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Two-step method to evaluate equibiaxial residual stress of metal surface based on micro-indentation tests

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ABSTRACT

The present study proposed a method to evaluate the equibiaxial compressive residual stress of a metal surface by means of a depth-sensing indentation method using a spherical indenter. Inverse analysis using the elastic–plastic finite-element model for an indentation test was established to evaluate residual stress from the indentation load–depth curve. The proposed inverse analysis utilizes two indentation test results for a reference specimen whose residual stress is already known and for a target specimen whose residual stress is unknown, in order to exclude the effect of other unknown mechanical properties, such as Young's modulus and yield stress. Residual stress estimated by using the indentation method is almost identical to that measured by X-ray diffraction for indentation loads of 0.49–0.98 N. Therefore, it can be concluded that the proposed method can effectively evaluate residual stress on metal surface.

1. Introduction

Residual stress on the surface of mechanical components and structures, which is induced by mechanical processing, surface modification, and heat treatment, greatly affects the mechanical properties and strength of the constituent metallic materials. For example, equibiaxial compressive residual stress on the surface of a metallic material improves its fatigue properties and prevents the initiation of stress corrosion cracks in the material [1]. In contrast, tensile residual stress has a negative effect. Surface modification using a peening technique [2–4] has often been employed to improve fatigue properties by introducing equibiaxial compressive residual stress on the material's surface. In these applications, it is important to evaluate the state of equibiaxial residual stress on the metal surface in order to ensure the performance and durability of the machine components.

Currently, some experimental methods effectively measure the residual stress on a metal surface by X-ray diffraction and neutron diffraction. However, they have not been widely used for quality control of mechanical components or during the service of machines because special care must be taken for radiation shielding and a large instrument is required for the measurement. In place of these methods, this study focuses on a technique to evaluate residual stress using an indentation method [5–10]. The present study aims to establish a methodology based on micro-indentation tests in order to quantify the equibiaxial compressive residual stress introduced on a metal surface.

A number of methods to evaluate equibiaxial residual stress utilizing micro-indentation tests were proposed in previous studies. For example, Suresh and Giannakopoulos [5] focused on the change of the plastically deformed area formed by an indenter (i.e., indented area) when equibiaxial residual stress was introduced. They proposed an analytical expression that related residual stress to the ratio of indented areas when equibiaxial residual stress was introduced or not introduced. Their analytical formula was based on the preliminary finding of Tsui et al. [11] that compressive residual stress remarkably changed the indented area, in contrast to tensile residual stress. They examined the validity of the analytical formula by comparison with the experimental results. In general, the hardness and Young's modulus of the material (i.e., material constitutive behavior) are closely related to the indented area given by micro-indentation tests [12,13], and the identification of residual stress is theoretically allowed by evaluating the indented area ratio between cases with or without residual stress [6]. However, measurement of the indented area was greatly affected by the pile-up and sink-in deformation of the material around the indenter tip, which caused a large scatter in experimental data [11,14]. Moreover, a recent study determined that the sensitivity of the indented area ratio to residual stress was rather small [7].

In contrast, Swadener et al. [7] used a straightforward approach based on the theory of plasticity that pre-introduced equibiaxial residual stress changes deviatoric stress as a driving stress of the plastic deformation under an indenter tip during indentation tests. They proposed a method utilizing the yield condition considering residual stress during depth-sensing indentation tests. In particular, they focused on the fact that a spherical indenter has high

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sensitivity to residual stress against the plastic deformation under an indenter tip. Their method is useful when an intermediate indentation load is used because the transition regime between elastic contact at small loads and fully developed plastic contact at large loads (i.e., elastic–plastic transition) is greatly affected by residual stress. To apply their method to general loading, precise depth measurement is required. However, this is not always feasible because of limitations of the experimental apparatus or the surface texture of the target metallic materials.

An alternative method has been proposed by some researchers. For example, Xu and Li [8] developed a method to estimate residual stress from the elastic recovery of indentation depth during unloading in indentation tests. Residual stress causes a change in the plastic deformation by indentation loading. In principle, their method is equivalent to that proposed by Swadener et al. [7] when it is normalized by the maximum indentation depth h_{max} (Fig. 1). Therefore, their method is effective when the elastic recovery depth h_e is larger than the residual indentation depth h_p: otherwise, precise measurement of the elastic recovery depth is required to quantitatively evaluate residual stress. In general, the depth-sensing technique is susceptible to measurement errors due to surface roughness [15,16], and experimental verification of the method is necessary to develop the methodology to evaluate residual stress from the indentation load–depth curve.

The present study proposed a method to evaluate equibiaxial compressive residual stress using the indentation method with a spherical indenter. In particular, inverse analysis was established to evaluate residual stress from the indentation load–depth curve while excluding the effect of other unknown mechanical properties, such as Young's modulus and yield stress, which also influence the load–depth curve [17,18]. The proposed inverse analysis consists of two steps. The first step is to identify the unknown Young's modulus and yield stress by conducting indentation tests on a reference specimen in a known state of residual stress. Here, inverse analysis based on response surface methodology was devised using an elastic–plastic finite-element model for an indentation test. As the second step, the residual stress of the specimen in an unknown state is identified from indentation test results, using the relationship between residual stress and indentation depth computed by elastic–plastic finite-element analyses, while substituting the Young's modulus and yield stress obtained from the reference specimen.

To develop the method, the effect of equibiaxial compressive residual stress on the indentation test was first investigated experimentally. An elastically bended specimen made of austenitic stainless steel (SUS316L) was used. The sensitivity of residual stress to the parameters (e.g., maximum indentation depth, elastic indentation depth, and residual indentation depth) was examined while varying a maximum indentation load. Second, equibiaxial stress was evaluated using the proposed inverse analysis by the indentation method with a spherical indenter. Finally, the identified residual stress was experimentally verified by comparison with that measured by X-ray diffraction.

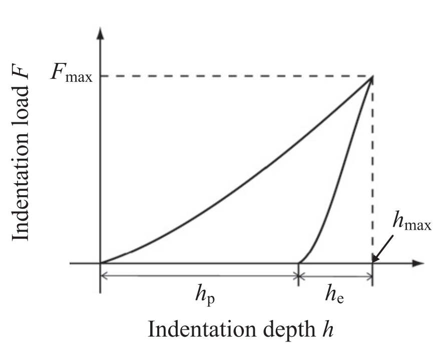

Fig. 1. Schematic of an indentation test.

2. Experimental and numerical procedures

2.1. Inverse analysis

The present study proposes a two-step method to evaluate unknown equibiaxial residual stress using micro-indentation tests, as stated in the Introduction. The first step is to conduct an indentation test on a reference specimen in a known state of residual stress and identify the unknown Young's modulus and yield stress. The residual stress of the reference specimen was measured by X-ray diffraction, and its value was regarded as a known quantity. Second, using the identified Young's modulus and yield stress for the reference specimen, the residual stress of the specimen in an unknown state of residual stress was identified from indentation test results. These steps are summarized in the flowchart in Fig. 2.

The residual stress σ_r for the reference specimen was measured based on the $\sin^2\psi$ method using X-ray diffraction system MSF-3M (Rigaku Corporation). We used the Ω-diffractometer method to measure X-ray diffraction. The inclination angle of the crystal lattice ψ was set to 0°, 22.8°, 33.2°, 42.1°, and 50.7°. The X-ray tube was a Cr tube operated at 35 kV and 8 mA. The diffractive plane was the (3 1 1) γ-Fe, and the reference diffractive angle $2\theta_0$ was 148.52°. The diffractive angle 2θ ranged from 146° to 152° with 0.2° increments within 8 s intervals. The stress factor for the X-ray diffraction was −368.93 MPa/deg.

Indentation tests were conducted using depth-sensing indentation testing machine ENT-1100a (Elionix, Inc.). A spherical indenter with a tip diameter of 100 μm was used. The bottom surface of the specimen was fixed. To avoid the influence of the oscillation of the apparatus or temperature drift, the testing machine was set on a vibration isolated table and the temperature was kept constant. The maximum load was set to F_{max} = 0.245 N, 0.49 N, 0.735 N, and 0.98 N. The indentation load was applied by 500 load increments within 20 ms intervals up to the maximum load. The loading time was 10 s, the holding time was 1 s, and the unloading time was 10 s. The relationship between indentation load P and depth h was obtained (Fig. 1). Each indentation test was conducted five times, and we evaluated the load–depth curve using the averaged value. To exclude the effect of load frame compliance [12,19] on the test results, the test results were corrected using a compliance factor of 0.294 N/μm, following the procedure of Sawa and Tanaka [20].

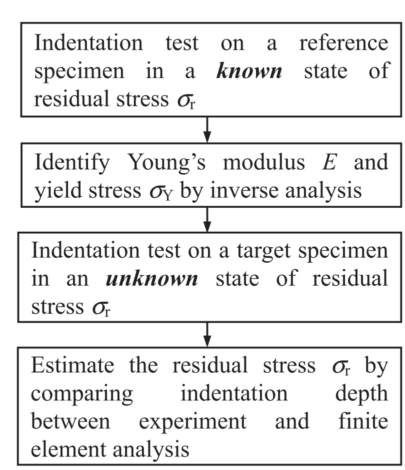

Fig. 2. Flowchart of the present method.