

Cyclic indentation behavior of metal–ceramic nanolayered composites

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ABSTRACT

The indentation behavior of metal/ceramic nanolayered composites is studied numerically using the finite element method. Attention is devoted to cyclic response under fixed maximum and minimum loads, with the primary objective of examining the evolving plastic deformation in the ductile metal constrained by the hard ceramic layers. The axisymmetric model consists of alternating aluminum (Al) and silicon carbide (SiC) thin films on a silicon (Si) substrate, with the Al/SiC layered structure indented by a conical diamond indenter. It is found that, unlike the homogeneous material where indentation unloading consists of purely elastic recovery, in the multilayered material plastic deformation in the Al layers continues to occur upon unloading and subsequent loading/unloading operations. With each additional cycle the indenter penetrates deeper into the composite. The modeling results are in qualitative agreement with the actual cyclic nanoindentation experiment conducted on the Al/SiC nanolayers.

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1. Introduction

Composite materials consisting of alternating thin layers of metal and ceramic can possess unique mechanical properties such as high strength, high toughness, and high damage tolerance, as well as other functionalities. As a consequence they have been a subject of intensive research [1–15]. The most commonly employed technique for characterizing the mechanical properties of thin-film materials is nanoindentation [16,17]. The behavior of metal–ceramic multilayers under indentation loading may be quite different from that observed in homogeneous materials. This is due to the high degree of heterogeneity, namely the hard/soft layer arrangement and the large amount of interfaces, associated with the composite. The local deformation field will be different from that in a homogeneous material, and internal damage may be induced by the indentation loading itself [18,19]. The effect of material heterogeneity on indentation response (and thus the measurement and interpretation of effective properties extracted from the indentation test) is not well understood.

We have recently conducted numerical finite element analyses of indentation loading on the aluminum (Al)–silicon carbide (SiC) nanolayered composite, and found that plastic deformation in the soft Al layers continues to occur during indentation unloading [20,21]. This was attributed to the internal mechanical constraint resulting from the hard SiC layers in the composite structure, as well as a build-up of special stress pattern in the layers. Therefore,

the unloading process can no longer be considered to consist of simple recovery of elastic deformation as in a homogeneous material.

The unloading induced plasticity described above was identified by comparing the equivalent plastic strain fields before and after unloading, and by tracking the deformation history of individual material elements in the computational model. There is a need to further investigate this phenomenon, as it has significant implications from both fundamental and practical standpoints. For instance, the unloading-induced plasticity immediately casts doubt on the validity of measuring the elastic modulus of the composite from the unloading response of the indentation.

The present study seeks to examine the cyclic indentation response of the Al–SiC nanolayered composite. When conducting nanoindentation on a “normal” material (such as a homogeneous elastic–plastic solid), one encounters both elastic and plastic deformation during loading. The elastic strains are recovered in the unloading phase. If the specimen is then cyclically reloaded and unloaded, the load–displacement curve will follow the prior unloading path, which characterizes the elastic nature of the process [22]. Therefore, cyclic indentation response will serve as an indicator for the possible inelastic behavior during the deformation history. The specific objectives of this work are:

- Gain further insight into unloading induced plasticity in the metal–ceramic system through cyclic indentation modeling.
- Explore the general cyclic indentation load–displacement response, which will also shed light on the contact fatigue behavior of the composite.

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- Conduct experimental verification of the model to determine whether the simulated behavior is in-line with experiments.

2. Numerical model

The composite consists of 41 alternating layers of Al and SiC on a substrate of silicon (Si). This model layout corresponds to that of the actual multilayer system used in our previous study [21]. A schematic of the model, together with the finite element mesh near the indentation site, is shown in Fig. 1. Both the top layer (in contact with the indenter) and the bottom layer (directly above the Si substrate) are Al. The indenter is a diamond cone with a semi-angle of 70.3° , which results in the same nominal projected contact area, for a given depth, as that of a Berkovich indenter. Use of the conical indenter is a practical way to model the indentation process in a two-dimensional setting [16]. The model is axisymmetric, with the left boundary being the symmetry axis. The specimen has a lateral span (radius) of $40\text{ }\mu\text{m}$ and a total height of $43\text{ }\mu\text{m}$. The thickness of each Al and SiC layer is 50 nm , so the total thickness of the Al/SiC nanolayers is $2.05\text{ }\mu\text{m}$.

During indentation the left boundary is allowed to displace only in the 2-direction. The bottom boundary is allowed to move only in the 1-direction. The right edge is not constrained. The top surface of the specimen, when not in contact with the indenter, is also free to move. The coefficient of friction between the indenter and the top surface is taken as 0.1, which is a typical value for the diamond/metal contact pair [23,24]. A total of 173,105 linear elements are included in the model, with a finer mesh size near the upper-left corner of the test material (Fig. 1). Mesh convergence was checked through the modeled indentation load–displacement curves resulting from meshes with different extents

of refinement. The finite element program ABAQUS (Version 6.8, Dassault Systemes Simulia Corp., Providence, RI) was used to carry out the analysis.

Young's moduli for Al and SiC used in the model are 59 GPa and 277 GPa, respectively, which are based on nanoindentation measurements of single-layer Al and SiC films [11]. The somewhat lower modulus of SiC is due to the fact that in the as-deposited condition, the SiC film is amorphous. Poisson's ratios for Al and SiC are taken as 0.33 and 0.17, respectively. The plastic response of Al is based on the tensile loading data of single-layer Al, with an initial yield strength of 200 MPa. Plastic deformation follows the von Mises criterion with isotropic hardening and the incremental flow theory. The piecewise linear strain hardening response features hardening slopes of about 200 MPa from initial yield up to the strain of 50.5% and then 40 MPa up to the strain of 300.7%, beyond which perfect plasticity ensues. The SiC ceramic is a much more brittle material. It is nevertheless treated as an elastic–plastic material, with a very high “yield point” of 8770 MPa (estimated from the indentation hardness of a single-layer SiC film), followed by perfect plasticity. This treatment is necessitated by the fact that a purely elastic SiC in the model will generate unrealistically high loads during the indentation simulation, and is validated by the fact that in the experiment the SiC layers exhibited a glassy/plastic-type response due to the amorphous nature of the film [21]. Young's modulus and Poisson's ratio of the diamond indenter are 1141 GPa and 0.07, respectively. All the interfaces between different materials in the structure are assumed to be perfectly bonded.

Cyclic indentation loading was simulated by first pressing the indenter to a depth of 500 nm (ten times the initial thickness of each layer), which corresponds to an indentation load of 27.5 mN. Unloading to 10% of the peak load, 2.75 mN, then follows. Subsequent cycles were carried out between these maximum and minimum loads. The same type of deformation history was also applied to a control model, where the Al/SiC multilayers are replaced by a homogeneous Al layer of the same total thickness. In this case the peak load is 5.18 mN, which corresponds to a depth of 500 nm during the first indentation loading. Subsequent cycles were then between 10% and 100% of the peak load. Although the simulation was performed under displacement control, we ensured that all load reversals during the cyclic process took place at the chosen maximum and minimum load values.

3. Modeling results and discussion

We present the result of the control case first (thick Al film on Si substrate). Fig. 2 shows the simulated indentation load–displacement curves for two full cycles. The maximum indentation depth, 500 nm, is at approximately 1/4th of the film thickness. It is observed that both the loading and unloading phases of the second cycle follow the same path as the first unloading response. This is an indication of the elastic nature of the deformation starting from the first unloading [22]. The elastic response can also be manifested by the equivalent plastic strain field, the contour plots of which are shown in Fig. 3. Fig. 3(a) and (b) corresponds to, respectively, the beginning and end of the unloading phase in the first cycle, and Fig. 3(c) is after reloading to the peak load. Only the material near the indentation site is included in the presentation. As expected, it can be seen that the equivalent plastic strains remain exactly the same during the process in the homogeneous film material.

We now turn to the Al/SiC nanolayered composite. Fig. 4 shows the simulated load–displacement curves for the first two full cycles. Although the maximum indentation depth during the first cycle is the same as in the previous case of homogeneous Al

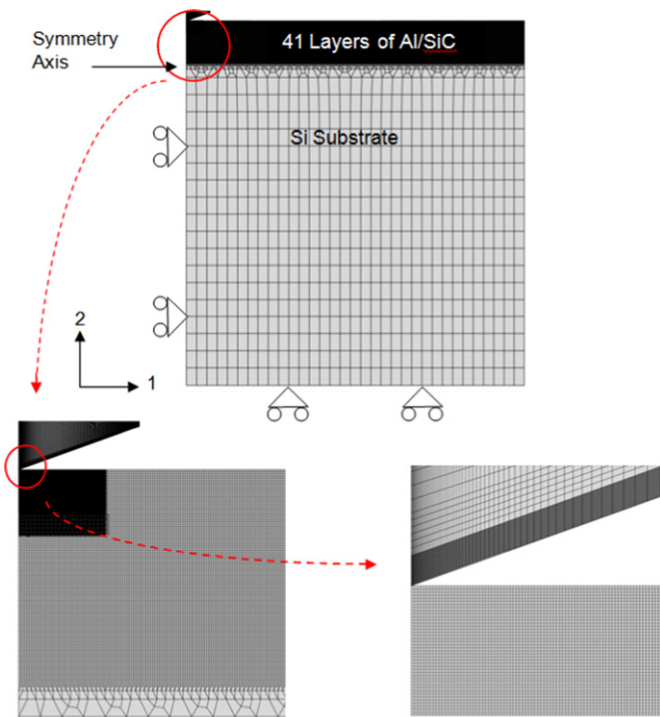


Fig. 1. Schematic showing the Al/SiC multilayers above a Si substrate, and the boundary conditions used in the axisymmetric model. The left boundary is the symmetry axis. The entire specimen is $40\text{ }\mu\text{m}$ in lateral span (radius) and $43\text{ }\mu\text{m}$ in height. The individual Al and SiC layers are 50 nm thick. The finite element mesh near the indentation site is also shown.

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