Analysis of Plastic Characteristics of Nanocontacts Through a Volumetric Indentation Work Approach

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In order to estimate the hardness and yield strength of an indented material, advanced methods have been developed for extracting closed boundaries of the contact area and the plastically deformed zone from 3D nanocontact morphologies. However, this image processing technique cannot be applied to shallow indentations as it results in weak surface pile-ups. Thus, we introduced a concept of indent volume analysis and recalculted the hardness and yield strength. Based on the modified volumetric approach, the new hardness and yield strength of Au film and fused quartz are compared with those from the indentation curve analysis and differential contact analysis.

INTRODUCTION

Nanoindentation measuring applied load and indenter penetration depth during a contact deformation is one of the most powerful techniques for evaluating the mechanical properties of small volume materials (Oliver and Pharr, 1992). Typical nanoindentation researches have been constrained within the determination of elastic modulus and hardness. However, the research scope is now being expanded to the analysis of plastic flow curve, yield strength, residual stress, fracture toughness, interfacial adhesion and various tribological properties (Ahn and Kwon, 2001; Lee et al., 2006; Lee and Kwon, 2002; Lee and Kwon, 1999). The hardness, \( H \) is formulated as contact pressure in Eq. 1:

\[
H = \frac{L_{\text{max}}}{A_c}
\]

where \( L_{\text{max}} \) and \( A_c \) are the indentation load and contact area, respectively. The reduced modulus, \( E_r \), is also formulated with the terms of the indentation unloading slope, \( S \) and contact area, \( A_c \). Thus, a determination of \( A_c \) is crucial to the nanoindentation data analysis.

However, since the deformation morphology under indentation loads less than \( \text{mN} \) cannot be easily observed, 2 models have been developed (Oliver and Pharr, 1992; Doerner and Nix, 1986) for characterizing \( A_c \) at the peak indentation load from the nanoindentation curve. The method commonly used for analyzing the nanoindentation load-depth curve is that proposed by Oliver and Pharr (1992), expanding on an earlier work by Doerner and Nix (1986). Below, the analyzed data based on the Oliver and Pharr method will be denoted as O&P. However, the O&P method (Oliver and Pharr, 1992) can strongly underestimate the contact area if a material pile-up is involved, as reported in the finite element simulation work of Bolshakov and Pharr (1998). They note that the O&P method gives a reasonable estimate of the contact area only when \( h_f/h_{\text{max}} \) is smaller than 0.7 and material shows significant elastic recovery after nanoindentation. Here, \( h_{\text{max}} \) and \( h_f \) are the peak penetration depth and residual depth, respectively. Some researchers (Hainsworth, Chandler and Page, 1996; Malzbender, With and Toonder, 2000; Lee, Baek, Kim and Nahm, 2007) have proposed indentation parameters, independent of the projected contact area, to characterize the mechanical properties. The elastic/plastic loading curve of a homogeneous sample can be well described by a linear relationship between the indentation load and the square of penetration depth. And its slope, implying combined responses of the elasticity and plasticity of the sample, is formulated as the ratio of the reduced modulus to the contact hardness, \( E_f/H \). If the hardness (or the reduced modulus) is already known, or is estimated from a separate testing technique, the reduced modulus (or the hardness) can be evaluated from the elastic/plastic loading curve or the contact stiffness of the unloading curve. However, a measurement of the elastic modulus or hardness using another micromechanical technique is a somewhat difficult and cumbersome process. Lee et al. (2007) have proposed a methodology for predicting the contact area by estimating Young’s modulus of the sample independently from the Hertzian reversible loading part in the nanoindentation curve. However, the reversible loading part cannot be easily found from the nanoindentation curves obtained from the sharp indentations on polycrystalline metals.

The use of an atomic force microscopy (AFM) or interferometer has thus been proposed to obtain the projected contact area of the ductile metal from direct observation of the residual impression (Lim, Chaudhri and Enomoto, 1999; Sangwal, Gorostiza, Servat and Sanz, 1999; Li, Cheng, Yang and Chandrasekar, 2002; Saha and Nix, 2001; Beegan, Choudhury and Laugier, 2003; Kese and Li, 2006). Lim et al. (1999) analyzed the indented surface of an Al thin film on sapphire and determined the contact boundary as the fastest slope change inside the remnant indent. A similar study was performed by Sangwal et al. (1999) for a MgO single crystal; however, this approach was proved to be effective for sink-in dominant materials (Li, Cheng, Yang and Chandrasekar, 2002). While Saha and Nix (2001) have tried to extract an approximate of the contact boundary by connecting a few peak points identified from AFM line profiles. A few studies (Beegan, Choudhury and Laugier, 2003; Kese and Li, 2006) also have been done.