the crack. The length of the non-uniform propagation X_0 is generally called the characteristic distance.⁶⁾

Whether ductile or brittle fracture, fracture toughness includes a parameter that characterizes the manner of fracture (*i.e.* the characteristic distance X_0 in this case). It is necessary to take notice of the fact that X_0 is governed by microcracks and it is necessary to establish a method to detect non-destructively X_0 .

2.2 Improvement in fracture toughness

2.2.1 Fail-safe materials - toughness improvement in brittle materials

The stress relaxation mechanism of low-toughness materi-

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Fig. 2 Improvement of fracture toughness by occurrence of microcracks. —Approach toward fail-safe materials—.

als comprises microcracks, phase transformation, crack-branching, crack-bridging and partial plastic deformation.^{3,7)} Therefore, formation of microcracks serving as the stress relaxation mechanism can give rise to an increase in fracture resistance, a phenomenon called microcrack toughening. In this relation, the author *et al.* found an interesting phenomenon: the fracture toughness increases when microcracking occurs significantly before ultimate fracture, as shown in Fig. 2. The materials in which this phenomenon occurs may be called “Fail-safe Materials” because formation of fine microcracks prevents the breaking of the whole through stress relaxation.

2.2.2 Fracture of composite materials - quantitative evaluation of interfacial mechanical characteristics and effectiveness of shear debonding⁸⁾

What governs mechanical properties of composite materials is the interfacial characteristics of individual particles and matrix in short-fiber reinforced composites and the interfacial characteristics of fibers and matrix in long-fiber reinforced composites. To determine such governing factors, it is necessary to detect and evaluate quantitatively the interfacial debonding, fracture mode (tensile or shear) and length of debonding. One interesting phenomenon is that the fracture resistance of unidirectional fiber-reinforced composite materials reaches maximum when the mode of debonding changes from shear to tensile. This indicates the importance of determining the mode of fracture.

2.3 Nondestructive evaluation

2.3.1 Method to secure reliability⁸⁾

Enhancement of reliability calls for the development of appropriate materials and the establishment of quality evaluation techniques including the screening of defective materials. Here, quality evaluation means quantitative evaluation of safety factors, damage probability, product life and other quality-related factors. The parameters constituting the basis for such quality evaluation are the Weibull parameter m indicating the degree of property-scattering, fracture toughness K_{Ic} (or K_{Id} for impact load) based on fracture mechanics,

and the crack propagation speed index n for time-dependent fractures such as static and dynamic fatigue. Generally, reliability is evaluated by using the values of m , n , K_{Ic} and the characteristics of defects. It should be recognized that improving fracture toughness K_{Ic} is synonymous with improving the defect-detecting capability.

2.3.2 Nondestructive inspection and nondestructive evaluation⁹⁾

Figure 3 shows the flow of nondestructive evaluation for quality assurance. Nondestructive evaluation comprises the steps of (1) detecting the presence of defects in materials, (2) locating the position, (3) classifying the type, (4) determining the size and shape of each defect, (5) clarifying the mode of cracking and other characteristics, (6) determining the mode of fracture by considering external load and environmental conditions, and judging the degree of the severity of the defects by using an analysis based on fracture mechanics, (7) making an ultimate judgment on acceptability or, in other words, implementing material screening, and then, (8) for materials that have proved acceptable, evaluating its safety factor and service life. Here, the steps (1) to (5) for detecting defects are in the category of nondestructive test and inspection, while nondestructive evaluation includes the steps (6) to (8) as well. In applying such nondestructive evaluation, therefore, it is necessary not only to enhance the accuracy of nondestructive inspection techniques for detecting defects but also to consider (1) undetectable defects, (2) correspondence between the size of the detected defects and the size of defects leading to fracture, (3) fracture models (representing formation, growth and coalescence processes of micro defects) and (4) uncertainties in the values of K_{Ic} , n and m (due to discrepancies in testing methods). Establishment of the concept of allowance for defects and extension of material life are also included in the nondestructive evaluation. In any case, techniques to evaluate microcracks are very important in low-toughness materials.

2.3.3 Nondestructive evaluation of microcracks^{10,11)}

The detection of microcracks is indispensable to non-

Fig. 3 Flow of reliability evaluation method.

destructive evaluation. Although various microcrack-detection methods, including X-ray, ultrasonic, microfocus X-ray based on electromagnetic equipments, high-frequency ultrasonic and ultrasonic microscope are being developed, it is still impossible to detect internal defects finer than several tens of microns, and there is no method to evaluate the mode of fracture. The following describes the method developed by the author *et al.* under these circumstances.

3. Quantitative Evaluation of Microcracks by Inverse Problem Analysis of Acoustic Emission (AE)

Although electric resistance, ultrasonic and acoustic emission analyses are used for the detection of microcracks, it is necessary to take note of the fact that the sensor signals used in these methods change with the propagation characteristics in the medium and the response characteristics of the measuring system. Therefore, the characteristics of cracks cleared of these propagation and measuring-system characteristics must be derived from the measured signals by inverse calculation.¹²⁾ Inversion problem analysis of acoustic emission (AE) related to fracture is described below (the obtained result is called a source wave of acoustic emission).¹³⁾

3.1 Quantification of microcracks (moment tensor)

To understand each individual microcrack, it is necessary to determine quantitatively the (1) position of occurrence, (2) size, (3) mode of cracking, (4) inclination of the crack surface, (5) shape and (6) forming speed of the crack, as shown in Fig. 4.

However, no definite concept to cover all these requirements and parameters to represent them has been clearly recognized.

In general, cracks can be replaced by dislocation array. Eigen strain used in the field of micromechanics¹⁴⁾ and seismic moment tensor in the field of seismology¹⁵⁾ are considered to give such characteristics. When microcracking occurs in a medium, its seismic moment tensor can be expressed as

$$D_{jk} = C_{jklm} \phi_l \Delta A_m \quad (1)$$

where C_{jklm} is the elastic constant, ΔA_m is the area of discontinuity, and ϕ_l is the magnitude of discontinuity. In the case of a crack of the tensile opening type of mode I shown in

Fig. 4 Parameters indicating characteristics of microcrack.

Fig. 5 Moment tensor and its time-function associated with formation of microcrack of tensile opening type (mode I).

Fig. 5, D_{jk} in the above equation can be expressed as

$$D_{33} = (\lambda + 2\mu) \Delta A_3 \phi_3 \quad (2)$$

Thus, $\Delta A_3 \phi_3$ is directly determined when D_{33} is determined. Here, λ and μ are Lamé's constants. The size of the crack a can be quantitatively determined by fracture mechanics as

$$a = (3(1 - 2\nu)D_{33}/16(1 - \nu)\alpha\sigma_y)^{1/3} \quad (3)$$

where ν is the Poisson's ratio, σ_y is the yield stress and α is a constant ($=1-2$).

As the magnitude of moment tensor is given as a function of time as shown in Fig. 5, the mean speed of crack formation is given by the following equation when the crack formation time Δt is determined:

$$\nu = 2a/\Delta t \quad (4)$$

This crack formation speed serves as a parameter to characterize the degree of ductile-brittle fracture of individual microcracks.

In addition, D_{jk} gives an information concerning the inclination angle of the crack surface and the mode of cracking of individual microcracks.

3.2 General theory of the acoustic emission source characterization¹⁶⁾

3.2.1 Formulation

When eigen strain exists in some region of an elastic body, the displacement can be expressed as

$$u_i(x', t) = \int_V C_{jkmn} \varepsilon_{mn}^*(x, t) * G_{ij,k}(x', x, t) dV(x) \quad (5)$$

where $G_{ij,k}(x', x, t)$ is the second Green's function and $*$ shows the convolution integral related to time. When the area of the region Ω in which eigen strain $\varepsilon_{mn}^*(x, t)$ exists is sufficiently smaller than $|x - x'|$, eq. (5) can be written as

$$u_i(x', t) = G_{ij,k}(x', x, t) * D_{jk}(x, t) \quad (6)$$

Fig. 6 Derivation of moment tensor by inverse problem analysis. (a) Conceptual diagram of inverse problem analysis of AE signal. (b) Flow of moment tensor derivation.

When linear response is valid in the entire measurement system and its response function is put as $S_i(x', t)$, output $V(x', t)$ on occurrence of $D_{jk}(x, t)$ can be expressed as

$$V(x', t) = S_i(x', t) * G_{ij,k}(x', x, t) * D_{jk}(x, t) \quad (7)$$

3.2.2 Derivation of moment tensor (source of acoustic emission) by inversion calculation

When S_i and $G_{ij,k}$ are obtained from eq. (7), D_{jk} can be derived by deconvolution. Figures 6(a) and (b) schematically show the concept of the acoustic emission source characterization. The source characterization comprises the steps of (1) implementing a three-dimensional location by measuring the arrival-time difference of acoustic emission between multiple transducers, (2) deriving the response function of the measurement system by using a pseudo sound source,¹⁷⁾ (3) determining $G_{ij,k}$ by three-dimensional finite difference or other similar method by inputting nine moment components into the sound source¹⁸⁾ because there is no analytical solution for the dynamic Green's function for the finite medium containing the main crack, (4) storing the acoustic emission waveforms detected by six to eight transducers in the wave memory and deriving D_{jk} by multi-dimensional deconvolution, and (5) determining the size, cracking mode, inclination of crack surface and cracking speed of each individual microcrack from D_{jk} .

3.3 Examples of moment tensor derived

3.3.1 A470 steel¹⁹⁾

Figure 7 shows an example of D_{jk} derived from a compact tension (CT) specimen of A470 steel. First, three-dimensional location revealed the occurrence of a microcrack in the plastic region around the leading edge of the main crack. Time-function analysis revealed that the microcrack was formed in 0.2 to 0.3 μs . Analysis of the moment tensor revealed that the crack surface inclined at an angle of 15 degrees to the surface of the main crack, the mode of cracking (58°) was a mixed mode of tensile and shear types, and the crack radius was 30 μm , as shown in Fig. 8.

$$D_{jk}(t) = \bar{D} \begin{bmatrix} 0.41 & 0.04 & -0.22 \\ & 0.17 & 0.01 \\ \text{Sym.} & & 1 \end{bmatrix} T(t)$$

$$\bar{D} = 5.02 \times 10^{-4} \text{ Nm}$$

Fig. 7 Moment tensor due to pseudo-cleavage facet in fracture toughness test for A470 (Cr-Mo) steel.

Fig. 8 Inclination (θ), cracking mode $\cos^{-1}([u] \cdot v)$ and size $2a$ of microcrack derived from moment tensor.

Fig. 9 Mean radius and cracking mode of microcracks in particle-dispersed glass-matrix composite material.

3.3.2 Application to SiC particle reinforced glass matrix composite²⁰⁾

Figure 9 shows an application to a glass matrix composite material. Derivation of the moment tensor determined the inclination of the crack surface and the mean crack radius. It was found that the inclination of the crack surface is mostly in the direction of 90 degrees and of the shear type. Analysis of the crack size and mode has made it possible to classify the type of fracture into debonding, matrix cracking, particle fracture, *etc.*

Furthermore, some interesting reports have recently been published regarding the microcrack evaluation of composite and coated materials. Measurement systems employing laser are also attracting attention.

4. Smart Materials and Structural Systems

4.1 Smart materials

Hopes and expectations are placed on 'the smart materials and structural systems' that are artificial materials and structures imparted with abilities to sense, judge, respond and some other functions similar to those of living organisms, and permitting assurance of structural reliability and cost reduction, resource and energy saving through the improvement of performance and efficiency. This is a concept that imparts repairing functions to nondestructive evaluation and is, as such, a technology in development.

4.2 Smart materials and structural systems²¹⁾

The smart materials and structural systems are based on the concept to incorporate sensors, actuators, *etc.* in the materials themselves and to integrate (fuse) materials with the structures, thereby imparting such functions as to (1) self-evaluate the occurrence and deterioration of strains and damages, (2) self-control vibrations and noises, (3) self-change their own shape depending on conditions, and (4) self-control the propagation of damages and repair them as the need arises. Figure 10 is a conceptual diagram of the smart materials and structural systems. While the mother structure supports strength, the optical fiber sensor and piezoelectric ceramic detect anomalies (such as defects), and

Fig. 10 Concept of the smart materials and structural systems.

the shape-memory alloy and piezoelectric actuator repair the anomalies. The electronic control circuit judges the signals detected by the sensor, and issues instructions.

The author served as a leader of the research and development project on the smart materials and structural systems, which was the first project under the NEDO's (New Energy and Industrial Technology Development Organization) system to conduct research and development on industrial and scientific technologies in conjunction with colleges and universities. This report shows examples of application to composite materials.

4.2.1 Development of health monitoring technology²²⁾

There is a need to monitor such anomalies as defects and vibrations at all times. It is therefore hoped that optical fibers, piezoelectric elements and electrical resistors and other measuring methods are established. Among others, optical fibers are being developed as a means to implement monitoring without lowering the strength of materials.

An attempt to manufacture new optical fibers with a diameter of 40 μm (finer than the conventional 125 μm diameter ones) and to embed them in composite materials without lowering strength succeeded. The fiber Bragg grating (FBG) sensor made of such material analyzed the intensity of transmitted and reflected lights, and proved effective in detection of not only transverse cracks but also delamination. As shown in Fig. 11, the principle of the FBG sensor is to detect the variation of the magnitude of light intensity and distribution of wave spectrum. The multiple use of FBG sensors have made it possible to locate the position of impact loading. The Brillouin optical time domain reflectometer

Fig. 11 Principle of FBG sensor.

(BOTDR) sensor capable of measuring strain distribution along the optical fiber sensors, which is the method using back scattering light, is going to apply to repeated loading. A potential to memorize the maximum damage in particle-dispersed fiber-reinforced plastics (FRP) based on changes in the electrical characteristics of electrically conductive FRP has been found. Regarding acoustic emission measurement, studies have been made on the mounting on the demonstrator with a view to putting into practical use the technique of locating the position of impact loading.

4.2.2 Development of smart manufacturing technology²³⁾

Smart structural systems are expected to allow the sensors and actuators embedded in composite materials and to bring their functions into full play. As shown in Fig. 12, the purpose of this study is a monitoring the forming process by the sensor embedded in the FRP and mold. It is particularly important to confirm that the embedded sensor system and actuator function properly after completion of forming.

4.2.3 Development of active/adaptive structure technology²⁴⁾

This technology manufactures structural systems to change materials to optimum shapes, and to reduce vibrations and noises by means of the centralized and/or distributed sensors and actuators embedded in the mother structure. The use of pre-strained shape memory alloy (SMA) wire in composite materials led to substantial attenuation of vibrations. The use of piezoelectric elements in large complicated structural components for vibration and noise control resulted in an attenuation coefficient of 20 percent and noise power reduction of 30 percent.

4.2.4 Development of materials and elements for actuator²⁵⁾

The biggest hurdle to clear in putting into practical use the concept of the smart materials and structural systems is the development of high-performance materials and elements for actuator. The existing piezoelectric elements and shape-memory alloys do not have enough damage-repairing strain and power for use as an actuator. The use of a hybrid sintering process combining the hot press and microwave heating succeeded in improving the piezoelectric coefficient d_{31} of PNN-PZT by 36 percent. Development of shape-memory alloy elements suited for use at high temperatures also succeeded by using the quenching solidification method, as shown in Fig. 13.

4.2.5 Airplane body demonstrator for demonstration test²⁶⁾

To integrate the results for the development of the four element technologies just described and to demonstrate the functions of the whole structural system, an integrated actual structural element model (a body structure of an airplane in this case) was prepared and the degree of target achievement in the individual study items was checked. The seven element technologies related to the smart materials and structural systems were examined by preparing a composite-material structure having a diameter of 1.5 m and a length of 3.0 m, as shown in Fig. 14. The panel was successfully manufactured by the smart manufacturing method, and the detection of damage, evaluation of impact load, suppression of damage and reduction of noise were confirmed.

Fig. 12 Monitoring of forming process.

Fig. 13 High-temperature shape-memory alloy.

Fig. 14 Structural element model for demonstration test.

5. Concluding Remarks

The importance of the role of microcracks and their detection and evaluation has been discussed. Examples of the quantitative derivation of the size, cracking mode, inclination of crack surface and forming speed of microcracks by determining their moment tensors by inverse problem analysis of acoustic emission signals have been presented. Approaches to the smart materials and structural systems with repairing functions as a continuation of nondestructive evaluation methods, and concrete examples of their application to actual structural systems have been also described.

Multiple functions and integration of materials and structural systems (or devices) will be important in the future development of smart materials.

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