INDENTATION AND FE ANALYSIS FOR CHARACTERIZATION OF MECHANICAL PROPERTIES IN SM520 STEEL WELD ZONE

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Abstract— Mechanical properties in the weld zone of a popular structural steel SM520 were characterized using indentation and finite element (FE) analysis. Indentation tests were performed across the weld zone including portions of weld metal (WM), base metal (BM), and heat-affected zone (HAZ). Hardness (H), elastic modulus (E), yield strength (σy), and strain hardening exponent (n) were extracted from indentation load-depth curve with the aid of FE analysis. The results showed that H, E, σ_y, and n values in the HAZ decrease in the direction from WM to BM region, the average values of H, E, σ_y, and n in HAZ are highest, whereas WM has a lower E but a higher H, σ_y, and n than does BM.

Keywords— Indentation; Mechanical properties; SM520 steel; Weld Zone.

I. 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 [1]-[3]. The performance of the weld joint is governed by the properties in WM, HAZ, and BM. Therefore, the mechanical properties in WM, HAZ, and BM including hardness (*H*), elastic modulus (*E*), yield strength (σ_y), and strain hardening exponent (*n*) need to be characterized, especially for the weld zone of SM520 steel, which is a very commonly used structural steel in Korea.

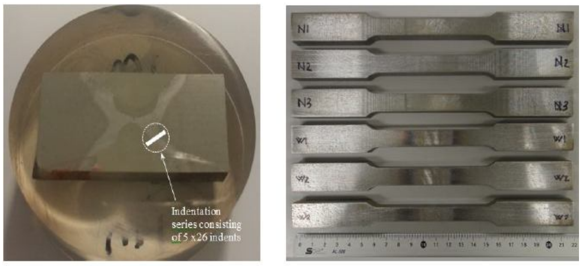
Indentation has been widely used in many engineering fields as a powerful tool for characterization of material properties [4]. While Oliver & Pharr's method is popular for extraction of *H* and *E* from the indentation test [5], a method proposed by the authors can be used for estimating σ_y and *n* of structural steels, which show plastic plateau in their stress-strain curve, from the load-depth curve of indentation [6]. Since indentation test allows accessing to the local properties in the indented area, it has been extensively utilized for investigating the properties of inhomogeneous materials such as steel weld zone.

This study aims to investigate the mechanical properties in the weld zone of SM520 steel by combining the aforementioned methods with the aid of FE analysis. For this purpose, indentation, tensile tests, and FE analysis were carried out.

II. EXPERIMENTAL DETAILS

Two SM520 steel plates with 12 mm thickness were welded in form of double V groove butt (12 mm of width and no root gap) by using metal arc welding. A slice cut across the weld and out from the welded plate was used for indentation specimen. The specimen surface was polished to be smooth and flat in order to reduce the error of indentation tests.

A series of indentation tests consisting of 5 x 26 indenting points was performed across the weld zone using a Nano Hardness Tester machine. The indenting series covered portions of weld metal, heat-affected zone, and base metal. Berkovich indenter made of diamond with elastic modulus of 1141 GPa and Poisson's ratio of 0.07 was employed. A fixed maximum load of 160 mN at a constant loading and unloading rate of 320 mN/min was applied for all indentation tests. Tensile tests were conducted by using an Instron testing machine for three specimens of SM520 (labeled N1, N2, and N3) and three welded specimens (W1, W2, and W3), which were cut out from the welded plate with the same dimensions as SM520 steel specimens. Fig. 1 shows specimens of indentation and tensile tests.



(a) (b)

Fig. 1. Specimens of (a) indentaion and (b) tensile tests.

III. PROCEDURE FOR DETERMINATION OF MECHANICAL PROPERTIES FROM INDENTATION AND FE ANALYSIS

A. Determination of H and E

Fig. 2 illustrates a typical load-depth (*P*-*h*) curve.

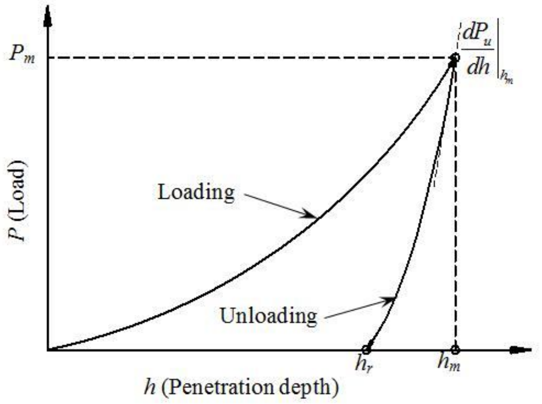


Fig. 2. Typical load-depth (*P*-*h*) curve.

Hardness and elastic modulus of indented material can be extracted from characteristics of the *P*-*h* curve, as follows [5]:

$$H=\frac{P_m}{A_c}, \qquad (1)$$

$$E_r=\frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A_c}}, \qquad (2)$$

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

where P_m is the maximum applied load; A_c is the projected contact area; E_r is the reduced modulus; *S* is the initial unloading slope; β is the correlation factor for indenter shape; and E, υ, E_i, and υ_i are the elastic modulus and Poisson's ratio of the indented material and indenter, respectively.

B. Determination of σ_y and n in BM

A method proposed by the authors was used for extracting σ_y and *n* of structural steel from the *P*-*h* curve of indentation. In this method, σ_y and *n* can be determined with respect to α using the following polynomial equations [6]:

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

$$\frac{S}{E_r^*h_m}=\sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3}b_{ijk}n^{j-1}\alpha^{k-1}\left[\ln\left(\frac{E_r^*}{\sigma_y}\right)\right]^{i-1}, \qquad (5)$$

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; $E_r^*=\left[\left(1-\nu^2\right)/E\right]^{-1}$; and a_{ijk} and b_{ijk} are coefficients. Since the α value of BM can be obtained from the tensile test of SM520 steel, the proposed method was directly used for determining σ_y and *n* in BM of the weld zone. The further details of the method can be referred to the literature [5].

C. Determination of σy and n in HAZ and WM

Since the α value of HAZ and WM regions in the weld zone regions in the weld zone could not be obtained from tensile test of the welded specimens, while preparing mini- or micro-specimens from the weld zone that allows determining α value of the weld zones is a rather difficult task due to the small-size of the zones [7], FE analysis is now currently considered an appropriate approach. To obtain the α value of HAZ and WM, the FE analyses of indentation were performed using the nonlinear finite element analysis program ABAQUS [8] for correlating the experimental with the simulated load-penetration depth curves. The material model for structural steel that was used in the previous work was applied in this study [6]. For the set of simulated *P*-*h* curves, FE analyses were conducted for the total of 560 combinations of different material parameters, in which α varied from 3 to 9 (for every 1), σ_y varied from 325 to 550 (for every 25 MPa), and *n* varied from 0.18 to 0.25 (for every 0.01). Poisson's ratio was chosen to be 0.3 and elastic modulus of E = 206.3 GPa that was averaged from E values obtained from all indentation tests in HAZ and WM regions was used for all FE analyses. The above ranges of α, σ_y, and *n* were chosen after paying a special attention to α, σ_y, and n values observed in BM and doing some prior FE analyses in order to reduce the number of FE analyses. The loading part of P-h curve drawn up to 160 mN was compared with the experimental curves at the middle indenting column in HAZ and WM regions to determine the corresponding α values and the obtained value of $\alpha = 5$ and $\alpha = 6$ was considered the representative α value for HAZ and WM region, respectively. Once α value of HAZ and WM was estimated, the yield strength and strain hardening exponent in HAZ and WM could be determined using (4) and (5).

IV. RESULTS AND DISCUSSIONS

A. Indentation response in the weld zone

The representative P-h curves in three regions of the weld zone are presented in Fig. 3. As is seen from this figure, the shape and magnitude of the P-h curves change significantly with the individual weld zone, signifying that the indentation response is highly sensitive to the metallurgical condition resulting during the welding. For the present weld zone, the maximum depth in HAZ is smallest, while the depth in BM is larger than that in WM.

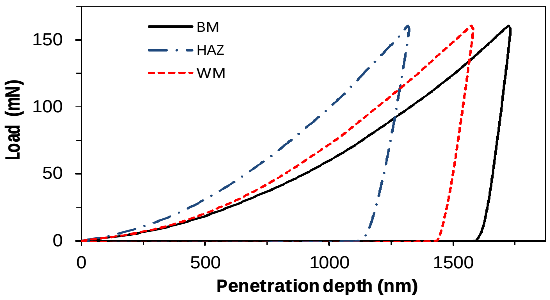
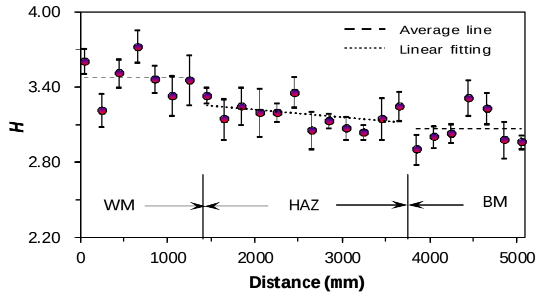


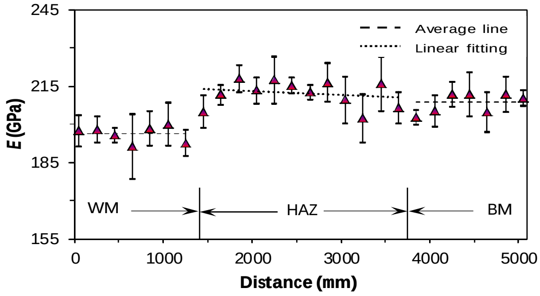
Fig. 3. Representative P-h curves in the weld zone.

B. Mechanical properties in the weld zone

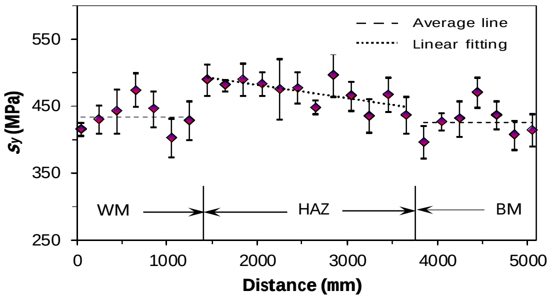
Fig. 4 shows the distribution of H, E, σ_y, and n across the weld zone, where each data is averaged from 5 values at each indenting column. The standard deviation of the data is also presented in the figure as an error bar. Note in this figure that the dashed lines represent the average values of all data points in the WM and BM regions, while the dotted line is the linear fitting of all values in HAZ regions. As the results, H, E, σ_y, and n values in HAZ gradually increase in the direction from BM to WM region. The average values of all properties in HAZ are highest, while WM has a lower stiffness but a higher hardness, strength, and strain hardening exponent than does BM, as shown in Table 1.



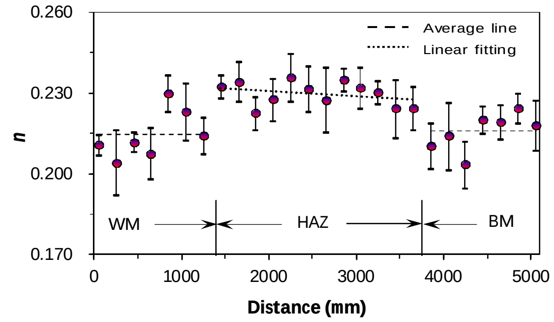
(a) Hardness



(b) Elastic modulus



(c) Yield strength



(d) Strain hardening exponent

Fig. 4. Mechanical properties in the weld zone.

Table 1: Mechanical properties obtained from indentation.

Location	*H* (GPa)	*E* (GPa)	σ_y (MPa)	*n*
BM	3.1	208.6	426.4	0.216
HAZ	3.2	212.2	470.9	0.230
WM	3.5	196.4	434.6	0.214

C. Verification

The results of E, σ_y, and n in BM obtained from indentations are recognized to be agreed well with the tensile test results of SM520 with a small relative error of -1.96%, 0.66%, and 7.46%, respectively, as listed in Table 2.

Table 2: Tensile test results of SM520 steel.

Test	Spe. No	*E* (GPa)	σ_y (MPa)	*n*	α
Tensile	S1	214.4	423.6	0.203	5.9
	S2	212.2	421.7	0.193	6.4
	S3	211.7	425.6	0.207	6.3
	Ave.	212.7	423.6	0.201	6.2
Indentation	BM	208.6	426.4	0.216	
% error		*-1.96*	*0.66*	*7.46*	

To examine the results obtained from indentation tests in HAZ and WM regions, FE analysis of tensile test using ABAQUS program was conducted [8]. The steel and welded specimens for tensile tests were modeled using 8-node element C3D8R. The material model for structural steel used in the previous work [6] was used for the material properties definition of SM520 steel as well as of both HAZ and WM regions. The FE model was first verified by simulating the tensile test of SM520 steel. The properties of SM520 steel in Table 2 were used for the input data in this simulation. Fig. 5 shows the comparison of the failure mode and Fig. 6 shows the comparison of load-strain curve between simulation and experiment of SM520 steel specimen. Good agreement between both the simulated and experimental failure mode and load-strain curve observed from the figures indicates that the developed FE model can be used to accurately simulate the tensile test.

(a) Experiment

(b) FE simulation

Fig. 5. Failure mode of SM520 steel specimen.

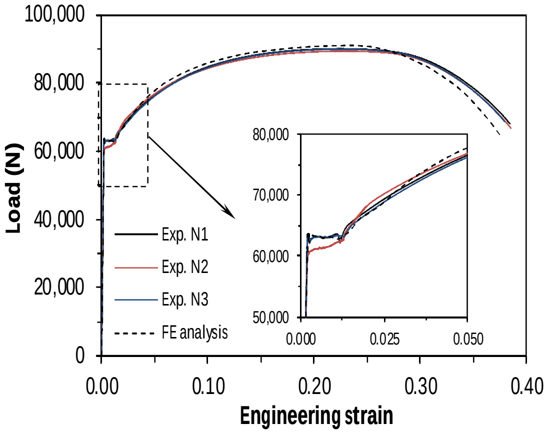
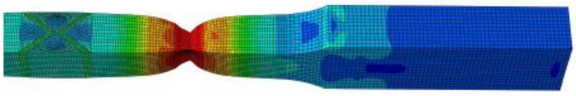


Fig. 6. Comparison of load-strain curve of steel specimen.

The tensile test of welded specimen was then simulated using the developed FE model. The weld portions including WM and HAZ regions were also taken into account and the mechanical properties obtained from indentation tests were used for the definition of the properties in these regions (see Table 1). Fig. 7 shows the comparison of the failure mode and Fig. 8 shows the comparison of load-strain curve between simulation and experiment of the welded specimen. Good agreement between both the simulated and experimental failure mode and load-strain curve observed from these figures indicates that the properties (E, σ_y, and n) determined from indentation tests in HAZ and WM regions are reliable and valid. Concerning the hardness, the values of H = 3.1 GPa, H = 3.2 GPa, and H = 3.5 GPa (Table 1) that represents to the hardness of BM, HAZ, and WM, respectively, are consistent with the related literature [1]-[3].

(a) Experiment



(b) FE simulation

Fig. 7. Failure mode of SM520 steel specimen.

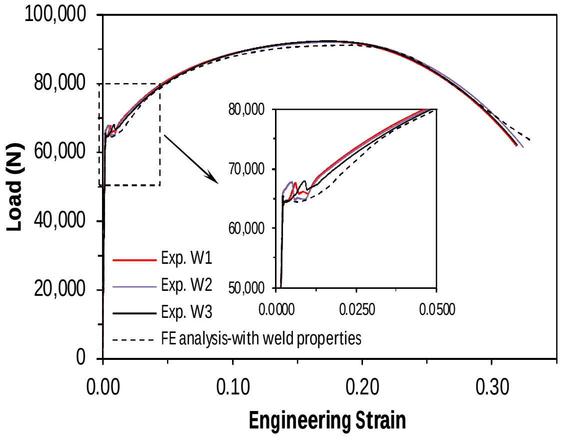


Fig. 8. Comparison of load-strain curve of welded specimen.

CONCLUSIONS

In this study, indentation with the aid of FE analysis was used for characterization of the mechanical properties in the weld zone of SM520 steel. Some following conclusions can be drawn from the test and analysis results:

The indentation responses in the weld zone are highly sensitive to the metallurgical conditions during the welding. The maximum penetration depth in HAZ is smallest, while the depth in BM is larger than that in WM.

The mechanical properties in the weld zone determined from the indentation tests with the aid of FE analysis were demonstrated to be valid and reliable by comparing with the results from tensile test, FE simulation, and other literature. For the present weld zone, the hardness, elastic modulus, yield strength, and strain hardening exponent values in the HAZ gradually decrease in the direction from WM to BM region. The average values of mechanical properties in HAZ are highest, while WM has a lower stiffness but a higher hardness, strength, and strain hardening exponent than does BM.

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