Estimation of uniaxial bauschinger effect using cyclic depth-controlled indentation test

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1. Introduction

Fatigue property, defined as a material's resistance to deformation under cyclic loading, is one of the most important aspects of structural integrity. Fatigue property can be measured using standardized test methods such as those developed by ASTM. However, it is difficult to measure fatigue property with those methods because it is required to apply specific geometry in preparing sample. Besides, its test procedure is complex and it is difficult to be applied to small-volume regions or in-field area because it has the destructive nature of the test.

For this reason, an alternative test method to measure in-situ mechanical properties has been developed. Instrumented indentation test (IIT), developed for nondestructive testing of in field structures, can be used to measure such mechanical properties as hardness, elastic modulus, tensile properties, residual stress, fracture toughness and fatigue property by analysis of the indentation load-depth curve. IIT makes just a small indent on the material surface and hence can be applied in in-situ and in-field measurement as nondestructive mechanical testing as well as for property mapping by local area testing on multi-scale levels. Most studies on instrumented indentation testing have focused on static indentation testing, and little work has been done on cyclic indentation testing. Cyclic indentation testing has great potential to complement conventional cyclic or fatigue testing because the advantages of static IIT also apply to cyclic indentation. In this work, we adapt cyclic instrumented indentation testing to evaluate fatigue properties.

We developed a model for evaluating the uniaxial Bauschinger effect, which has a relation with kinematic hardening behavior. The estimated Bauschinger effect was compared to values obtained in conventional fatigue tests.

2. Indentation stress field

At the end of the indentation loading process, the material beneath a spherical indenter deforms plastically. For an ideal plastic material, the stress directly beneath the indenter along the axis of symmetry (i.e. along the z axis, r=0) is expressed by the Tresca yield criterion as Eq. (1). During elastic unloading, the unloading causes a uniform tensile pressure, so that the stress beneath the indenter along the axis of symmetry is expressed by the Tresca yield criterion as Eq. (2) [1]. The uniform pressure can be assumed to be approximately $3\sigma_y$ in fully plastic indentation. This pressure $3\sigma_y$ acting on the contact area is expressed by elastic contact theory at the location at which the maximum Tresca stresses develop as Eq. (3). Combining equation Eq. (1) with equation Eq. (3) using superposition yields the residual stress difference is expressed as Eq. (4). Thus, at the location of maximum Tresca stress, z = 0.64a, plastic deformation is not to be expected during subsequent unloading. In other words, for an ideally plastic material, the material beneath the indenter deforms elastically during unloading. However, in materials that exhibit kinematic hardening, reverse plastic yielding can occur during unloading because the kinematic hardening induces permanent softening in the material when a reverse strain is applied. The decrease of yield stress induced by kinematic hardening is called back stress.

3. Indentation back stress

To estimate the uniaxial back stress quantitatively, the indentation back load must be represented as a stress term. We thus adapt Tabor's representative approach [2]. Tabor suggested that the yield stress at the edge of an indentation should be regarded as an average or a 'representative' value for the whole region of deformed zone beneath the indenter and that the mean pressure can be expressed in a linear relationship with uniaxial true stress as Eq. (5). Tabor also suggested that the representative strain be defined using a geometric parameter, a/R on the basis of the deformation shape and strain distribution under a spherical indenter as follows Eq. (6). Using Tabor's approach, we represent the indentation back load ΔL_b^i as uniaxial back stress $\Delta\sigma_b^i$. Substituting the indentation back load ΔL_b^i and uniaxial back stress $\Delta\sigma_b^i$ into equation Eq. (5), we rewrite equation Eq. (5) as Eq. (7).

$$\left|\sigma_z - \sigma_r\right| = \sigma_y \tag{1}$$

$$\left|\sigma_r - \sigma_z\right| = Kp_m = Kc\sigma_y \qquad (2)$$

$$\left|\sigma_r - \sigma_z\right| = Kc\sigma_y = 0.66 \times (3\sigma_y) \quad at\ z{=}0.64a \qquad (3)$$

$$\left|\sigma_r - \sigma_z\right|_R = [(3 \times 0.66) - 1]\sigma_y = 0.98\sigma_y \qquad (4)$$

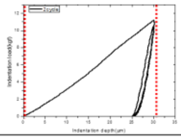
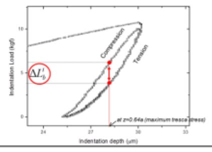
Procedure	Detail
1. Pre-determination of target experimental condition → Uniaxial strain amplitude ≈ Indentation depth range	$\Delta\varepsilon = 0.2\frac{(\Delta a)}{R} = 0.2\frac{\sqrt{2R(\Delta h) - (\Delta h)^2}}{R}$
2. Cyclic depth controlled indentation test	
3. Determination of indentation bauschinger load	
4. Derivation of bauschinger uniaxial stress	$\Delta\sigma_b^i = \frac{1}{\psi}\frac{\Delta L_b^i}{\pi a_c^2}$

Fig.1 Procedure for determining bauschinger stress

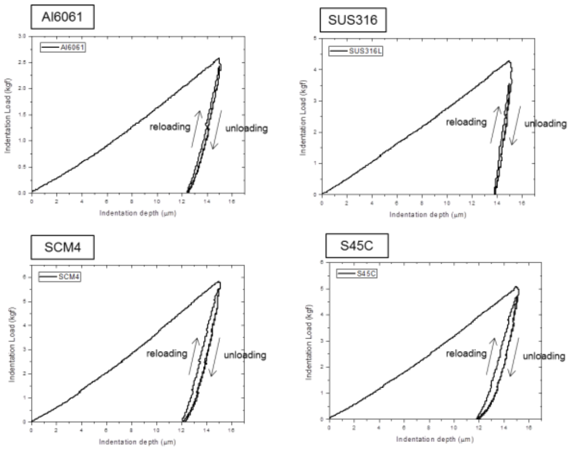


Fig.2 Hysteresis loop of indentation curve of materials

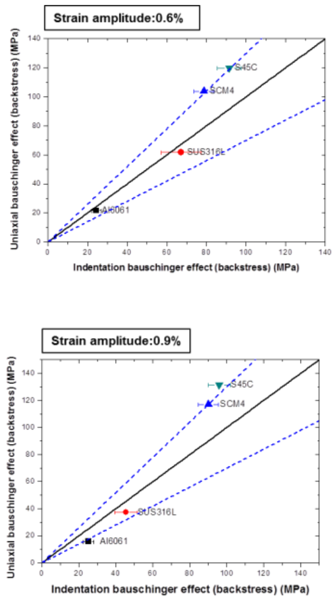


Fig.3 Comparison of indentation bauschinger effect and Uniaxial baushcinger effect at strain amplitude 0.6 %, 0.9 %

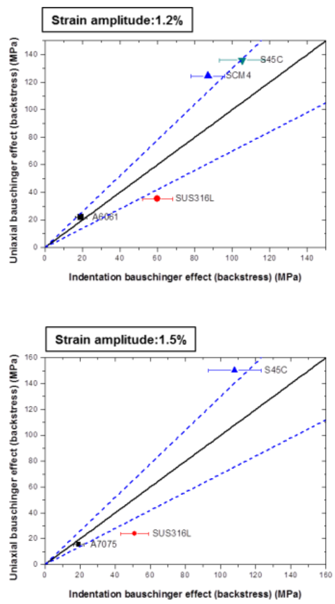


Fig.4 Comparison of indentation bauschinger effect and Uniaxial baushcinger effect at strain amplitude 1.2 %, 1.5 %

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References

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[2] D. Tabor, The Hardness of Metals, Clarendon Press (1951).