International Journal of Mechanical Sciences 103 (2015) 265–274

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Instrumented indentation testing and FE analysis for investigation of mechanical properties in structural steel weld zone

Jung J. Kim [a], Thai-Hoan Pham [b], Seung-Eock Kim [c,*]

[a] Dept. of Civil Engineering, Kyungnam University, Changwon-si, South Korea
[b] Dept. of Civil and Environmental Engineering, Sejong University, Seoul, South Korea
[c] Dept. of Civil and Environmental Engineering, Sejong University, 98 Gunja-dong, Gwangjin-ku, Seoul 143-747, South Korea

ARTICLE INFO

Article history:
Received 17 May 2015
Received in revised form
14 September 2015
Accepted 25 September 2015
Available online 9 October 2015

Keywords:
Mechanical properties
Structural steel
Weld zone
Instrumented indentation
FE analysis

ABSTRACT

In this paper, a procedure for determining mechanical properties in structural steel weld zone using indentation test and finite element (FE) analysis was established and applied for investigating mechanical properties in an SS400 steel weld zone. Instrumented indentation tests were performed across the weld zone and the mechanical properties (E, H, σ_y, and n) were then determined from their load–depth data with the aid of FE analysis. The obtained mechanical properties in the weld zone were verified to be reliable by comparing with the results from tensile tests and their FE simulations of both steel and welded specimens. It is shown that in the investigated weld zone, base metal has lower values of mechanical properties (E, H, σ_y, and n) than does the weld metal, and mechanical properties within heat affected zone (HAZ) gradually increase from the base metal to weld metal regions. Based on the optical microscopy examination results, the gradient of mechanical within HAZ is found to be associated with the change of grain sizes from base metal to weld metal regions.

1. Introduction

Structural steels are one of the most prevalent and commonly used materials in civil and industrial building construction due to several of advantages, such as their low cost and excellence in machinability and weldability. In many applications of structural steel, it is essential to form strong joints that allow transferring load between components. Generally, welding is considered as the preferred joining method due to such advantages as continuous joint forming, design simplicity, and high rigidity compared to others [1]. However, the weld joints in welded components are generally considered as potential "weakest link" due to the microstructural inhomogeneity or weld defects [2]. Since the performance of weld joint is governed by its components: base metal (BM), heat affected zone (HAZ), and weld metal (WM), a comprehensive understanding of the mechanical properties including elastic modulus, hardness, yield strength, and strain hardening exponent in these components is essential for the integrity assessment of structural steel members that have a weld zone.

Instrumented indentation testing has been used in many engineering fields including biomedical, civil, mechanical, and material engineering [3]. Many researchers have developed analytical methods for characterization of basic mechanical properties (elastic modulus, yield stress, strain hardening exponents, etc.) from the load–penetration depth data of indentation tests [4–9]. Since instrumented indentation testing has various advantages in practical applications and provides access to the local material properties in the indented region, it has been extensively used in characterizing mechanical properties of inhomogeneous materials such as weld zone [2,10–13]. For example, Ye et al. [2] conducted a series of experiments including indentation tests, low-cycle fatigue tests, and optical microscopy examinations to study the local mechanical properties and microstructures in individual zone of 304L SS welded joint in both as-welded and cyclic loading conditions. Chung et al. [10] used indentation tests and finite element (FE) analysis to investigate the mechanical properties of DP590 steel weld zone, of which isotropic hardening law along with the non-quadratic anisotropic yield function Yld2000-2d was assumed as material property model. Yonezu et al. [12] utilized spherical indentation to measure local mechanical properties of welded stainless steel SUS316L at high temperature by using FE method to establish functional relationship between indentation response and plastic property of material. Recently, Sun et al. [13] applied micro-indentation and inverse modeling to determine mechanical properties of the weld line of two typical dual phase high strength steels DP600/DP980. In the research, the FE model was constructed based on the power law constitutive model to simulate the elastoplastic response of each

* Corresponding author. Tel.: +82 2 3408 3291; fax: +82 2 3408 3332.
E-mail address: sekim@sejong.ac.kr (S.-E. Kim).

http://dx.doi.org/10.1016/j.ijmecsci.2015.09.015
0020-7403/

Table 1
Chemical compositions SS400 steel and ER70S-6 weld material (in wt%).

Material	C	Si	Mn	P	S	Al	Ca	Cu
SS400	0.05	0.037	0.46	0.013	0.002	0.044	0.0017	–
ER70S-6	0.04	0.92	0.45	0.011	0.015	–	–	0.2

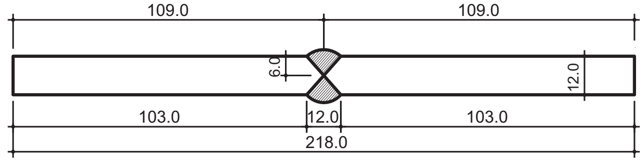

Fig. 1. Dimensions for the double V butt welding plate.

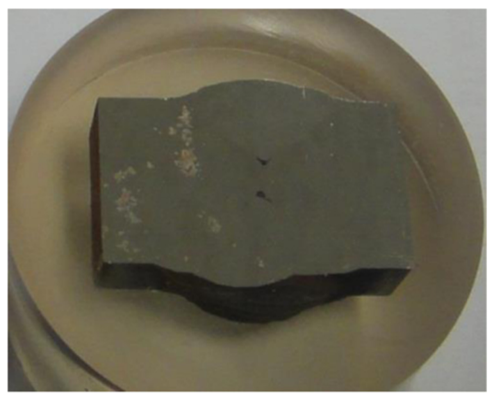

Fig. 2. Sample for indentation tests.

individual weld zone and the mechanical properties in the different zones were identified by comparing the experimental data and simulation results. However, the materials used in above studies could be accurately assumed as isotropic hardening law or power law formulation while materials with plastic plateau in their constitutive equations such as structural steel were not covered.

The aim of this study is to investigate the mechanical properties in the weld zone of a structural steel, SS400, by further extending the proposed method [9] in application for estimating the mechanical properties (yield strength σ_y and strain hardening exponent n) in structural steel weld zone from indentation results with the aid of FE analysis. Instrumented indentation, tensile tests, FE analyses, and optical microscopy examinations were conducted. The mechanical properties in the weld zone were extracted from indentation load–depth data and the correlation between microstructures and mechanical properties in the weld zone was investigated.

2. Experimental procedure

A welded plate of SS400 steel was chosen for investigation. The manual metal arc welding with electrode ER 70S-6 was used. The major chemical composition in percentage weight of SS400 and weld metal are listed in Table 1. The weld was completed with a voltage of 22 V and a current of 100 A. The dimensions for the double V groove butt welding plate are shown Fig. 1.

For instrumented indentation test, one slice of $8 \times 20\ mm^2$ containing BM, HAZ, and WM regions was cut out from the welded plate by water-jet. This slice was then mounted in epoxy and polished with different silicon carbide papers, poly diamond particles, and colloidal silica in order to obtain a flat and smooth surface. This procedure was achieved in seven stages of increasing fineness, with the last in the range of 40 nm. Fig. 2 shows the sample after being mounted and polished. A series of instrumented indentation tests consisting of 5×25 indenting points across the weld zone were performed at room temperature using a Nano Hardness Tester with an Berkovich indenter made of industrial diamond (elastic modulus E_i=1141 GPa and Poisson's ratio υ_i=0.07). A fixed maximum load of 150 mN at a constant loading and unloading rate of 300 mN/min was applied for all indentation tests. The indenting series covered portions of base metal, heat-affected zone, and weld metal. In order to look for the correlation between microstructures and mechanical properties in the weld zone, the microstructural examinations were carried out. To reveal the microstructure, the polished specimen was etched for 30 s with 2% nital, and the microstructures were observed by optical microscopy.

Tensile tests were conducted on three specimens of SS400 (labeled N1, N2, and N3) and three welded specimens (labeled W1, W2, and W3) using an Instron tensile testing machine and tested according to ASTM standard [14]. Note that the welded specimens were directly cut from the welded plate and specimens of SS400 steel have the same thickness of 12 mm as welded plate. Fig. 3 shows the dimensions of specimens and representative specimens for tensile tests.

3. The procedure for determining mechanical properties from indentation and FE analysis results

Fig. 4 presents a load–penetration depth (P–h) curve of an elasto-plastic material to sharp indentation. From this curve,