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On the effect of a general residual stress state on indentation and hardness testing

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Abstract

During indentation experiments, residual stresses are superimposed on the applied indentation stress field and influence the measurement of the volume of interest. The residual stress state can vary in magnitude and biaxiality, and the resultant error in the measured hardness is difficult to estimate. A prediction of the effect in the contact pressure with and without residual stresses is carried out by a new model that accounts for nonlinearities caused by the von Mises' flow rule. The model can also be used for the correction of the effect of a general residual stress state on any further analysis of mechanical properties and stress–strain behaviour from the measured indentation data. The model provides an estimation of the measurement uncertainty when the stress ratio or the strength of the material is unknown – a situation that is a commonly encountered with hardness testing of thin films and welded materials.

Keywords: Hardness test; Nanoindentation; Residual stresses; Yield phenomena; Analytical methods

1. Introduction

Residual stresses play an important role in many technological applications. Depending on how residual stresses interact with external loads, they can influence the mechanical behaviour and lifetime of components in a positive or negative way. Advantageously, surface compressive residual stresses can hinder the initiation of fatigue cracks. Disadvantageous effects of residual stresses in metals include highly varying stress gradients (e.g. in the vicinity of welded joints) and reduced dimensional accuracy of a component due to distortion. Residual stresses can reach the magnitude of the yield limit and can cause plastic deformation. Therefore the control and minimization of residual stresses through the production process is an important technological challenge.

It is often impossible to eliminate residual stresses, particularly when post-heat-treatment is too expensive or when it would destroy the well-designed microstructure of the component. At the same time, the investigation of the local property variation either after production or during service is very important for assessing the reliability of a component. Since depth- and force-sensing indentation systems have become a standard technique, a great deal of development of theoretical models and numerical procedures has been observed in the application of indentation to the problems of residual stress.

It has been shown experimentally [1] as well as by finite element simulations [2] for various alloys that internal uniaxial or biaxial stresses influence hardness measurement results. It was found that the hardness decreases with internal tensile stresses. However, the effect of internal compressive stresses is not as large as that of internal tensile stresses, i.e. the effect is nonlinear. Motivated by pure shear plasticity theory, which dictates different slip planes in case of tensile and compressive residual stress, Tsui et al. [1] fitted the measured change in hardness vs. the applied stress data by a bilinear relationship with a higher sensitivity for tensile stresses.

To estimate the effect of residual stresses and to develop models for its description, it is possible to compare

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indentation depth [3], indentation force [4], unloading behaviour [5], contact area [6], pile-up [7] or hardness [1] with and without residual stress.

Suresh and Giannakopoulos [6] proposed a model in which the effect of an equibiaxial stress state is described through a hydrostatic stress plus a uniaxial compressive stress component inducing a differential indentation force. They introduced the von Mises effective yield stress and accounted for its increase through the plastic deformation by power-law hardening. Only the residual stress components are considered, while the normal stress component, which represents the contact pressure, was set to zero in the calculation of the effective yield stress. Their theoretical model is specific for sharp indenters, such as Vickers or Berkovich tips, and is restricted to equibiaxial residual stress states. It should be pointed out that the resulting smooth curve describing the real contact area as a function of the residual stress agrees with the nonlinear trend from compression to tension, as observed earlier by Tsui et al. [1].

Swadener et al. [8] proposed two methods for spherical indentation based on the onset of yielding and the contact pressure. The first approach requires the yield stress of the material to be known independently, and also needs a very smooth surface or a very large indenter radius in the experiment. The latter is based on the empirical observation that the curve representing mean contact pressure vs. normalized contact radius is vertically shifted by an amount very close to the applied biaxial stress, as compared to the unstressed material. This means that Swadener et al. observed a linear relationship between an equibiaxial residual stress and the resulting mean contact pressure.

Carlsson and Larsson [7] recognized that the residual compressive stress enhanced the pile-up and was thus misleading in plastic contact area determination, while residual tension stress reduced the plastic contact area. As a result of their investigation, they found that the increase in the contact area from A_{nom} to A can be estimated by the simple relation $A/A_{\mathrm{nom}} = c^2 = 1 - \sigma^{(\mathrm{res})}/(3\sigma_y)$, where $\sigma^{(\mathrm{res})}$ is the applied residual stress and σ_y denotes the yield strength of the material. Besides the experimental validation in the second part of their work [9], Carlsson and Larsson mentioned that a direct extension of the equibiaxial results to a general solution would be to determine the apparent yield stress when an indentation-induced compressive and equibiaxial stress field is superimposed over the surface residual stresses in the material using the von Mises yield criterion. In contrast to Suresh and Giannakopoulos's approach, the normal stress component has not been set to zero. Instead, Carlsson and Larsson suggest using the apparent yield stress $\sigma(\varepsilon_{\mathrm{res}})$ at the corresponding representative strain. However, Carlsson and Larsson did not provide a solution for a general residual stress state either in their original work or in subsequent articles [10,11].

Lee and Kwon modified the idea of Suresh and Giannakopoulos, by simply interpreting the effect of the residual stress as the normal component in the resulting deviatoric part of the stress tensor [3,12], and found that the contribution of an equibiaxial residual stress $\sigma^{(\mathrm{res})}$ on the indentation force is $P_{\mathrm{res}} = -(2/3)\sigma^{(\mathrm{res})}A_{\mathrm{C}}^{\mathrm{T}}$, where P_{res} is the contribution to the indentation force caused by the residual stress and $A_{\mathrm{C}}^{\mathrm{T}}$ is the real contact area in the tensile stress state. In subsequent work [12–14] they extended and validated their deviatoric stress model towards a general residual stress state by introducing the stress ratio κ as the ratio of the minor residual stress component $\sigma_3^{(\mathrm{res})}$ to the major residual stress component $\sigma_1^{(\mathrm{res})}$, i.e. $\kappa := \sigma_3^{(\mathrm{res})}/\sigma_1^{(\mathrm{res})}$. Note that a different notation of the indices is used here to achieve a consistent coordinate system within this paper. Inserting the stress ratio κ into the previous equation, Lee et al. obtained an equation of the form $P_{\mathrm{res}} = -(1+\kappa)/3 \cdot \sigma_1^{(\mathrm{res})}A_{\mathrm{C}}^{\mathrm{T}}$. Experiments were in good agreement with this relation, although it cannot predict the known nonlinearities reported by Tsui et al. [1].

In addition to the work on theoretical models some groups applied numerical simulations and fitted these data to provide explicit relationships for an inverse approach [15–17]. These approaches are again restricted to equibiaxial stress states. A fully numerical inverse approach was presented by Bocciarelli and Maier [18], where it has been shown that the inverse solution is unique also for a general residual stress state when an imprint map, i.e. the topography of the indented surface under a general residual stress state, is provided as input to the objective function.

The goal of the present work is to illuminate the mechanics of indentation with a general but plane residual stress state, i.e. residual stresses normal to the surface are assumed to be zero. Of particular interest is the understanding and description of the nonlinearities, which are caused by different stress ratios. To this end, we concentrate on the change of the average pressure in contact by introducing a pressure ratio Π as the ratio of the contact pressure at a given residual stress state to the contact pressure for a residual stress-free state at a given indentation depth. This avoids mixing up the effect in contact pressure and contact area, and circumvents a discussion of pile-up effects.

The model validation is carried out using data from literature as well as experiments with bending bars made of an aluminium alloy Al2024 T351. Estimates for the effect will be given for a wide range of residual stresses and stress ratios. Furthermore, uncertainties can be derived for measurements with unknown mechanical properties.

2. Theoretical model

2.1. Finite element simulations

A three-dimensional finite element model was used, which has been validated regarding its accuracy and prestress application elsewhere [19]. The finite element model is presented in Fig. 1. Based on its symmetry, only a quarter of the specimen is modelled. All nodes on the symmetry