APPROACHES TO REMOVE SIZE EFFECT DUE TO INDENTER ROUNDNESS IN NANO-INDENTATION

Rong Yang[*a)], Taihua Zhang[*], Qun Zhang[*] & Yilong Bai[*],
[*]*State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China*

Summary The influences of indenter roundness on nano-indentation hardness are investigated with analytical solution and FEM calculations. The size effect and its range owing to the roundness are determined. Based on the results, some approaches to remove the false size effect and to extract the actual size effect resulting from material properties are proposed.

INTRODUCTION

Indentation size effect (ISE) [1] of hardness from experimental observations is considered as one proof for the existence of materials' size effect, and therefore nano-indentation technique becomes ideally candidate to extract the size effect dependent parameters from materials. However, the imperfection of the indenter due to manufacture and abrasion in everyday use is inevitable and unpredictable, and becomes significant factor when the indention depth is in the range of nanometres (see Fig.1). The uncertainty of the indenter may cloud the assessment of the results, and made the task of reversing materials' size effect mission impossible. Thus, it is essential to develop approaches to estimate the effect of the roundness of indenter to the hardness, then to eliminate the influence of the indenter and obtain the intrinsic properties of the materials. Here, a sphero-conical indenter is considered, which is an axisymmetric conical shape of half-include angle θ and with spherical tip of radius R.

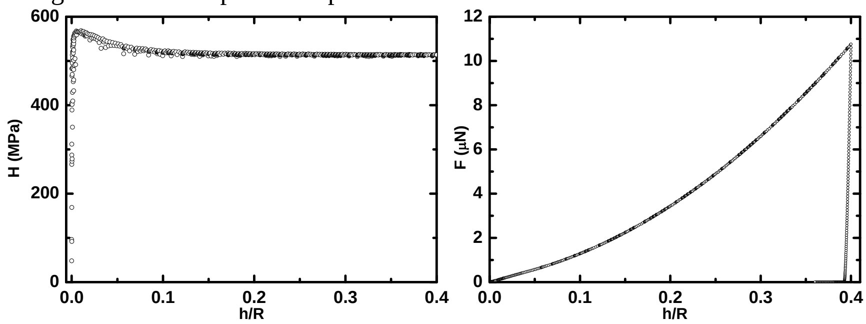

Fig.1 Hardness and force curves of sphero-conical indentation on continuum material with no size effect. The material is annealed steel like elastic-perfectly plastic one, with $\sigma_y/E = 10^{-3}$, E=200 GPa and ν=0.3. For the indenter, θ=70.3˚ and R=50 nm. The max indentation depth is 20 nm, which is more than 6 times of the spherical cap height of about 3 nm.

ANALYTICAL AND NUMERICAL APPROACHES

Firstly the effect of indenter geometry on hardness is investigated. By deriving the analytical solution of the relation between the ratio of hardness (H) to reduce modulus (E_r) and the ratio between two energy parameter unloading work (W_u) and total work (W_t), the hardness of indentation on homogenous linear elastic media can be express as a function of relative depth h/R and work ratio W_u/W_t (here W_u/W_t=1), as shown in Fig. 2. The results are compared with FEM calculations and fitting relations from Cheng's work on conical indentation [2] and on spherical indentation [3].

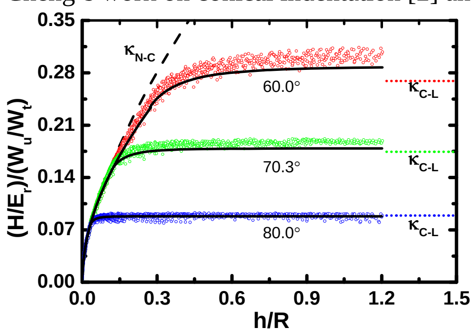

Fig.2 Analytical results of the relation between ratio ((H/E_r)/(W_u/W_t)) and relative depth h/R for linear elastic material (solid lines), in compare with FEM results (scatter points) and two fitting relations for spherical indenter and conical indenter by Cheng et al. [2,3] (dashed lines)

[a)] Corresponding author. Email: yangr@lnm.imech.ac.cn.

Then this approach is extended to account into plasticity and to material with changing in modulus or yield strength normal to the surface. A typical result is illustrated in Fig. 3.

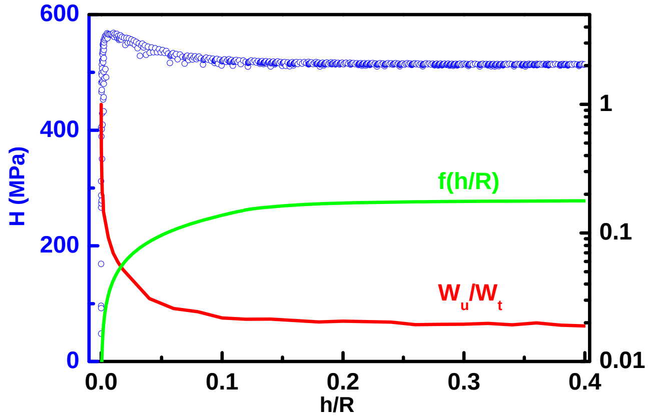

Fig.3 Hardness H over the relative indentation depth h/R and its dependences upon function of h/R and work ratio W_u/W_t. $f(h/R)$ and W_u/W_t are with opposite trend: $f(h/R)$ begins from zero and then comes to constant while W_u/W_t begins from one and decrease to a value less than one.

RESULTS AND DISCUSSIONS

The result in Fig. 2 indicates that hardness H depends on three factors: reduced modulus E_r, the function of relative depth $f(h/R)$ and the work ratio in indentation W_u/W_t. In fact, E_r mainly depends on the tested material (if the indenter is considered to be rigid), $f(h/R)$ depends on the indenter roundness and W_u/W_t on both. The effects of the last two on hardness can be shown in Fig. 3. When the indentation depth remains within the spherical part and the deformation is elastic, W_u/W_t is equal to 1. Afterwards the work ratio decreases and finally tends to a constant less than 1, when indentation goes to the stage dominated by conical part of the indenter (h>~$4h_s$). On the other hand, the effect of h/R increases to a constant when h increases. In-between (h_s<h<~$4h_s$), these two effects are combined and then the measured hardness could either increase or decrease. The most significant issue is that the value of h_s is governed by the half-included angle and the tip radius. So, in order to suppress the influence of indenter roundness on the measurement, one can reduce tip radius by making the indenter close to the ideally conical one or increase the conical angle.

CONCLUSIONS

The influences of indenter roundness on the size effect of hardness are investigated based on continuum approaches. Mechanisms of the tip radius's effect on the hardness are revealed. Approaches to remove this false size effect and to extract the true size effect resulting from material properties are proposed. Both of reducing tip radius to make the indenter close to ideally conical and increasing the conical angle can suppress the false size effect due to indenter roundness.

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