Advances in Engineering Software 000 (2016) 1–6

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Inverse analysis for interface fracture toughness of Ti coating film by laser spallation method

Masahiro Arai [a,*], Yoshitaka Sato [b], Daisuke Sugiura [b], Masaomi Nishimura [c], Hiroaki Ito [d], Hideo Cho [d]

[a] *Department of Aerospace Engineering, Nagoya University, Japan*
[b] *Graduate School of Shinshu University, Japan*
[c] *Department of Mechanical Systems Engineering, Shinshu University, Japan*
[d] *Department of Mechanical Engineering, Aoyama Gakuin University, Japan*

ARTICLE INFO

Article history:
Received 7 July 2015
Revised 14 March 2016
Accepted 6 April 2016
Available online xxx

Keywords:
Laser ultrasonic waves
Inverse analysis
Boundary element method
Coating film
Interface fracture toughness

ABSTRACT

In the present paper, the interface fracture toughness between a Ti coating film and Al-alloy substrate is evaluated using a laser spallation method and a boundary element method. The fracture toughness can be estimated using inverse analyses by the boundary element method using a transfer function computed from the history of the displacement of the specimen. In the present study, an alternative boundary element program is developed for unsteady state vibration of an axi-symmetric solid body. The mode I interface fracture toughness between the Ti coating film and Al-alloy substrate is confirmed to be about 0.66 $MPam^{1/2}$ from the present investigation.

1. Introduction

Many materials used in mechanical structures and equipment have various film coatings intended to improve their heat resistance, wear resistance, friction modulus, and corrosion resistance. For example, carbon-based coatings, such as diamond or DLC, which has high hardness, rigidity, and chemical stability, are used as a surface treatment for cutting tools. For glass-molding dies used to make aspherical lenses, DLC or Pt coatings are employed to improve the friction characteristics and the accuracy of the surface profile of the lens.

Scratch testing and micro/nano indenting methods are generally used to evaluate the adhesion strength between coating films and substrates. However, there is not an established absolute evaluation technique for estimating the adhesion strength, and any test method has some difficulty in terms of a lack of versatility. Although the pin-pull-out test is also often used to estimate the adhesion strength of a coating film, the reliability of the calculated results is low because the stress concentration of the bonded part is neglected.

In this work, we use a laser spallation method [1–5] to evaluate the adhesion strength between a coating film and substrate. In this technique, the displacement history of a specimen on which a pulse laser is irradiated is measured. The interface stress history of the specimen is then computed by inverse analysis using the supplementary displacement data.

The author's group has previously suggested the use of an advanced technique based on laser spallation to evaluate the adhesion strength of coating films [6], and developed an axi-symmetric-type, boundary element method program to compute the stress history of the interface between a coating film and substrate.

In the present study, the above technique was improved to evaluate the interfacial fracture toughness between a Ti film coating and Al-alloy substrate. The validity of the numeric technique developed in the present report was confirmed using numeric demonstrations.

2. Theory

2.1. Boundary integral Eequation

Let us consider a three-dimensional infinite elastic body Ω and the boundary *S*. Displacement components u_i and stress tensor σ_{ij} satisfy the following equilibrium equation:

$$\sigma_{ij,j} = \rho \ddot{u}_i, \tag{1}$$

where ρ is a density of the elastic body, and '$,_j$' denotes partial differential for the coordinates x_j, '$\ddot{}$' is second derivative by time.

* Corresponding author. Tel.: +81527893294.
E-mail address: arai@nuae.nagoya-u.ac.jp (M. Arai).

http://dx.doi.org/10.1016/j.advengsoft.2016.04.003

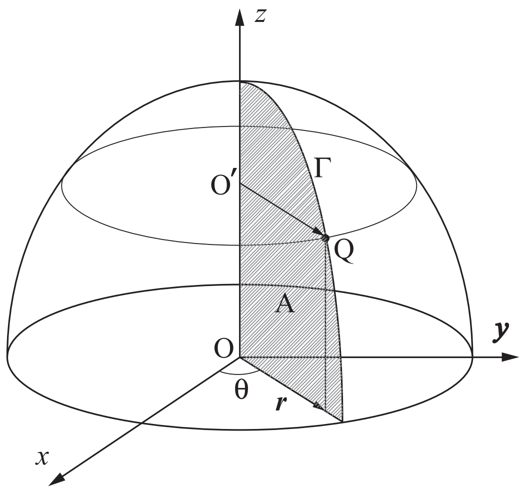

Fig. 1. Definition of coordinates for axi-symmetric analyses.

The Laplace transform of the Eq. (1) is

$$\bar{\sigma}_{ij,j} = \rho s^2 \bar{u}_i, \tag{2}$$

where s is a parameter of Laplace transform. $\bar{}$ denotes a Laplace transform of the quantity in the present study.

Applying the basic function $\bar{U}_{ij}$ (Laplace transform of the green function U_{ij}) to Eq. (2) and integrating it in the consideration domain Ω, then applying Gauss divergence theorem and Betti reciprocal theorem, we have the following boundary integral representation:

$$C_{ij}\bar{u}_j(\mathrm{P}) = \int_S \{\bar{U}_{ij}(\mathrm{P},\mathrm{Q})\bar{t}_j(\mathrm{Q}) - \bar{T}_{ij}(\mathrm{P},\mathrm{Q})\bar{u}_j(\mathrm{Q})\} dS, \tag{3}$$

where T_{ij} is a traction tensor for the green function U_{ij}. C_{ij} is a position constant decided by boundary shape, and it is $1/2\delta_{ij}$ on a smooth boundary (δ_{ij}: Kronecker delta). P denotes the unit source point of the green function, and Q is the integral point on the boundary Γ. By Solving Eq. (3) using suitable boundary conditions, the Laplace transforms of stress and displacement distribution in an elastic body can be obtained. The displacement and stress histories in the real-time domain of the solid body can be calculated by numerical Laplace inversion of the displacement and stress obtained in the Laplace conversion domain [7,8].

2.2. Boundary element analyses for axi-symmetric problems

Let us consider the axi-symmetric domain as shown in Fig. 1 and the formulation of boundary element analyses for the axi-symmetric body. In the case of axi-symmetric body, the symmetry plane conferred in the domain A in Fig. 1 should be dealt with in the numerical analyses.

Here, the boundary integral equation to an axi-symmetry problem is derived using the fundamental solution to a three-dimensional elastic body. First, displacement $u_j = (u_x, u_y, u_z)^T$ is converted to $u_k^* = (u_r, u_\theta, u_z)^T$ using transformation matrix, where u_r is radial direction component and u_θ azimuthal component. The relation between the displacement component u_j for x-y-z coordinate system and u_k^* for r-θ-z coordinate can be written as

$$u_k^*(\mathrm{Q}) = N_{kj}(\mathrm{Q})u_j(\mathrm{Q}), \tag{4}$$

where

$$N_{kj}(\mathrm{Q}) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{5}$$

In these equations, θ denotes the angle between the vector $\overrightarrow{\mathrm{O'Q}}$ and $x$axis as shown in Fig. 1.

Then, the traction tensor $t_j = (t_x, t_y, t_z)^T$ can be transformed as

$$t_k^*(\mathrm{Q}) = N_{kj}(\mathrm{Q})t_j(\mathrm{Q}). \tag{6}$$

Using Eqs. (4)–(6), we obtain the alternative expression of Eq. (3) for the r-θ-z coordinate as the following form:

$$N_{mi}(\mathrm{P})C_{ij}(\mathrm{P})N_{jk}^{-1}(\mathrm{P})\bar{u}_k^*(\mathrm{P}) = \int_S \{N_{mi}(\mathrm{P})\bar{U}_{ij}(\mathrm{P},\mathrm{Q})N_{jk}^{-1}(\mathrm{Q})\bar{t}_k^*(\mathrm{Q}) - N_{mi}(\mathrm{P})\bar{T}_{ij}(\mathrm{P},\mathrm{Q})N_{jk}^{-1}(\mathrm{Q})\bar{u}_k^*(\mathrm{Q})\} dS. \tag{7}$$

Furthermore, the above expression can be rewritten as

$$C_{mk}^*(\mathrm{P})\bar{u}_k^*(\mathrm{P}) = \int_S \{\bar{U}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{t}_k^*(\mathrm{Q}) - \bar{T}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{u}_k^*(\mathrm{Q})\} dS, \tag{8}$$

where

$$C_{mk}^*(\mathrm{P}) = N_{mi}(\mathrm{P})C_{ij}(\mathrm{P})N_{jk}^{-1}(\mathrm{P}), \tag{9}$$

$$\bar{U}_{mk}^*(\mathrm{P},\mathrm{Q}) = N_{mi}(\mathrm{P})\bar{U}_{ij}(\mathrm{P},\mathrm{Q})N_{jk}^{-1}(\mathrm{Q}), \tag{10}$$

$$\bar{T}_{mk}^*(\mathrm{P},\mathrm{Q}) = N_{mi}(\mathrm{P})\bar{T}_{ij}(\mathrm{P},\mathrm{Q})N_{jk}^{-1}(\mathrm{Q}). \tag{11}$$

Taking boundary Γ around the domain of a axi-symmetric cross-section of the angle θ, Eq. (8) can be rewritten as the following double integral form:

$$C_{mk}^*(\mathrm{P})\bar{u}_k^*(\mathrm{P}) = \int_\Gamma \int_0^{2\pi} \{\bar{U}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{t}_k^*(\mathrm{Q}) - \bar{T}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{u}_k^*(\mathrm{Q})\} r(\mathrm{Q}) d\theta d\Gamma. \tag{12}$$

If the displacement and traction defined on the boundary S satisfy axi-symmetric conditions, Eq. (8) can be treated only on the axi-symmetric cross-section A. In this case, because $\bar{u}_k^*$, $\bar{t}_k^*$ does not depend on θ owing to the axi-symmetry, Eq. (12) can be expressed in the following form:

$$C_{mk}^*(\mathrm{P})\bar{u}_k^*(\mathrm{P}) = \int_\Gamma \{\hat{\bar{U}}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{t}_k^*(\mathrm{Q}) - \hat{\bar{T}}_{mk}^*(\mathrm{P},\mathrm{Q})\bar{u}_k^*(\mathrm{Q})\} d\Gamma, \tag{13}$$

where,

$$\hat{\bar{U}}_{mk}^*(\mathrm{P},\mathrm{Q}) = \int_0^{2\pi} \bar{U}_{mk}^*(\mathrm{P},\mathrm{Q}) r(\mathrm{Q}) d\theta, \tag{14}$$

$$\hat{\bar{T}}_{mk}^*(\mathrm{P},\mathrm{Q}) = \int_0^{2\pi} \bar{T}_{mk}^*(\mathrm{P},\mathrm{Q}) r(\mathrm{Q}) d\theta. \tag{15}$$

The detail forms of Green function $\bar{U}_{ij}$ and $\bar{T}_{ij}$ can be given as the following equations:

$$\bar{U}_{ij}(\mathrm{P},\mathrm{Q}) = \frac{1}{4\pi m}(\psi\delta_{ij} - \chi r_{,i} r_{,j}), \tag{16}$$

$$\bar{T}_{ij}(\mathrm{P},\mathrm{Q}) = \frac{1}{4\pi}\left[\left\{\left(c^2-2\right)\left(\frac{\partial\psi}{\partial r} - \frac{\partial\chi}{\partial r} - 2\frac{\chi}{r}\right) - 2\left(\frac{\chi}{r}\right)\right\} r_{,i} n_j + \left(\frac{\partial\psi}{\partial r} - \frac{\chi}{r}\right)\left(\frac{\partial r}{\partial n}\delta_{ij} + n_i r_{,j}\right) - 2\left(\frac{\partial\chi}{\partial r} - 2\frac{\chi}{r}\right)\frac{\partial r}{\partial n} r_{,i} r_{,j}\right], \tag{17}$$

$$\psi = \left(1 + \frac{1}{\alpha_2 r} + \frac{1}{\alpha_2^2 r^2}\right)\frac{\exp(-\alpha_2 r)}{r} - \frac{1}{c^2}\left(\frac{1}{\alpha_1 r} + \frac{1}{\alpha_1^2 r^2}\right)\frac{\exp(-\alpha_1 r)}{r}, \tag{18}$$

$$\chi = \left(1 + \frac{3}{\alpha_2 r} + \frac{3}{\alpha_2^2 r^2}\right)\frac{\exp(-\alpha_2 r)}{r} - \frac{1}{c^2}\left(1 + \frac{3}{\alpha_1 r} + \frac{3}{\alpha_1^2 r^2}\right)\frac{\exp(-\alpha_1 r)}{r}, \tag{19}$$

Please cite this article as: M. Arai et al., Inverse analysis for interface fracture toughness of Ti coating film by laser spallation method, Advances in Engineering Software (2016), http://dx.doi.org/10.1016/j.advengsoft.2016.04.003