

Residual Stress Estimation with Identification of Stress Directionality Using Instrumented Indentation Technique

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Abstract. The instrumented indentation technique (IIT) has recently attracted significant research interest because it is nondestructive and easy to perform, and can characterize materials on local scales. Residual stress can be determined by analyzing the indentation load-depth curve from IIT. However, this technique using a symmetric indenter is limited to an equibiaxial residual stress state. In this study, we determine the directionality of the non-equibiaxial residual stress by using the Knoop indentation technique. Different indentation load-depth curves are obtained at non-equibiaxial residual stresses depending on the Knoop indentation direction. A model for Knoop indentation was developed through experiments and theoretical analysis.

Introduction

Residual stress can combine with applied stress to be detrimental to the performance of in-service structures [1]. There are numerous methods to evaluate residual stress [2]. Among these, the instrumented indentation technique (IIT) has the advantage that it can be applied to in-field structures nondestructively, locally and easily. IIT yields an indentation load-depth curve. The indentation load of the compressively stressed material is higher than that of the unstressed material at a given indentation depth, and the indentation load of the tensilely stressed material is lower than that of the unstressed material at the same depth. Lee and Kwon [3] developed a sharp indentation model to predict the individual principal residual stress by quantitative analysis of the residual-stress-induced load difference. However, previous IIT using a symmetrical indenter including Vickers tip is limited to equibiaxial ($p=1$) or uniaxial ($p=0$) residual stress states:

$$\sigma_{\text{res}}^x = \frac{3}{1+p} \frac{\Delta L}{A_c} = \frac{3}{1+p} \frac{(L_0 - L_{\text{res}})}{A_c}, \quad \sigma_{\text{res}}^y = p\sigma_{\text{res}}^x \quad (1)$$

Here L_0 , L_{res} are determined by the load-depth curve [3] and A_c is calculated by the Oliver-Pharr method [4]. If we know p (stress directionality), the residual stress is determined only by the indentation parameter. An attempt was made to obtain stress-directionality information by using a

pile-up height ratio [5], but this method necessitated observation of the indentation morphology. In this study, we developed a Knoop indentation method to predict the stress ratio.

Theoretical modeling

The Knoop indenter is an asymmetric indenter with elongated four-sided pyramidal geometry. The general algorithm for deriving the stress directionality is simple, as shown in Fig. 1. It was found experimentally that the change in the load-depth curve was dependent on the penetration direction of the Knoop long diagonal. When the Knoop long diagonal coincides with the σ_{res}^y direction in the biaxial state ($\sigma_{res}^x \geq \sigma_{res}^y \geq 0$), the load is the lowest value at a given depth. The load-depth curve from this is L_1 and that from the Knoop long diagonal normal to the σ_{res}^y direction is L_2 (see Fig. 1).

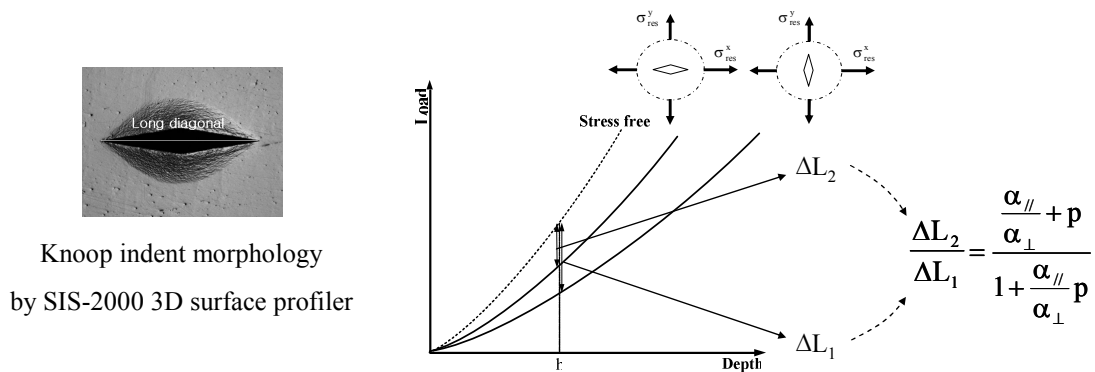


Fig. 1. Knoop indentation method: Algorithm and equation for stress directionality

The load differences ($\Delta L_1, \Delta L_2$) can be derived by considering the effect of each residual stress on the indentation load. The load difference increases proportionally to the increase in residual stress [3]. Knoop modeling is developed analytically, taking Knoop asymmetry into consideration, and is confirmed experimentally:

$$\Delta L_1 = \alpha_{\perp} \sigma_{res}^x + \alpha_{//} \sigma_{res}^y, \quad \Delta L_2 = \alpha_{//} \sigma_{res}^x + \alpha_{\perp} \sigma_{res}^y \tag{2}$$

Here $\alpha_{\perp}, \alpha_{//}$ are conversion factors that are depth variables relating the residual stress to the indentation load difference, and $\alpha_{\perp}, \alpha_{//}$ are determined by the long diagonal direction, as shown in Fig. 2.

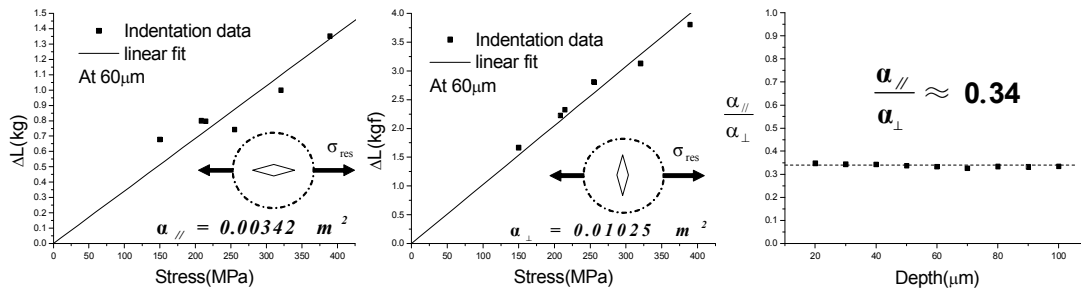


Fig. 2. Conversion factor: determination by experiment; conversion factor ratio

The load difference ratio is a function of stress directionality and the conversion factor ratio, where the conversion factor is derived experimentally and the ratio $\alpha_{//} / \alpha_{\perp}$ is 0.34. The conversion

factor ratio can be derived from the geometry of the sharp indenter. For a Vickers tip, the ratio is 1 by symmetry.

Experimental procedure

The material in this study is API X65 steel of weight 0.08% C, 0.019% P, 1.45% Mn, 0.003% S and 0.31% Si. Rectangular and cruciform specimens with 15 mm thick were machined and heat-treated to remove internal stress. Stress below the yield strength (440 MPa) was applied to the specimen (detailed information on the apparatus and procedures appears in [3]). IIT was performed using a Knoop indenter for the artificially stressed region at the specimen center by monotonic loading with depth 100 μm and testing speed 0.1 mm/min. The equipment used was Frontics Inc.'s AIS3000, and the Knoop indenter was manufactured by Synton MDP.

Result and Discussion

For the various stress ratios including the stress-free state, Knoop indentation was performed by rotating the indenter 90° for the long diagonal in order to have identical contacts for each applied stress direction. The relative locations of the indentation curve at every 10 μm depth were compared to that in the unstressed state. With 100 μm depth-controlled indentation, the long diagonal length reached 3.5 mm and at least a few hundred grains were contained beneath the indenter, so that crystal orientation effects were negligible. We could thus evaluate the effect of stress directionality on the Knoop load-depth curve change.

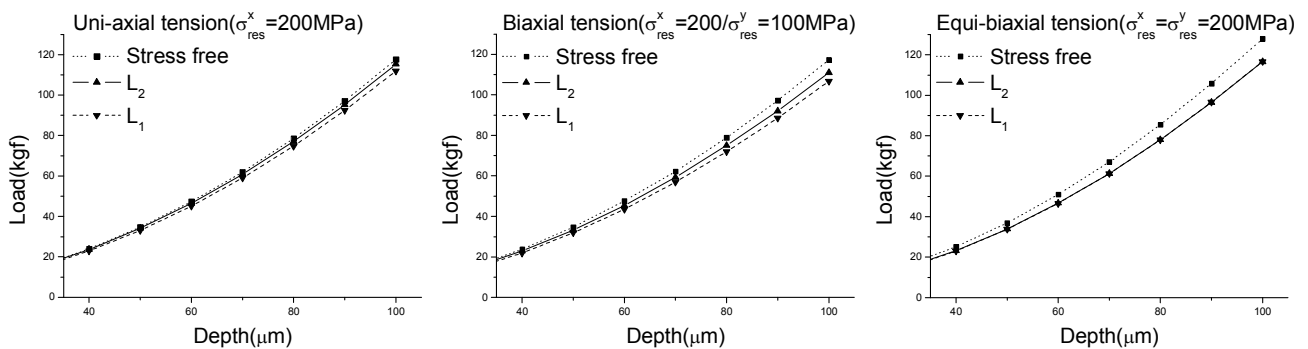


Fig. 3. Load-depth curve change vs. residual stress directionality

The load difference ratio changed from 0.34 for the uniaxial state to 1 for the equibiaxial state. We developed a Knoop indentation model for stress directionality by analyzing this change in indentation load ratio theoretically and experimentally. The conversion factor changed with the depth and indenting direction. We extracted α_{\perp} , α_{\parallel} to derive the load difference and found that the conversion factor ratio $\alpha_{\parallel}/\alpha_{\perp}$ was 0.34 regardless of indentation depth. The residual stress directionality could be expressed as a function of the load difference ratio calculated from these load-depth curves as

$$\frac{\Delta L_2}{\Delta L_1} = \frac{0.34 + p}{1 + 0.34 \times p} \quad (3)$$

This modeling was verified for various stress states, and these results, including non-equibiaxial stress states, were compared with the real stress ratio. Figure 4 shows that this modeling yielded good agreement.

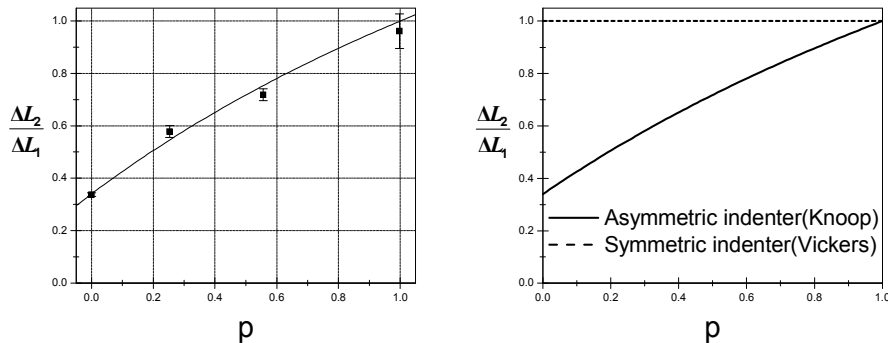


Fig. 4. Verification of Knoop modeling for different stress directionality

For a Vickers tip (symmetric indenter), the direction of indentation had no effect on the load-depth curve. However, a Knoop tip (asymmetric indenter) having a 7.11:1 ratio for long and short diagonal lengths yielded a stress-directionality-induced load-difference change with indenting direction. We expect that if the asymmetry is greater, the load-difference ratio will become an actual stress ratio. FEM studies of this model will appear soon.

Summary

An asymmetric Knoop indenter was used to analyze the residual stress ratio. The residual stress directionality obtained from the Knoop indentation model shows good agreement with an intentionally applied stress ratio, i.e. a real stress directionality, in cruciform bending specimens.

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