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Determination of uniaxial residual stress and mechanical properties by instrumented indentation

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Abstract

We propose an improved technique to determine the uniaxial residual stress, elastic modulus, and yield stress of a linear elastic, perfectly plastic bulk material from the force–displacement curve of one conical indentation test. Explicit relationships between the indentation loading–unloading parameters, material properties, and residual stress are established through extensive finite element analyses. Good agreement is found between the input material parameters used in numerical indentation tests and the properties identified from the reverse analysis, with an error of less than 10% in most cases. The technique is applied to a nanoindentation experiment on the cross-section of a thermal barrier system, to measure the elastic–plastic behavior and the residual stress in the bond coat. Likewise, the improved method may be used to measure effectively the material properties and uniaxial residual stress of a multilayer system.

Keywords: Microindentation; Finite element analysis; Residual stresses; Mechanical properties

1. Introduction

Instrumented indentation has been shown to be very useful in measuring the elastic and plastic properties of bulk materials and such a technique is well established for stress-free specimens [1–3]. However, residual stresses occur in many structures, usually being induced by the thermal expansion mismatch between different components, or by mechanical and thermal processing. The presence of residual stress has a significant impact on the mechanical reliability of bulk materials and coatings (e.g., fatigue, fracture, corrosion, and wear) [4]. Moreover, the existence of residual stress prior to an indentation experiment strongly affects the indentation load–depth data [5,6]. Therefore, it is very important to understand the correct way of probing the elastic–plastic properties in a stressed specimen, and to deduce the residual stress quickly and effectively from the inverse analysis of an indentation experiment. To the knowledge of authors, in previous theoretical studies (e.g. Refs. [6–10], including our recent effort [5]), the residual stress was taken to be equi-biaxial which permits a simple axisymmetric formulation of the indentation problem.

In a multilayer structure such as a thermal barrier system [11], a ceramic topcoat (the thermal barrier coating) is deposited on top of a metallic bond coat, which is attached to the superalloy substrate. Both topcoat and bond coat are relatively thick, with thickness of the order of 100 μm. The residual stresses in the topcoat and the bond coat are primarily caused by the thermal expansion mismatch with the substrate. For an indentation test normal to the free surface of the topcoat (shown schematically in Fig. 1(a)), the substrate effect is negligible, as long as the indentation depth is small compared to the ceramic coating thickness. In this case, the residual stress in the topcoat can be regarded as equi-biaxial, which can be effectively measured by the techniques proposed earlier [5]. For the thermal barrier coating, the effects of columnar microstructure and porosity during normal indentation have also

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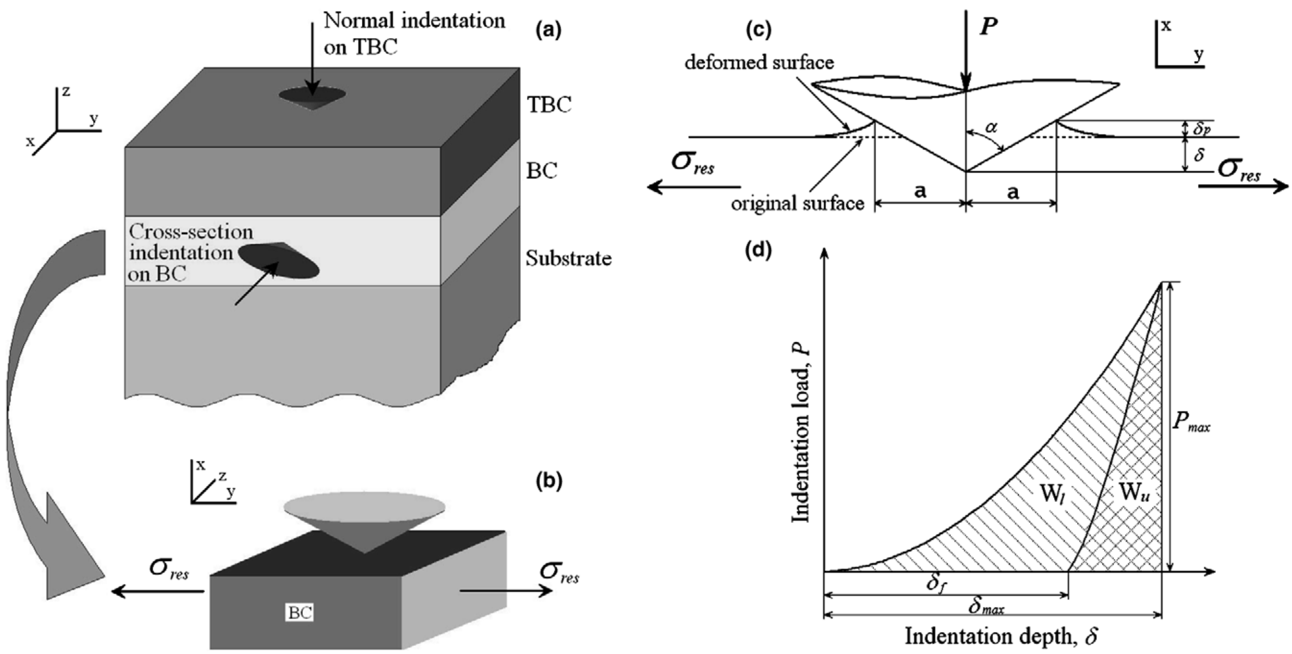

Fig. 1. Schematic of instrumented indentation with a conical indenter. (a) Normal indentation on the topcoat and cross-section indentation on the bond coat of a thermal barrier system. (b) As long as the impression is small, the cross-section indentation may be modeled as an impression on a semi-infinite bulk with uniaxial residual stress. (c) Side view of conical indentation on a specimen with uniaxial in-plane residual stress. (d) Typical indentation depth–load curves obtained from an indentation experiment with loading work and unloading work indicated as the areas enclosed by the curve triangles.

been incorporated in our previous studies [12,13]. However, the mechanical properties and residual stress of all layers in a multilayered system are critical to the system performance; i.e., the bond coat in a thermal barrier system [4,11,14]. Since the bond coat is below the topcoat, the normal indentation technique described above cannot be used to probe directly the intrinsic properties of the bond coat.

One way to access the bond coat is by making a cross-section of the coating and to measure the properties on the cross-section. The specimen is usually sectioned by diamond wire cutting. After mounting, surface grinding, and polishing, the indentation experiment is carried out on the cross-section of the specimen [15] (shown schematically in Fig. 1(a)). If the size of the impression is much smaller than the thickness of the bond coat, the bond coat can be modeled as a semi-infinite and homogeneous bulk material. For an indentation experiment on the cross-section with shallow penetration, the problem can be reduced to normal indentation on a bulk bond coat specimen where the thermal residual stress is essentially uniaxial (Fig. 1(b)). Similarly, the residual stress field induced by mechanical or thermal processing is primarily uniaxial for a range of engineering applications. In all of these cases, the indentation problem becomes three-dimensional. It is therefore important to develop a new indentation technique that effectively measures the mechanical properties and uniaxial residual stress of a bulk specimen from one simple test.

In this paper, a numerical framework is established using three-dimensional finite element analysis, correlating the uniaxial residual stress and the elastic–plastic properties with the indentation load–depth data obtained during loading and unloading. Reverse analysis is used to determine the uniaxial residual stress and mechanical properties of a linear elastic, perfectly plastic specimen. The new technique has been applied to evaluate parallel experiments, where the nanoindentation tests are carried out on the cross-section of a thermal barrier system. The residual stress, elastic modulus, and yield stress of the bond coat are measured and the values are found to agree with those from the literature.

2. Numerical approach

2.1. Model and assumptions

Schematic representations of the three-dimensional model are shown in Figs. 1(b) and (c). The relationship between the indentation force, P, and the indentation depth, δ, during loading and unloading can readily be measured during the experiment and a typical example is given in Fig. 1(d). The friction and the finite compliance of the measuring system and the indenter tip are ignored. We make two simplifications in this study:

(1) The bulk specimen is taken to be linear elastic, perfectly plastic. Such a property is a good approximation for many high-strength alloys and ceramics, including a considerable number of metals, intermetallics, and superalloys, which have small or negligible strain hardening exponents (less than 0.05 or so). Thus, the idealized property applies to the bond coat NiCoCrAl (a multiphase intermetallic) [11,16], which