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Spherical indentation method for measuring local mechanical properties of welded stainless steel at high temperature

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A B S T R A C T

Indentation method was employed to evaluate the local mechanical properties of welded stainless steel at a high temperature of 320 °C. The welding process often changes the mechanical properties (in particular the plastic properties), and make the material property inhomogeneous. An indentation method was proposed to effectively evaluate the stress–strain relationship (approximated by the Ludwick-type hardening law) in the welded SUS316L at 320 °C. Functional relationship between the indention response and plastic property was established using finite element method (FEM). The dimensional function was deduced based on sufficiently-deep indentation, so that it can directly estimate plastic properties up to large uni-axial strain (about 20%). Spherical indentation tests applied to welded SUS316L may enable the evaluation of the distribution of plastic properties, such as the yield stress, plastic strain and tensile strength. The properties around the welded area were estimated to be higher than the base material of SUS316L, owing to the local plastic deformation from welding-induced thermal expansion and construction. Parallel test was conducted to validate the model. The proposed indentation technique can quantitatively evaluate the local mechanical properties at high working temperature, and supply useful information on inhomogeneous property distribution in materials.

1. Introduction

Stainless steel is widely used for corrosion resistant structural materials, such as underground pipe for oil well and cooling water piping for nuclear power system. In practice, the engineering components often undergo plastic work (cold work) and welding joint processes. During the welding process, the local heat input leads to local thermal expansion, which induces large local plastic strain – such welding deformation often leads to significant work-hardening and residual stress [1–5]. For instance, Piatti and Vedani showed that the tensile property of welded stainless steel was changed due to local dissimilarities in thermal and mechanical history during welding [1]. Trough micro Vickers hardness measurements around welded area, Song et al., reported that welding induces inhomogeneous mechanical property [5]. Since the inhomogeneous distribution of plastic property often leads to environmental assisted cracking and fatigue fracture [6,7], the distribution should be clarified. In other words, for the sake of structural integrity and the optimization, quantitative evaluation of the inhomogeneous distribution of material property is desired for a "local" area (e.g. a limited area of material surface). Note that in some cases (e.g. power plants), the operating temperature is relatively high and the in situ material characterization prohibits the use of conventional testing methods (e.g. uniaxial tension).

Indentation is a useful method to probe mechanical property of materials in small volume [8]. In this method, a hard indenter impresses against the specimen surface at a given force and then unloads. The relationship between indentation response (force-penetration depth relationship) and the elastoplastic property of material can be established through theoretical or numerical analyses, such as finite element method (FEM) simulations. By assigning the indentation responses to the established functions, reverse analysis can be employed to identify the material constants in the constitutive equation [9–15]. Dao et al. [9] [13] introduced the representative strain concept to dimensionless function [16] which can correlate the indentation curve with elastoplastic properties in a simplified way. Following this idea, the uses of plural sharp indenter with different angle [14] and spherical indenter [10,12] were proposed in order to make accurate estimations. An appropriate application of such a framework may enable the evaluation of welding joint or plastic worked materials, such that their local

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plastic properties can be quantitatively evaluated, thus supplying critical information on "mapping" of inhomogeneously distributed property.

One of the practical issues of the indentation method is the uniqueness of reverse analysis, that is, whether there is a one-to-one correspondence between indentation response and material constitutive relationship. Previous studies have shown the existence of special sets of materials which have distinct elastoplastic properties, yet whose indentation curves are almost the same [11,17,18]. These materials cannot be effectively distinguished by the indentation method unless very deep spherical indentation tests are carried out [18]. Another important issue is the data scattering from experiments and error sensitivity of reverse analysis. In all cases, experimental verification of the proposed method is required.

In addition, most previous studies were focused on materials that obey the power law hardening behavior (sometimes called the Hollomon law); these types of materials involve only two unknown variables for plastic property (the yield stress and work hardening exponent). However, sometimes the power-law hardening behavior is insufficient to describe practical materials, and other constitutive equations (e.g. linearly hardening law, Swift-type, Voce-type, Ludwick-type etc.) may be employed to describe the stress–strain curves in engineering steels. Indeed, appropriate selection of the type of constitutive relationship is a first step for a robust indentation-based reverse analysis. Some studies have reported that the plastic flow behavior of stainless steel is difficult to be expressed by the power law equation (Hollomon law) [1,19,20]. It is suggested that, when the reverse analysis based on power law hardening was experimentally applied to stainless steel, the estimations of plastic behavior may be of poor accuracy [19,21,22]. Thus, Kim et al. emphasized that an appropriate constitutive equation is required a priori for indentation-based estimation [19].

Based on the above considerations, this study aims to develop a robust and effective indentation analysis framework for SUS316L welding joint. We first investigated the plastic constitutive equation of the stress–strain curve of SUS316, so that the present indentation method can be applied to both the as-received and drawn SUS316L. Based on the appropriate constitutive equation, functional relationship between the indentation response and plastic property was next established by extensive FEM simulations of deep spherical indentation tests. The formulations were simplified through the use of the representative strain, which makes it possible for the identification of several materials constants by using one test (single indentation). The indentation framework was applied to the evaluation of the local plastic property in welding stainless steel at 320 °C (operating temperature of power plant). The estimations from the present indentation method were verified by comparing with the stress–strain relationship evaluated from tensile tests at both room temperature and 320 °C. This study also evaluated the local plastic properties of welded stainless steel at 320 °C. The distribution of the properties, including the yield stress, plastic strain and tensile strength, around the welding joint were quantitatively evaluated. Thus, the present method (which can readily evaluate local properties) may be extended to various welded components, plastic worked material and surface hardening treatment (carburizing and peening etc.), which often have inhomogeneous distribution of plastic property.

2. Materials

The material considered in the present study is an austenitic stainless steel and its welding joint. To investigate the appropriate constitutive equation of the plastic flow behavior, stress–strain curves under uniaxial tensile test were first investigated, according to previous study [23]. One is the as-received material (base material) and the other is cold-drawn material (the reduction area is about 16%). Fig. 1 shows the relationship between true stress and true strain (true stress – true strain curve) of both materials, exhibiting non-linear behavior of plastic flow. Here, the horizontal axis indicates true plastic strain, since this study will use Ludwick law for appropriate constitutive law. It was observed that the flow stress behavior of cold-drawn material was higher than that of based material. The Young's moduli E was 175 GPa. The yield stresses σ_Y were 260 MPa and 620 MPa.

Next, the non-liner regions of plastic flow for both materials (in Fig. 1) were approximated by two constitutive equations, i.e. power hardening law (Hollomon type, Eq. (1)) and Ludwick type hardening law (Eq. (2)). These equations are expressed as follows.

$$\sigma = E\varepsilon \quad \text{for} \quad \sigma \leqslant \sigma_Y, \quad \text{and} \quad \sigma = K\varepsilon^n \quad \text{for} \quad \sigma \geqslant \sigma_Y \tag{1}$$

$$\sigma = E\varepsilon \quad \text{for} \quad \sigma \leqslant \sigma_Y, \quad \text{and} \quad \sigma = \sigma_Y + K\varepsilon_p^n \quad \text{for} \quad \sigma \geqslant \sigma_Y \tag{2}$$

where σ_Y is the yield stress, n is the work-hardening exponent, K is the work-hardening strength and E is the Young's modulus. Note that in Eq. (1) strain ε is total strain, while ε_p in Eq. (2) is plastic strain.

The power hardening law in Eq. (1) is the most-used constitutive equation whose independent parameter is only two (σ_Y and n), when E is known prior, and its elastoplastic property identification through indentation has been widely studied. On the other hand, the Ludwick type hardening law has three independent

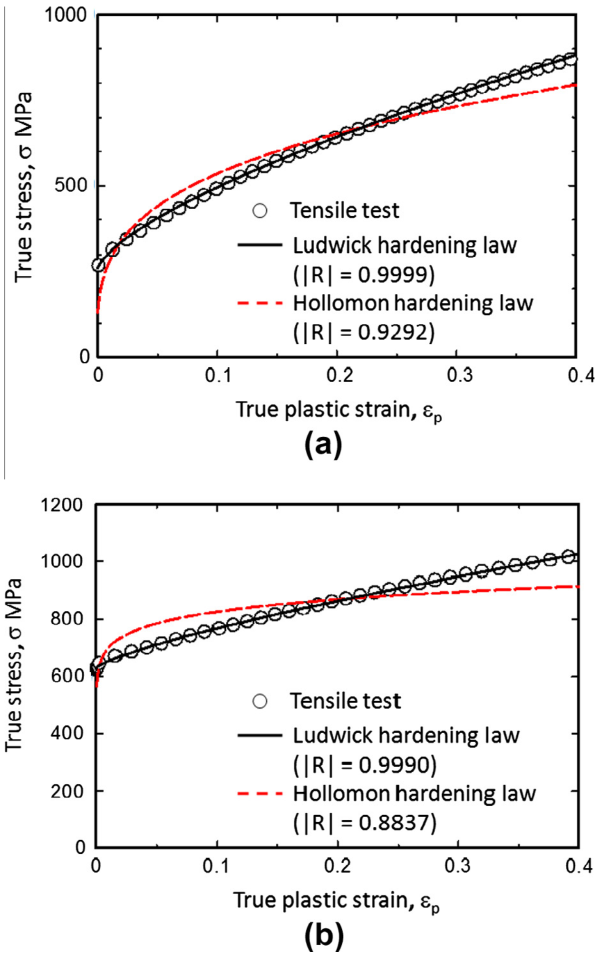

Fig. 1. Stress–strain curve of SUS316L$^{(23)}$; (a) base stainless steel and (b) cold worked one. This compares the fitted curves with Ludwick law and Hollomon law.