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Indenter surface area and hardness determination by means of a FEM-supported simulation of nanoindentation

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Abstract

Stress–strain curves are obtained through a finite element method (FEM) simulation of nanoindentation, and the actual indenter tip geometry is determined by additional experimental and FEM-based procedures. Based on such material stress–strain laws and on the actual indenter tip geometry, the following are determined employing the "HANI" algorithm (HArdness determination by means of a FEM-based simulation of NanoIndentation): first, the contact surface due to elastic and plastic deformations during the loading phase of nanoindentation; second the occurring impression geometry after unloading and finally the related hardness values after Martens, Vickers, etc.

Moreover, the indenter surface area functions of Vickers and Berkovich indenters are determined experimentally/analytically, by nanoindentations on Si(100) reference material of known Martens hardness. Applying these functions, Martens and Vickers hardness are determined correspondingly for various materials and they are compared to hardness values obtained by the "HANI" algorithm. Significant deviations occur, if the hardness of the reference material is quite different than the hardness of the test pieces.

Keywords: Nanoindentation; Stress–strain curve; Indenter surface area; Hardness

1. Introduction

A significant requirement for attaining a high accuracy in nanoindentation evaluation procedures [1–4] is the precise knowledge of the indenter tip geometry, since in nano-scale penetration depths, deviations from the ideal sharp tip geometry affect strongly the obtained results [5–8]. These nano-deviations, due to indenter manufacturing errors, cannot be described precisely, even through atomic force microscope (AFM) observations, according to which the tip surface geometry has been considered as spherical [9–11].

The Berkovich and Vickers indenter tip geometries, used in the frame of the present investigations, were determined by means of nanoindentations on Si(100) with known Martens hardness as reference material [7] and the FEM-based algorithm "SSCU-BONI", introduced in [6]. This algorithm simulates stepwise the physical procedure of the indenter penetration into the examined material and simultaneously determines the stress–strain curve of the tested material, through repetitive trial and error iterations.

Manufacturers of nanohardness measurement instruments have established calibration procedures [4,12], according to guidelines described in ISO 14577-1 [5], to exclude the indenter tip shape errors effect while determining the hardness by means of nanoindentations, wherein reference materials with known hardness characteristics are utilized. Detected hardness values by both the previously mentioned methods will be compared and introduced in the present paper.

2. HArdness determination by means of a FEM-based simulation of NanoIndentation ("HANI" algorithm)

The geometry of the contact area between the diamond indenter and the specimen during the indentation is of crucial importance in determining the resulting material hardness. The FEM model simulating the nanoindentation procedure, introduced in [6–8], is applied to calculate the contact and shape of the surface impression and the specimen's hardness values [13]. The contact surface between the indenter and the specimen is calculated, as presented in Fig. 1a, where the deformed network, applied in these calculations is also displayed. Through the radius r_C and the length of contact

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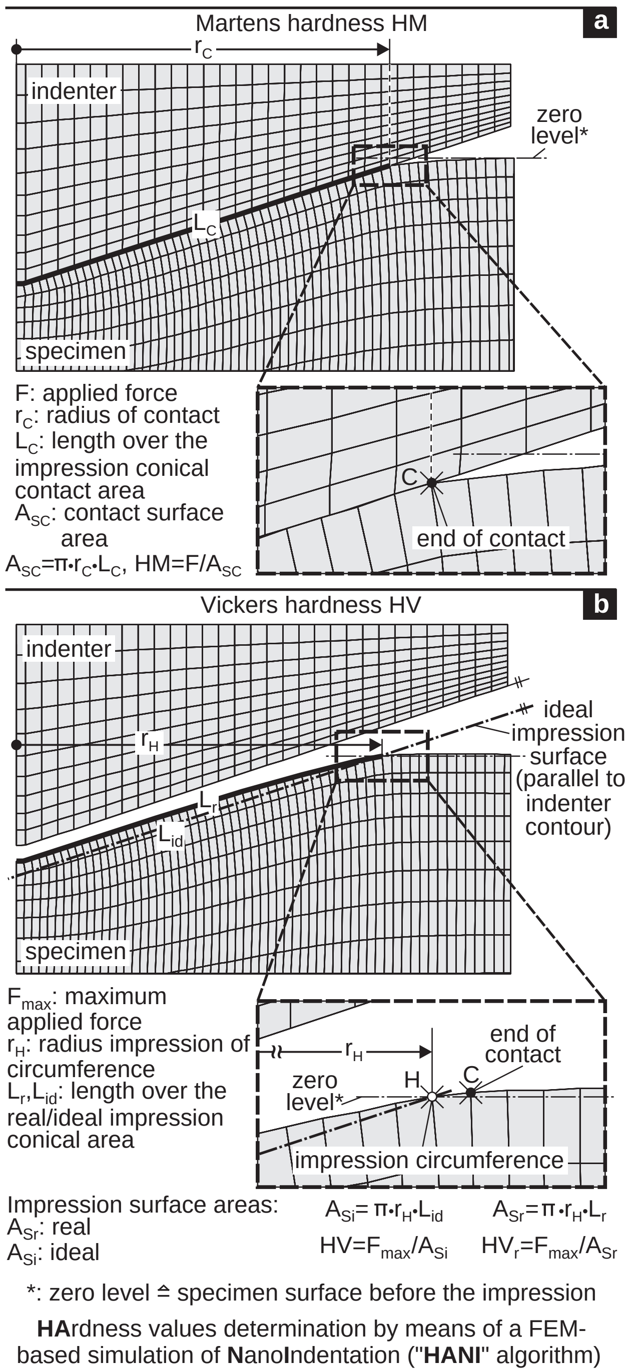

Fig. 1. "HANI" algorithm to determine (a) Martens and (b) Vickers hardness.

L_C over the equivalent conical contact [6], the contact surface A_{SC} is calculated by:

$$A_{SC} = \pi r_C L_C \tag{1}$$

The Martens hardness HM as prescribed in [5], at every penetration depth h, is the ratio of the applied force F to the resulting contact surface A_{SC}, namely:

$$HM = F/A_{SC} = F/(\pi r_C L_C) \tag{2}$$

The unloading stage of the nanoindentation reveals a remaining impression, due to the plastic deformation of the specimen material, as exhibited in Fig. 1b. The size of this impression is characterized by the radius r_H, which is the distance of point H from the symmetry axis. The impression contour crosses the zero level, i.e. the specimen surface before the indentation at this point.

The Vickers hardness calculation as in [5] considers an impression surface, corresponding to the ideal geometry of the applied Vickers pyramid, with the same angles between the opposite plane pyramid sites of the impression surface. This ideal geometry corresponds, in the case of the used FEM model, to the equivalent cone, occurring by plotting a line parallel to the indenter inclination, starting from the point H of the impression circumference (see Fig. 1b). The residual real impression conical surface area A_{Sr} can be calculated by means of the following equation:

$$A_{Sr} = \pi r_H L_r, \tag{3}$$

where L_r is the length of the formed conical area. The ideal impression conical surface is computed considering the length L_{id}, as shown in Fig. 1b, as follows:

$$A_{Si} = \pi r_H L_{id} \tag{4}$$

The Vickers hardness is then determined according to the subsequent relation:

$$HV = F_{max}/A_{Si} = F_{max}/(\pi r_H L_{id}), \tag{5}$$

and the Vickers hardness associated to the real residual impression surface applying the equation:

$$HV_r = F_{max}/A_{Sr} = F_{max}/(\pi r_H L_r) \tag{6}$$

The described procedure is considered by the developed algorithm "HANI" (HArdness determination by means of a FEM-based simulation of NanoIndentation).

3. Mechanical properties of the applied specimen materials

Various specimen materials with high surface integrity were used (see Fig. 2). In order to determine their mechanical properties, nanoindentations were conducted. The surface roughness was low in order to restrict its effect on the nanoindentation results scatter [8]. Based on these measurements, the SSCUBONI algorithm was applied considering the indenter tip geometry, as calibrated according to [7]. Hereupon, the indenter tip cross section is described through a curve, having a vertical tangent to the symmetry axis at the indenter tip top (tangent 1) and an additional one to the indenter side region (tangent 2), as shown in Fig. 2a. The determined stress–strain curves of the examined materials are presented in Fig. 2b. As it was expected, the $(Ti_{46}Al_{54})N$ coating has comparably the most elevated stress–strain characteristics and the Si(100) material the lowest ones. The corresponding main material data are listed in the table of Fig. 2c.

4. Indenter surface area determination

Although diamond pyramids possess very high elasticity modulus and hardness, their elastic deformation during