# A SUBSTRATE EFFECT OF HARDNESS IN FILM/SUBSTRATE INDENTATION: FINITE ELEMENT STUDY ON 'OVERSHOOT' PHENOMENON OF HARDNESS

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## 1. Introduction

Nanoindentation tests are used as a means to determine the mechanical properties of small sized materials from the measured force-depth curves, specifically to extract the elastoplastic properties of thin film deposited on the substrate. For this purpose, the quantities of the thin film must be decoupled from those of the substrate, and it is important to understand how the substrate influences the entire indentation process. We have carried out extensive finite element (FE) simulations on this indentation problem and found a new phenomenon. The measured hardness *overshot* the substrate hardness in a certain combination of the elastoplastic properties of the film and the substrate materials.

## 2. Computational method

The specimen, consisting of a semi-infinite substrate with a thin film deposited on it, is indented by a sharp conical indenter, as shown in Fig. 1. The thickness of the film is denoted by *d*, and half apex angle of the conical indenter, $\theta$ ($\theta$ =70.3°). We assume that those two materials are homogeneous and their uniaxial stress-strain ($\sigma$-$\varepsilon$) relations obey a power-law form:

(1) $\sigma = E\varepsilon$ for $\varepsilon \le Y/E$ and $\sigma = R\varepsilon^n$ for $\varepsilon \ge Y/E$,

where *E* and *Y* are Young's modulus and yield strength, respectively, and *n* is the work-hardening exponent with $R = Y(E/Y)^n$.

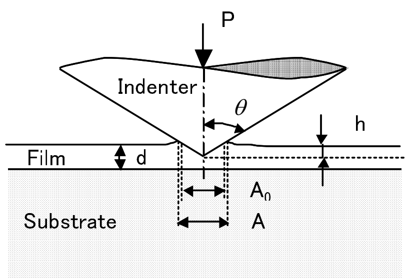


Fig. 1. Schematic of conical indentation on film/substrate specimen.

When the specimen is of a homogeneous bulk, i.e., both the film and substrate materials are identical, the relation between the force *P* and the indentation depth *h* is described by a quadratic law: $P = Ch^2$. Here the loading curvature *C* is a constant during the indentation, which is determined by the material properties and the indentation angle $\theta$. When the specimen is made of two layers (Fig. 1), however, *C* no longer remains constant, and varies as a function of depth *h*, namely *C*(*h*). The modified loading curvature *C*(*h*) is then defined by the following relation and satisfies latter two conditions:

(2) $C(h) = P/h^2$, $C(h) \to C_f$ when $h/d \to 0$, and $C(h) \to C_s$ when $h/d \gg 1$.

Here, subscripts *f* and *s* mean that the specimen is made of bulk film material and of bulk substrate material, respectively. Indentation hardness *H* is given by the definition:

(3) $$H = P/A, \quad A = A_0 = 24.5\,h^2,$$

where $A$ and $A_0$ represent true projected contact area and nominal contact area, respectively. In this study $A_0$ is used in place of $A$ to calculate the hardness. This means that both pile-up and sink-in effects of the indented material are ignored.

## 3. Combination of material properties and calculated results

We have carried out elastoplastic axisymmetric FE calculations with ANSYS, for the material properties and their combinations, shown in Table 1, where $\nu$ means Poisson's ratio of the material.

Table 1. Material properties used in the analysis.

| Case | Film | | | | Substrate | | | | $H_f/H_s$ |
|---|---|---|---|---|---|---|---|---|---|
| | $E$ (GPa) | $\nu$ | $Y$ (GPa) | $n$ | $E$ (GPa) | $\nu$ | $Y$ (GPa) | $n$ | |
| A | 410 | 0.25 | 4.0 | 0.0 | | | | | 0.675 |
| B | 410 | 0.25 | 4.0 | 0.2 | 470 | 0.25 | 7.0 | 0.0 | 0.838 |
| C | 410 | 0.25 | 2.0 | 0.5 | | | | | 0.931 |
| D | 410 | 0.25 | 2.5 | 0.5 | | | | | 1.008 |

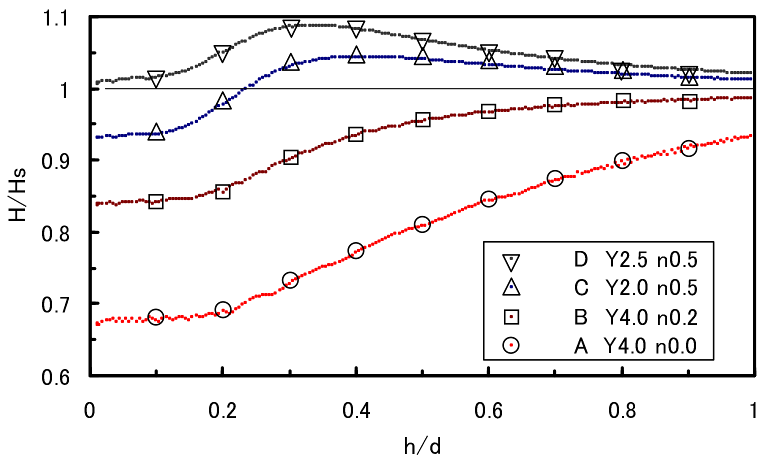


Fig. 2. Relative hardness $H/H_s$ as a function of relative indentation depth $h/d$.

Calculated results are shown in Fig. 2 for the four cases shown in Table 1. In the cases of A and B, the relative hardness $H/H_s$ remains almost constant at their own hardness of film $H_f$, in a relatively small depth range ($h/d < 0.2$). It then monotonically increases with increasing depth, and finally converges to $H_s$ ($H/H_s \to 1$). The behavior is very different in cases C and D, where $H_f \approx H_s$. In these two cases, starting from $H_f$, the hardness is observed to overshoot both values of $H_f$ and $H_s$ with increasing depth before converging to $H_s$. Then, a question arises: why has this overshoot phenomenon not been observed or reported previously? We can think of the following two reasons: (1) The combination of material properties of C or D has not been tried in hardness tests yet, or (2) the overshoot quantity is no greater than 10 % of the hardness ($H_s$), and therefore, easy to be overlooked.