Construction and Building Materials 155 (2017) 176–186

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characteristics of microstructural phases relevant to the mechanical properties in structural steel weld zone studied by using indentation

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HIGHLIGHTS

- Nano- and micro-indentations were performed on the weld zone of SM520 steel.
- Compositions and properties (E, H, and σ_y) of microstructural phases in weld zone are identified.
- Mechanical properties across the weld zone were estimated from micro-indentation and FE analysis results.
- Compositions and properties of microstructural phases relevant to mechanical properties in the weld zone.

ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form 21 July 2017
Accepted 6 August 2017

Keywords:
Mechanical properties
Indentation
SM520 steel
Volume fraction
Weld zone

ABSTRACT

The volume fraction (f) and properties of microstructural phases, the mechanical properties in the weld zone, and their relevance of commonly used steel, SM520, were investigated by using instrumented indentation. The volume fraction and properties of microstructural phases in fusion zone (weld metal –WM), heat-affected zone (HAZ), and base metal (BM) of the weld zone were identified by applying the statistical analysis for observed frequency density of hardness (H), elastic modulus (E), and yield strength (σ_y) spectra from nano-indentation tests. The mechanical properties distributed across the weld zone were determined from the micro-indentation tests. Two different stiffness ferrite types can be characterized in each individual weld zone from the analysis of H and E results, while two different strength ferrite types can be identified in WM from the analysis of the σ_y spectrum obtained from nano-indentations. The results from micro-indentations exhibited that the E, H, σ_y, and n values in the HAZ decrease in the direction from WM to BM region and all the average values of E, H, σ_y, and n in HAZ are higher than those in BM. The relevance of f, E, H, and σ_y of microstructural phases and E, H, and σ_y in the weld zone and was also discussed.

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1. Introduction

Welding has been used as an advantageous method to form strong connection for transferring loads between members in steel structures. During the welding process, the temperature change causes solid-state phase transformations, which lead to three different main regions; fusion zone (weld metal-WM), heat-affected zone (HAZ), and base metal (BM) in the weld zone as well as the complex microstructure in WM and the difference in microstructures of HAZ and BM [1–3]. The properties in WM, HAZ, and BM regions, which are dominated by their final microstructure characteristics such as the volume fraction and mechanical properties of microstructural phases, govern the performance of the weld joint. Therefore, the final microstructural characteristic including volume fraction and basic mechanical properties (hardness H, elastic modulus E, and yield strength σ_y) of component phases, these basic properties in WM, HAZ, and BM regions, as well as the relevance between them need to be investigated, especially for the weld zone of SM520 steel, which is a very commonly used structural steel in Korea.

Instrumented indentation technique has been widely used in many engineering fields as a powerful tool for characterization of material properties [4]. Since the technique allows accessing to the local properties in the indented area, it has been extensively utilized for investigating the properties of inhomogeneous materials such as cementitious materials, concrete, asphalt binder, or steel weld zone [5–11]. It has been indicated that in the indentation test on inhomogeneous material, the high indentation depth, roughly $h/D > 6$ (h is the indentation depth and D is the character-

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http://dx.doi.org/10.1016/j.conbuildmat.2017.08.033
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istic size of the phases) of the phase provide access to homogenized material properties of the composite, while low indentation depth ($h/D < 1/10$) provide access to the properties of microstructural phase [11–13].

In this study, the volume fraction and properties of microstructural phases, the mechanical properties in the weld zone of SM520 steel and the relevance between them was investigated. For this purpose, indentation tests with low and high indenting depths that provide the response of microstructural phase and composite, respectively, were performed on the weld zone of SM520 steel. Since the indentation tests with low and high indenting depths in this work were undertaken at nano- and micro-length scales, they were denoted as nano- and micro-indentation, respectively. Optical microscopy examinations, statistical analysis of indentation test results, and finite element (FE) analyses were also conducted.

2. Methods

2.1. Instrumented indentation testing

A typical load – penetration depth (*P-h*) curve of an elastic-plastic material to a Berkovich indentation is illustrated in Fig. 1. Several mechanical properties of indented material including hardness, elastic modulus, and yield strength can be extracted from the *P-h* curve. One of the most popular methods to determine the hardness and elastic modulus of material at indenting point is that of Oliver and Pharr [14]. According to this method, the hardness can be determined from the applied load P_m at the maximum penetration depth h_m and the projected contact A_c, as follows:

$$H = \frac{P_m}{A_c} \tag{1}$$

The elastic modulus can be determined using the relations between reduced modulus E_r and the initial unloading slope S, the projected contact A_c, the correlation factor for indenter shape β, the elastic modulus and Poisson's ratio of the indented material and indenter E, ρ, E_i, and ρ_i, respectively, as follows [14]:

$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A_c}} \tag{2}$$

$$E_r = \left[\frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}\right]^{-1} \tag{3}$$

where E_i, ρ_i, and β are known for a given indenter and other parameters P_m, h_m, S, and A_c can be directly or indirectly obtained from the

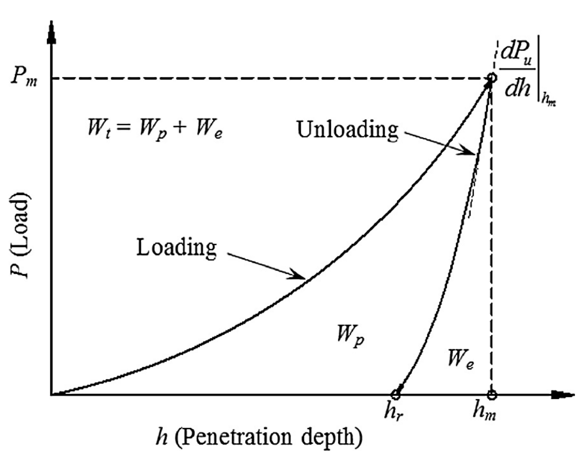

Fig. 1. Typical load – penetration depth (*P-h*) curve.

P-h curve of indentation. The details for determination of these parameters can be found in the literature [14]. Note that Oliver and Pharr's method allows extracting the hardness and elastic modulus of microstructural phase and composite in case of nano- and micro-indentation, respectively.

The microstructural phase in steel can be considered as a pure metal and its true elastic-plastic stress-strain behavior can be closely approximated by a power law description, which is illustrated in Fig. 2a and expressed as follows [15–18]:

$$\sigma = \begin{cases} E\varepsilon & (\varepsilon \leqslant \varepsilon_y) \\ \sigma_y[1 + E(\varepsilon - \varepsilon_y)/\sigma_y]^n & (\varepsilon \geqslant \varepsilon_y) \end{cases} \tag{4}$$

where σ_y is the initial yield stress, and n is the strain hardening exponent.

The structure steel (composite in this work) exhibits Luders behavior, which is a plastic instability associated with the unpinning of dislocations from the interstitial elements in solid solution such as carbon or nitrogen [19], in their stress-strain curve and the solid curve in Fig. 2b is an illustration of a typical true stress-strain behavior of structural steel. The Luders band (plastic plateau) initiates from the yield strain (ε_y) and ends at the beginning-point of strain hardening (ε_{st}) can be assumed to be perfectly plastic plateau that is represented by the dotted line in Fig. 2b. From this assumption, which is demonstrated to be acceptable to accurately reflect the material properties of structural steel [20–24], the true stress-strain curve of structural steel can then be expressed as [20]:

$$\sigma = \begin{cases} E\varepsilon & (\varepsilon \leqslant \varepsilon_y) \\ \sigma_y & (\varepsilon_y \leqslant \varepsilon \leqslant \varepsilon_{st}), \\ \sigma_y[1 + E(\varepsilon - \varepsilon_{st})/(\alpha\sigma_y)]^n & (\varepsilon \geqslant \varepsilon_{st}) \end{cases} \tag{5}$$

Since the true stress-strain behaviors of microstructural phase and the composite obey different constitutive laws, two separate methods need to be used for determination of their yield strength.

For determination of the yield strength of microstructural phase, a reverse algorithm proposed by Dao et al. [15], which has been considered a common method for determining the yield strength σ_y and strain hardening exponent n of material exhibited a power law elastic-plastic stress-strain behavior from the indentation *P-h* curve was used. The details of the algorithm can be referred to the literature [15]. For determination of the yield strength of the composites in the weld zone, an algorithm proposed by the authors that allows extracting yield strength σ_y and strain hardening exponent n of structural steels, of which exhibit plastic plateau in their true stress-strain curve (Eq. (5), was used [20]. In this method, the yield strength σ_y and strain hardening exponent n of composite materials can be determined with respect to α using the following polynomial equations [20]:

$$\frac{E_r^*}{\sigma_y} = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} a_{ijk} n^{j-1} \alpha^{k-1} \left(\frac{E_r^*}{C}\right)^{i-1} \tag{6}$$

$$\frac{S}{E_r^* h_m} = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} b_{ijk} n^{j-1} \alpha^{k-1} \left[\ln\left(\frac{E_r^*}{\sigma_y}\right)\right]^{i-1} \tag{7}$$

where α is defined as the ratio of the strain at starting point of strain hardening and the yield strain, C is the loading curvature, $E_r^* = \left[(1-\nu^2)/E\right]^{-1}$, and a_{ijk} and b_{ijk} are coefficients (Appendix A). The α value of the weld zones can be obtained with the aid of FE analysis of indentation by correlating the experimental with the simulated load-penetration depth curves. The details of the procedure for determination of the yield strength in the weld zones from the proposed method and FE analysis can be found in the previous works [21,22].

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