DECIPHERING NANOINDENTATION LOAD-DISPLACEMENT CURVES

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Measurement of thin film mechanical properties by load and depth sensing indentation methods, often referred to as nanoindentation, is based on load-displacement data obtained as an indenter is driven into and withdrawn from a material. For sharp indenters like the Berkovich three-sided pyramid used frequently in nanoindentation studies, indentation loading curves are usually well-described the simple power law relation $P = Bh^2$, where P is the load, h is the penetration depth, and B is a constant related to the geometry of the indenter and the elastic and plastic properties of the material. The dependence of the load on the square of the penetration depth is a natural consequence of the self-similarity of the pyramidal indenter, as it would also be for indentation by a rigid cone. During unloading, the load-displacement behavior is considerably more complicated due to the complex elastic and plastic processes which determine the shape of the permanently deformed surface after the indenter is withdrawn. Despite this, experiments have shown that the unloading curve can also be described by a power law function of slightly different form. The relation $P = A(h-h_f)^n$ is often used, where h_f is the final depth after complete unloading, and A and n are material constants. However, unlike the loading curve, the power law exponent for the unloading curve is not fixed at an integral value, but varies from material to material in the range n=1.2-1.6. Simple models based on observations from finite element simulations of indentation by a rigid cone are presented which provide a physical explanation for these behaviors. The models also provide a means by which the material constants appearing in the power law relations can be related to more fundamental material properties such as the elastic modulus and yield strength.

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