Computational studies of the nanoindentation load depth curves

A S Bhattacharyya
Centre for Nanotechnology, Central University of Jharkhand, Ranchi-835205

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The load depth curves obtained during nanoindentation depends on several factors. Load depth curves were generated computationally and an insight in the different parameters have been presented in this article.

Keywords: Nanoindentation, load-depth curves.

Introduction
Nanoindentation is an effective tool for determination of material properties based on its depth sensing capabilities. The load-depth curve obtained during nanoindentation gives the load which is required to penetrate a certain depth in the material and also provides the elastic and plastic work done during the indentation process. The nature of the load-depth is a function of both the material under test and tip blunting $^{1-4}$.

Results and discussions
For initial penetration, the load and depth follow the relation $P = k h$ when the initial spherical blunt potion of the indenter is in contact. The relation changes to $P = k h^{1.5}$ and later to $P = k h^2$ for higher depths as the conical sides comes in contact$^5$. For the loading portion of the curve the relation $P = k h^m$ where $m$ varies from 1 to 3 has been plotted in Fig 1 (a). A closer variation is observed in Fig 1(b) where $m$ has varied from 1.75 to 2.25. The experimental load depth curve for SiCN coatings deposited on Si (100) substrates $^6$ was fitted with a computer generated load-depth curve using the relation $P = k h^2$ for the loading curve and $P = k h^2 - k (h_{max} - h)^2$ for the unloading curve. The value of the $k$ for the fitted simulated curve came out to be 2.19e-4. For a depth of 500nm, the experimental load-depth curve reaches to a maximum value of 28 mN for an electropolished 304SS material and 54mN for SiCN deposited on Si (100). The simulated load depth curves for different values of $k$ are given in Fig 1(e). Fig 2 shows the possible load depth curves for different elastic plastic responses of the film. For a 100% elastic response the unloading curve follows exactly the same path followed by the loading curve. As the plastic repose starts to take place the unloading curve starts to deviate from the loading curve. However it should be kept in mind that the nature of

* Author for correspondence
E-mail: 2006asb@gmail.com

![Fig. 1](image-url)
the curve are also a function to wear as for the same material, a blunt tip will give higher elastic response for the same depth compared to a sharper tip. The unloading curve equations were different for each of the cases.

\[ P = k h^2 \]
\[ P = k h^2 - k^2 (h_{\text{max}} - h)^{1/2} \]
\[ P = k h^2 - k (h_{\text{max}} - h)^{3/2} \]
\[ P = k h^2 - k^2 (h_{\text{max}} - h)^{5/2} \]

So the parameters \( k, m, n \) and \( r \) are the ones which are actually controlling the shape of the load depth curve. Integration of these expressions gives us the area under the curves. A further research is however required to get a further insight about these parameters.

\[ \int k h^m \, dh = \text{Total energy} \]
\[ \int \left[ k^n (h_{\text{max}} - h)^r \right] \, dh = \text{Elastic energy} \]
\[ \int \left[ k h^n - k^n (h_{\text{max}} - h)^r \right] \, dh = \text{plastic energy} \]

The established power law equation \( P = (h - h_f)^m \) to fit the unloading portion of the curve is used to determine the stiffness in which \( h \) is the penetration depth and \( h_f \) the final displacement.

\[ S = \frac{dP}{dh} \text{ at } h = h_{\text{max}} \text{ which in our case comes out to be } S = m \frac{k h_{\text{max}}^m}{h_{\text{max}}} \text{ which is comparatively much simpler than the existing form } S = B \frac{(h - h_f)^m}{h_{\text{max}}} \]

**Conclusions**

Computational studies were done to generate load depth curves on nanoindentation based on Oliver and Pharr model. The parameters for generating the curves showed a significant effect on the nature of the curves which corresponds to experimental and sample conditions while doing the nanoindentation experimentally.

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**References**