Application of FEM simulation and abductive network during nanoindentation process of the thin film on bulk metal

T. S. Yang, S. Y. Chang and B. Y. Lee

Department of Mechanical and Computer-Aided Engineering, National Formosa University, 64 Wunhau Road, Huwei, Yunlin, 632 Taiwan

1. Introduction

FEM has been widely used for numerical simulation of indentation tests on bulk and film material in order to analyze its deformation response. Bhattacharya and Nix [1] used the finite element method (FEM) to solve for an indentation problem with an axisymmetric cone. The results compared well with experimental data. Huber et al. [2,3] developed a neural network methodology for the identification of material parameters of film–substrate systems.
This study applies the finite element method (FEM) in conjunction with an abductive network to predict the indentation load during the nanoindentation process of the thin film on bulk metal. Loading-unloading curve is investigated for different material parameters, such as Young's modulus, yielding stress and tangent modulus of film, by finite element analysis. Finally, prediction model is established by abductive network for predicting indentation load under a suitable range of material parameters of film.

2. Finite element indentation modeling

This study applies finite element code DEFORM-2D [4] to simulate the indentation process. Fig. 1 shows the FEM model of the film–substrate system. An axisymmetric cone with half-included angle is 70.3°. Nanoindentation is measurement of the load and the displacement (Fig. 2 (b)). Fig. 2 (c) presents the stress-strain curve with bilinear constitutive law of material. Note that E is Young's modulus; E_T is tangent modulus; Y is yielding strength. During FE analyses, the indenter is assumed to be rigid. The bulk metal is assumed as elastic material, while the film material is assumed as elastic-plastic material. Axisymmetric condition is used in the present simulation. The thin film and bulk metal are modeled using approximately 1000 elements and 973elements, respectively.

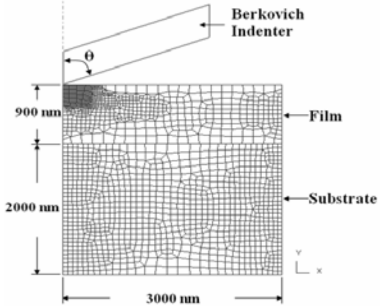
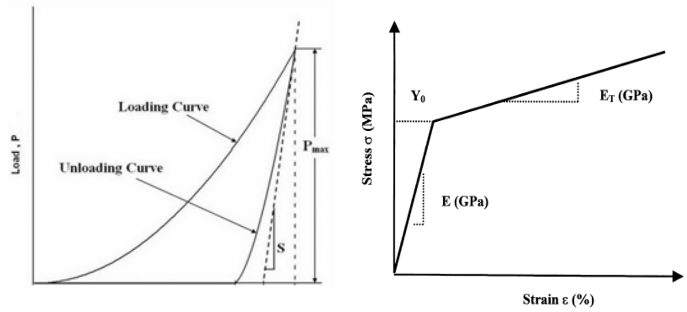
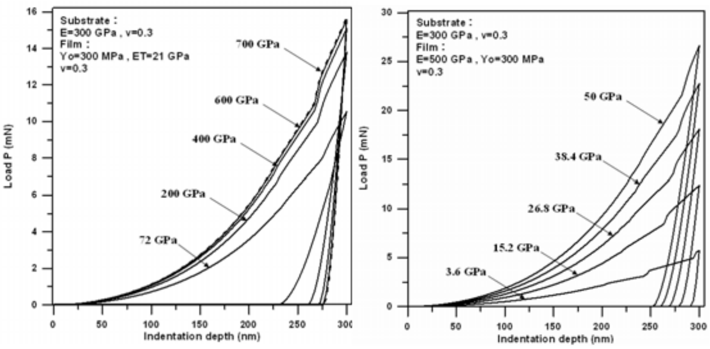


Fig. 1. FEM model of film–substrate system

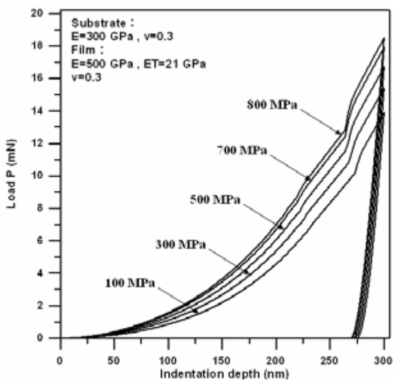


(a) load-depth curve (b) stress-strain curve
Fig. 2 load -depth curve and stress-strain curve

To investigate the effects of material parameters of film, such as Young's modulus E_f, tangent modulus E_{Tf} and yielding strength Y_f on the loading and unloading curve of film on substrate composites. Numerical analysis was performed for each change in these values. The thickness of substrate and film material is 2 *u*m and 0.5 um, respectively. The depth of indentation is 300 nm.
Fig. 3(a) shows the effect of the $\boldsymbol{E_f}$ on the loading and unloading curve of nanoindentaion process. Large values of Young's modulus result in high values of maximum indentation load. The slope of unloading curve increases as the film Young's modulus increases. Fig. 3(b) shows the effect of the E_T on the loading and unloading curve. Large values of tangent modulus result in high values of the maximum loading force. The slopes of unloading curves are almost the same as the tangent modulus increases. Fig.3(c) shows the effect of the Y_f on the loading and unloading curve. Large values of film yielding stress result in high values of the maximum loading force. The slopes of unloading curves are almost the same as the film yielding stress increases. Fig. 4 shows the stress distribution for the nanoindentation process by FEM. The maximum effective stress occurs at the portion near the tip of indenter. The values of maximum effective stress of loading process are larger than that of unloading process.



(a) film Young's modulus (b) film tangent modulus



(c) film yielding stress

Fig. 3. Effects of film material properties on loading and unloading curve

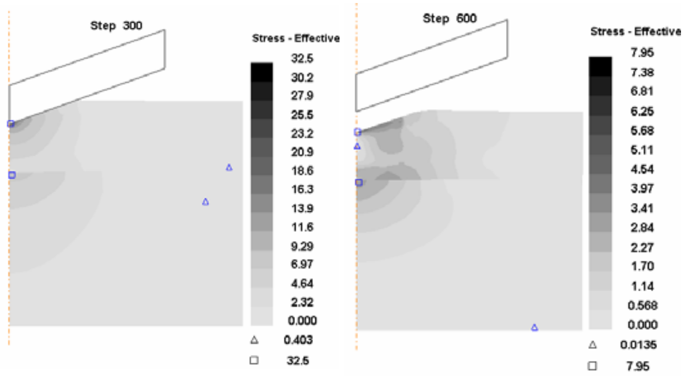


Fig. 4. Stress distribution for the loading and unloading

3. Abductive network synthesis and evaluation

The polynomial network proposed by Ivakhnenko [5] is a group method of data handing (GMDH) techniques. Theses nodes evaluate the limited number of inputs by a polynomial function and generate an output to serve as an input to subsequent nodes of the next layer. To build a complete abductive network, the first requirement is to train the database. The information given by the input and output parameters must be sufficient. A predictive square error (PSE) criterion [6] is then used to automatically determine an optimal structure.

The substrate is assumed as the elastic material with Young's modulus E_s 300 GPa. The film thickness is 900 nm and the indentation depth is 300 nm. The film material parameters are selected by varying the film Young's modulus E_f, film yielding stress Y_f and film tangent modulus E_{Tf} in the ranges of 72-700 GPa, 100-800 MPa and 3.5-50 GPa, respectively. There are three process variables and each of theses variables was set at three levels. Therefore, 27(3×3×3) combinations of material parameters are constituted. Base on the training database regarding to the film material parameters for the nanoindentation process. The abductive networks with a criterion of minimum square error can be developed for predicting the indentation load.

To validate the accuracy of the prediction model, another 5 data sets of the suitable range are tested for the maximum indentation load predictions. Fig. 4 shows the comparison of the indentation load between the abductive network prediction and FEM simulation under various combinations of material parameters of film. The predicted results of the indentation load are consistent with those obtained from FEM simulations quite well.

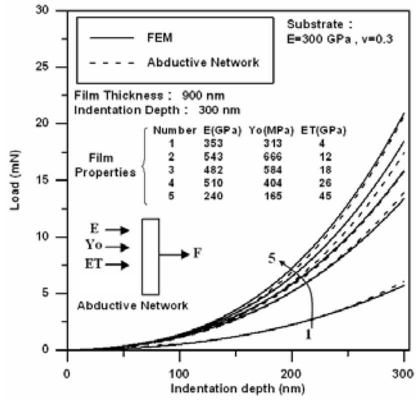


Fig. 4 Comparison between FEM and Abductive networks prediction for indentation load

4. Conclusions

This study applies the finite element method (FEM) in conjunction with an abductive network to predict the indentation load during the nanoindentation process of the thin film on bulk metal. Loading-unloading curve and effective stress distribution are investigated for different material parameters, such as Young's modulus, yielding stress and tangent modulus of film, by finite element analysis. The abductive network is then utilized to synthesize the data sets obtained from numerical simulations. Finally, prediction model is established for predicting indentation load under a suitable range of material parameters of film.

Acknowledgements

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