International Journal of Solids and Structures 000 (2017) 1–14

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

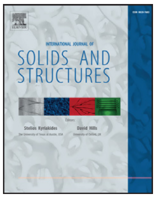

Image-based interface characterization with a restricted microscopic field of view

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ARTICLE INFO

Article history:
Received 22 February 2017
Revised 18 July 2017
Available online xxx

Keywords:
Digital image correlation
Full-field identification
Integrated digital image correlation
Inverse methods
Interface characterization
Cohesive zone model
Adhesion properties
Finite element model
Microelectronics

ABSTRACT

Accurate characterization of adhesion properties in microelectronic systems is challenging due to (1) the far-field load application that often falls outside the microscopic field of view, (2) the ultra-small loads associated with specimen deformation, and (3) the load-case and specimen dependent interface response. To overcome these challenges, a generic method based on Integrated Digital Image Correlation (IDIC) is proposed, which identifies cohesive zone model parameters (of an arbitrary model not intrinsic to the identification method), by correlating images of a delamination process from a restricted field of view at the microscopic scale, whereby far-field loading data cannot be exploited.

To quantify the effects of potential error sources on the performance of the proposed IDIC-routine, virtual experimentation is first conducted. Inaccurate application of boundary conditions in the FE-model of IDIC is thereby shown to be the most critical source of error. Subsequently, a real double cantilever beam (DCB) experiment has been analyzed as a well-defined test-case for characterization of adhesion properties. Since the Young's modulus of the bulk material is generally well known, the imaged, elastically deforming bulk material acts as a force sensor. External load measurement can therefore be omitted from the identification process, thereby rendering the interface identification method independent of the particular test method. The implemented IDIC-algorithm is shown to be robust for accurately identifying the two cohesive zone parameters of interest: the work of separation G_c and the critical opening displacement δ_c.

1. Introduction

Further down-scaling in the microelectronic industry requires the fabrication of dissimilar materials into a dense stack with a complex 3D geometrical structure. Thereby, the number of interfaces per unit of volume increases, as well as the loads on these interfaces due to the mismatch between the coefficients of thermal expansion of the interfaced materials. Interface failure therefore jeopardizes the integrity of the entire system. Hence, the strength and toughness of such interfaces are of great importance during fabrication and usage of microelectronic devices. In the microelectronic industry, the micro-fabrication process scheme of microelectronic devices with adopted process parameters is typically strongly regulated and restricted. Therefore, the optimization of the microelectronic design for preventing interface failure is currently based on a lengthy (and costly) trial and error procedure. In order to improve the design geometry by means of predictive numerical failure analysis instead, the mechanical behavior of the critical interfaces needs to be characterized in detail. This requires interface tests to be performed on specimens with the same microstructure, residual stress conditions, and thermo-mechanical deformation history in the layers as in the actual application, since all of these aspects may strongly influence the interface behavior. In other words, the test specimens should be processed using the same micro-fabrication process as the actual device, including restrictions on maximum in-plane dimensions, thus ruling out dedicated blanket specimens with a simplified material layer stack. Only then can the identified interface behavior truly be used in a predictive fashion to further optimize the geometry of the microelectronic design. Conventional methods rely on accurate knowledge of the applied forces (or moments) to induce interface delamination, and their use is restricted to simplified specimen geometries that do not resemble the actual application (Andersson and Biel, 2006; Andersson and Stigh, 2004; Högberg et al., 2007; Kolluri et al., 2011; Sørensen and Jacobsen, 1998; Sørensen and Kirkegaard, 2006; Stigh et al., 2010; Sun et al., 2008). Because of

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https://doi.org/10.1016/j.ijsolstr.2017.08.020
0020-7683/© 2017 Published by Elsevier Ltd.

Please cite this article as: A.P. Ruybalid et al., Image-based interface characterization with a restricted microscopic field of view, International Journal of Solids and Structures (2017), https://doi.org/10.1016/j.ijsolstr.2017.08.020

Nomenclature

BC	boundary condition(s)
CZ	cohesive zone
DCB	double cantilever beam
DIC	digital image correlation
FE	finite element
IDIC	integrated digital image correlation
LVDT	linear variable differential transformer
MMMB	miniaturized mixed mode bending
ROI	region of interest
VE	virtual experiment

the complex multilayer material structure in microelectronic devices, both of these prerequisites are not trivially met for specimens extracted directly from these devices. In contrast, the present proposal is set up specifically to realize an identification method that is independent of such requirements, and that can be used on intricate specimen designs that are fabricated with the same processing scheme as the application. Measuring the ultra-small loads associated with mechanical testing of microelectronic specimens imposes additional demands on the sensitivity of the load measurement, which therefore requires non-commercial, highly specialized measuring equipment that is difficult to use (Bergers et al., 2014).

As a first step towards realizing microelectronic interface characterization, here, a generic method for the identification of cohesive zone (CZ) model parameters is developed. A general, yet arbitrary cohesive zone model is employed here, and it is stressed that the chosen model is not intrinsic to the method, meaning that other models may also be used. To this end, the method of *Integrated Digital Image Correlation (IDIC)* is investigated, which employs finite element (FE) simulations to correlate images of a mechanical deformation process. Literature has demonstrated IDIC to be a versatile and robust method for mechanical parameter identification in general (Blaysat et al., 2015; Mathieu et al., 2012; Ruybalid et al., 2016; Réthoré et al., 2013; Ruybalid et al., 2016; Mathieu et al., 2014). Interface behavior, however, can only be observed indirectly by analyzing its kinematic effect on the surrounding bulk material during a mechanical experiment, which puts additional demands on the sensitivity of the IDIC-routine. The typical measurement resolution of DIC is ~0.01 of a digital pixel (Hild and Roux, 2006; Lava et al., 2009; Schreier et al., 2000; Wittevrongel et al., 2015). In combination with a smallest pixel size approaching ~100 nm for commercially-available optical microscopes, this is sufficient for capturing the displacements associated with the delamination of microelectronic material layers in the order of nanometers. Hence, the required sensitivity can only be achieved through microscopic investigation of the deforming bulk material with sufficient magnification. Under these conditions, the load application generally falls outside the microscopic field of view and a proper method is required to substitute these inaccessible, far-field boundary conditions (BC) of the experiment by local BC applied to the FE-model within the restricted field of view. A problem that consequently arises is the validation of the local reaction forces, which generally differ from the measured force at the location of load application in the experiment (because of the reduction of a system of forces at another location). However, when stiffness properties (e.g., Young's modulus) of deforming adjacent material layers are known, it should be possible to identify CZ-parameters from the elastic deformation of the adjacent layers only, i.e., without using the (possibly measured) applied load. This brings the additional advantage of the proposed method not requiring this load data which in many small-scale experiments cannot be measured accurately. The demanded high sensitivity of IDIC to the kinematic effects of the CZ-parameters requires the method to be rather insensitive to various potential error sources. Experimental errors result from the imaging technique and modeling errors arise from (1) the applied geometry in the FE-model, (2) the boundary condition application, and (3) the adopted constitutive model.

Therefore, the goal of this paper is to develop an IDIC method that properly transforms the far-field boundary conditions to local boundary conditions in a FE-model matching the restricted microscopic field of view. The developed method is applied to the well-known double cantilever beam (DCB) test-case for interface characterization in microelectronic systems, which makes validation of the method accessible. Firstly, virtual DCB experiments are performed to analyze the performance of IDIC when subjected to various artificially applied error sources, with special focus on the application of boundary conditions. The optimized method is then validated using single and double cantilever beam experiments.

This manuscript briefly reviews the underlying theory and methods of IDIC and CZ-models in Section 2. The development and validation of an appropriate IDIC-methodology, adopting local boundary conditions, and its experimental results are presented in Sections 3–6, followed by general conclusions in Section 7.

2. Methods

To characterize interfaces, the following methods are required: (1) Integrated Digital Image Correlation, see Section 2.1, and (2) a cohesive zone model to be employed in FE-simulations, see Section 2.2.

2.1. Integrated digital image correlation

Integrated digital image correlation is a full-field identification method allowing to directly identify the constitutive parameters of a material model (Leclerc et al., 2009; Réthoré et al., 2009; Roux and Hild, 2006). Images of a deformation process, taken at different moments in time t (e.g., by a digital camera sensor), are correlated (Sutton et al., 1983; Hild and Roux, 2012; Neggers et al., 2015b; 2016) by optimizing towards the constitutive parameters of a material model that governs the deformation. A random pattern is typically applied to the tested material to promote uniqueness of contrast in the images.

Conservation of brightness in the images is assumed and forms the starting point of the optimization procedure:

$$f(\vec{x},t_0) \approx g\big(\vec{\Phi}(\vec{x},t)\big) = g\circ\vec{\Phi}(\vec{x},t), \tag{1}$$

$$\vec{\Phi}(\vec{x},t) = \vec{x} + \vec{U}(\vec{x},t), \tag{2}$$

where f and g are the scalar intensity fields of, e.g., light detected by an optical camera. The vector function $\vec{\Phi}$ maps the pixel position vector $\vec{x}$ in image f (corresponding to the reference material state at time t_0), to the pixel position vector in image g (corresponding to the deformed state at time t). The displacement field $\vec{U}(\vec{x},t)$ can be approximated by the results from a FE-simulation of the experiment: $\vec{U}(\vec{x},t) \approx \vec{h}(\vec{x},t,\theta_i)$, which, in turn, depends on the constitutive model parameters $\theta_i = [\theta_1,\theta_2,\dots,\theta_n]^T$, where n is the total number of unknown parameters. The mapping function is therefore also directly dependent upon these parameters: $\vec{\Phi}(\vec{x},t) \approx \vec{\phi}(\vec{x},t,\theta_i)$. A least squares residual problem is introduced as follows:

$$\Psi = \int_\tau \int_\Omega \frac{1}{2}\Big(f(\vec{x},t_0) - g\circ\vec{\phi}(\vec{x},t,\theta_i)\Big)^2 \mathrm{d}\vec{x}\mathrm{d}t. \tag{3}$$

This residual is minimized simultaneously at all pixel intensity levels in space-time, defined by a spatial domain Ω and a time

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