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INDENTATION FOR INVESTIGATION OF STRAIN RATE EFFECT ON MECHANICAL PROPERTIES IN STRUCTURAL STEEL WELD ZONE

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Abstract

In this study, instrumented indentation testing was conducted at room temperature for the investigation of the effect of strain rate on the hardness and yield strength in the weld zone of a commonly used structural steel, SM520. A number of indentation tests were undertaken at a number of strain rate values from 0.02 s^{-1} to 0.2 s^{-1} in the weld metal (WM), heat-affected zone (HAZ), and base metal (BM) regions of the weld zone. The mechanical properties including yield strength (σ_y) and hardness (H) in WM, HAZ, and BM were then computed from the applied load-penetration depth curves using a proposed method. As the result, the effects of strain rate indentation on yield strength and hardness in all regions of the weld zone were evaluated. The results displayed that hardness and yield strength in the weld zone's components are influenced on the strain rate, where both hardness and yield strength decrease with the decreasing strain rate.

Keywords: indentation; mechanical properties; strain rate effect; structural steel; weld zone.

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1. Introduction

The excellent weldability and machinability of structural steel, which caused by it's high strength, stiffness, toughness, and ductility, have led to the common usage of this material in many construction fields including buildings, bridges, tunnels and in the manufaction of machinery parts and equipments [1–3]. Welding is considered as the efficient method to form the strong joints between the steel parts, where the structural steel is used. However, the welding joints are also considered as the weakest parts of structures [4]. The heating or cooling stages influence the microstructures in the weld zone, including the weld metal (WM) region, the heat-affected zone (HAZ), and base metal (BM) region near the weld due to the transformation of solid-state phases, leading to the change of material properties in the weld zone [5–8]. Thus, the properties in the local regions of weld joints need to be evaluated. The high ductility and energy dissipation capacity have also been the important reason for the wide utilization of structural steel in both static and seismic applications. It has been pointed out that the mechanical properties of structural steel are governed by the metallurgical aspects and strongly

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dependent on the conditions of strain rate [9–11]. For example, Luecke et al. [11] carried out the dynamic loading tensile tests for several low-carbon steel types and concluded that their tensile and yield strength decrease with the decreasing strain rate. However, the influences of strain rate on the hardness and yield strength in the weld zone of structural steel have not been well reported. Since these effects are the important factor for the engineering analyses as well as the steel structure designs in the both static and dynamic problems, it is essential to have a comprehensive investigation of the strain rate influences on the hardness and yield strength in the weld zone of structural steel.

Instrumented indentation testing (IIT) has been known as an efficient method in extracting material properties at both the macro- and nano-scales [12]. For characterization of the mechanical properties under different strain rate levels, it has also proved to be reliable and efficient since this approach can not only provide accurate results [13–16] but also overcome the uneconomical and time-consuming dynamic tensile loading tests.

This work aims to evaluate the strain rate influences on the hardness and yield strength in the weld zone of structural steel using instrumented indentation tests. A number of indentations were undertaken at a number of strain rate values from 0.02 s^{-1} to 0.2 s^{-1} in the weld zone (WM), heat-affected zone (HAZ), and base metal (BM) regions. The mechanical properties including yield strength (σ_y) and hardness (H) in WM, HAZ, and BM were then computed from applied load-penetration depth curves of indentation using a proposed method. As the result, the effects of strain rate indentation on yield strength and hardness in all regions of the weld zone were investigated.

2. Methods

Fig. 1 illustrates a typical load-depth (P-h) curve of an elastic-plastic material to a three-sided Berkovich indentation [17]. From this curve, several indentation characteristic parameters, such as the maximum penetration depth h_m, the maximum applied load P_m, the residual depth after unloading h_r, the initial unloading slope S, the loading curvature C, the projected of contact A_c, the residual plastic work W_p, and the recovered elastic work W_e, can be extracted. As can be seen in Fig. 1, h_m, P_m, h_r, W_p, and W_e, can be directly obtained from the P-h curve, while S, C, and A_c can only be extracted based on the description of loading and unloading curves. For sharp indenters, the initial unloading slope S, the loading curvature C, and the projected of contact A_c can be expressed, respectively, as follows [17]:

$$S = \left.\frac{dP}{dh}\right|_{h=h_m} = mB\,(h_m - h_r)^{m-1} \tag{1}$$

$$C = \frac{P_m}{h_m^2} \tag{2}$$

$$A_c = 24.5h_c^2 \tag{3}$$

where $h_c = h_m - \varepsilon^* P_m/S$ and $\varepsilon^* = 0.75$ for sharp indenters [17].

The mechanical properties of the indented material, such as elastic modulus E, yield strength σ_y, strain hardening exponent n, and hardness H, can thus be evaluated from these above indentation parameters. Numerous analytical approaches that allow the determining of the mechanical properties from the indentation load-penetration depth curve have been proposed in recent years [17–21]. Among which Oliver and Pharr's method [17] has been considered as one of the most popular methods to extract elastic modulus and hardness of indented material, while the algorithm proposed by Pham et al. [21] could be considered as a representative approach for determination of yield strength and

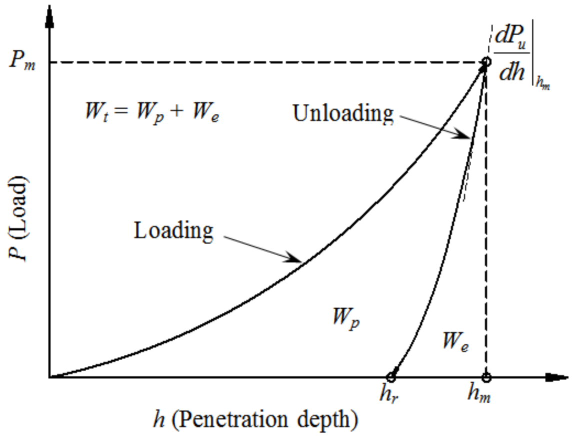


Figure 1. Typical load-depth (*P*-*h*) curve of indentation

strain hardening exponent of structural steel. In Oliver and Pharr's method, the value of E and H can be extracted from the following relations [17]:

$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A_c}} \tag{4}$$

$$E_r = \left[\frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i}\right]^{-1} \tag{5}$$

$$H = \frac{P_m}{A_c} \tag{6}$$

where E_r is the reduced modulus owing to the effects of elastic deformation of the indenter. E, υ, E_i and υ_i are the elastic modulus and Poisson's ratio of the sample and indenter, respectively.

For determination of the yield strength, the algorithm proposed by Pham et al. [21] that allows extracting yield strength σ_y of structural steel was used. In this method, the yield strength σ_y in the weld zone can be determined with respect to α using the following polynomial equations [21]:

$$\frac{E_r^*}{\sigma_y} = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} a_{ijk} n^{j-1}\alpha^{k-1}\left(\frac{E_r^*}{C}\right)^{i-1} \tag{7}$$

$$\frac{S}{E_r^* h_m} = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3} b_{ijk} n^{j-1}\alpha^{k-1}\left[\ln\left(\frac{E_r^*}{\sigma_y}\right)\right]^{i-1} \tag{8}$$

where α is defined as the ratio of the strain at starting point of strain hardening and the yield strain and a_{ijk} and b_{ijk} are coefficients [21]. 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- 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 work [22].

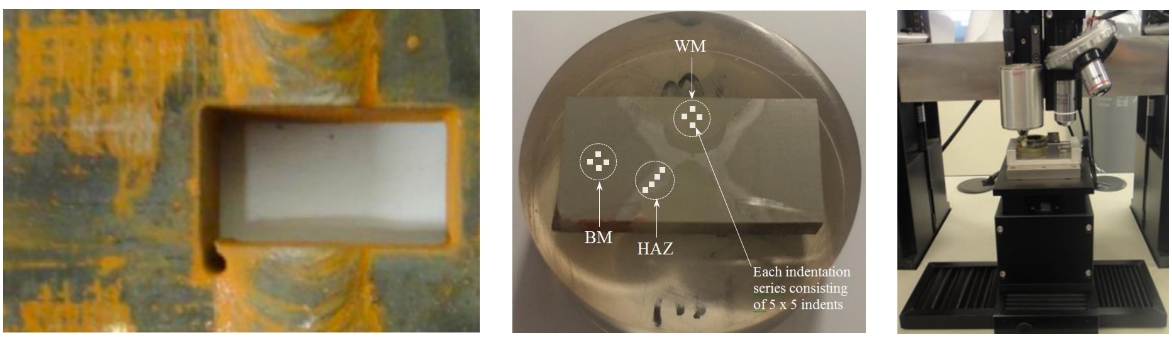
3. Experiments

One of the most common used structural steel (SM520) with the chemical composition listed in Table 1 was chosen to be investigated. The weld with suitable weld material in the form of double V groove butt with no root gap was employed to connect two 12 mm-thickness steel plates by welding using metal arc method under an 100 A of current and 22 V of voltage.

Table 1. Compositions of weld and steel material (in wt.%)

Material	C	Si	Mn	P	S	Al	Cu	Ni
Steel	0.17	0.41	1.39	0.017	0.001	0.04	0.02	-
Weld	0.12	0.35	1.44	0.010	0.003	0.04	-	0.13

From the welded plate, a slice across the weld was cut out by water jet cutting method. Such cutting method did not affect the transformation of properties in the weld zone. The slice was then used for the preparation of indentation specimen according to ASTM E3-01 standards [23]. The smooth and flat of specimen surface were ensured to meet the requirement of the indentation standard after being polished in seven stages by silicon carbide papers, poly diamond particles, and colloidal silica with the fineness of the last stage about 40 nm. Such a smooth and flat surface of specimen for indentation tests is considered as main criterion to eliminate the surface roughness in the similarity analysis and to minimize the occurance of error in the tests [24]. Indentation testing was carried out using a Nano Hardness Tester at room temperature comforming to ASTM E2546-07 standard [25]. The diamond Berkovich indenter with elastic modulus of E_i = 1141 GPa and Poission ratio of υ = 0.07, was employed. Indentation tests were undertaken in three regions, WM, HAZ, and BM of the weld zone by using the displacement control mode without a holding time at a number of strain rate values from 0.02 s^{-1} to 0.2 s^{-1}. A 50 µm spacing - grid of 5×5 indenting points were performed at each strain rate value of 0.02 s^{-1}, 0.04 s^{-1}, 0.1 s^{-1}, and 0.2 s^{-1} for each region of the weld, leading to the total of 100 and 300 indenting points in each region and in all regions of the weld, respectively. All indentations were also carried with a maximum applied load of 2000 nm in order to obtain the composite behavior instead of a microstructural phase response from the tests. Fig. 2 shows the cut-out location of the specimen from the welded plate and the polishing specimen surface, on which the indenting positions are also illustrated, and the installation of the sample in the indentation test machine.



(a) (b) (c)

Figure 2. (a) Cut-out from the welded plate by water jet, (b) Indenting positions in each region and (c) Sample installed in the indentation test machine

4. Results and discussion

4.1. Indentation response

The representative indentation responses of the material in BM, HAZ, and WM, at different strain rate levels, together with the averaged load-depth curves in these regions at a certain strain rate level of 0.2 s^{-1} are displayed in Fig. 3. It is seen from Figs. 3(a)–3(c) that strain rate during indentation tests influences both the shape and the magnitude of the load-depth curves of the tests. For all regions in the weld, the loading curvature tends to decrease with the decreasing strain rate during the tests, leading to the higher maximum applied load with the higher strain rate level due to the applied constant maximum displacement in all the tests. Regarding to the correlation between the indentation response in different regions of the weld, the distinguishable variation of the indentation curves obtained from BM, HAZ, and WM can be observed in Fig. 3(d). It can be seen from this figure that both loading curvature and applied load of the indentation curves in the BM are lowest and these parameters are highest in the WM among three regions. This observation consists with the available results of indentation responses for the weld zone of other structural steels [3, 6, 22] and corresponds to the lowest hardness and yield strength in BM among three regions, respectively, which will be discussed below.

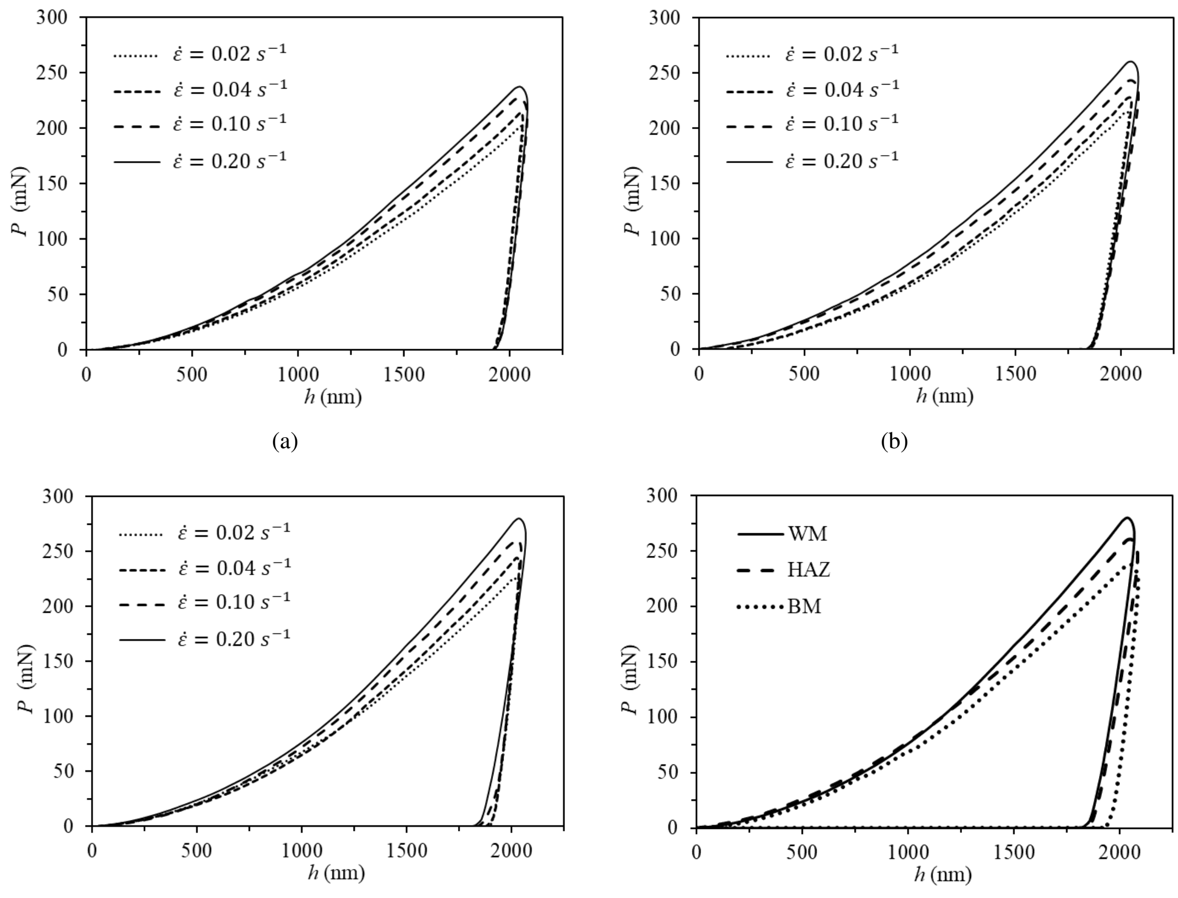


Figure 3. Indentation responses (*P*-*h* curves) in (a) BM, (b) HAZ, (c) WM and (d) All regions at $\varepsilon = 0.2$ s^{-1}

4.2. Strain rate effect on mechanical properties in the weld zone

From the applied load-depth curve of indentation test, the contact area Ac and maximum load P_m can be easily measured and then the hardness was computed using Eq. (6). The calculated results are presented in Fig. 4 in such the way to show the change of hardness with respect to different strain rate levels in all regions of the weld as well as the distinguishable hardness values in the three regions. In this figure, each presented hardness value is the mean of 25 values obtained from an indentation test series in individual region, together with the corresponding error bar of ±1 standard deviation, which are listed in Table 2. The best fit curve of the changing trend of hardness in each region is also accompanied.

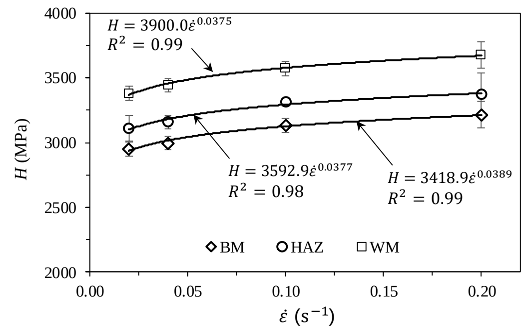


Figure 4. Strain rate effect on hardness of the weld zone

Table 2. Hardness in each region of weld zone at different strain rate levels

Strain rate	BM		HAZ		WM	
	H (MPa)	STDEV* (MPa)	H (MPa)	STDEV (MPa)	H (MPa)	STDEV (MPa)
0.02	2950	70	3110	148	3380	85
0.04	2996	57	3159	76	3441	74
0.10	3130	62	3312	44	3572	82
0.20	3216	138	3375	240	3680	153

*Standard deviation

From Fig. 4, the effecta of strain rate on the hardness in individual region of weld zone are clearly observed. The same trend is that higher strain rate level leads to the higher hardness for all regions WM, HAZ and BM of the weld zone. This trend is recognized that the hardness value quite rapidly increases as strain rate level increases from 0.02 s^{-1} to 0.04 s^{-1} and the increment of hardness reduces when strain rate levels change from 0.1 s^{-1} to 0.2 s^{-1}. It is interesting to observe that the change of hardness in individual region with respect to different strain rate levels seem to be obeyed an exponential function, as can be seen in Fig. 4. It is also noted that the hardness in BM is lower than the corresponding one in HAZ at a certain strain rate level, while the corresponding hardness value in WM is highest in the weld zone. These results match well with the trends reported in previous works for the weld zone of other structural steels [3, 22].

While the hardness can be directly extracted from indentation curve *P-h*, the yield strength in the regions of the weld zone was determined using Eqs. (7) and (8), in which an unknown parameter corresponding to the yielding part of the structural steel's σ-ε curve (α) needs to be pre-estimated for each region. The α value of each region is estimated using the results from the analysis of indentation FE simulation, which are detailed in previous works [3, 6, 22]. In present work, by applying such approach, the α values at each strain rate values for BM, HAZ, and WM regions were estimated and the yield strength in each region of the weld zone was extracted for certain strain rate level. With the same illustrated way for hardness in Fig. 4, the extracted yield strength in each region of the weld zone at different values of strain rate are presented in Fig. 5. The corresponding values in this figure are also listed in Table 3 for more clarity.

Table 3. Yield strength in each region of weld zone at different strain rate levels

Strain rate	BM		HAZ		WM	
	σ_y (MPa)	STDEV* (MPa)	σ_y (MPa)	STDEV (MPa)	σ_y (MPa)	STDEV (MPa)
0.02	420.08	14.19	455.61	20.42	436.18	23.96
0.04	432.03	16.87	465.69	7.80	447.10	13.79
0.10	448.28	14.79	480.42	15.04	464.13	8.44
0.20	461.18	11.32	495.55	15.66	474.73	18.42

*Standard deviation

From Fig. 5, the strain rate influences on the yield strength in individual region are clearly observed. The same trend is that higher strain rate level leads to the higher yield strength for all regions BM, HAZ and WM of the weld zone. This trend is also recognized that the increment of yield strength values when strain rate value changes from 0.02 s^{-1} to 0.04 s^{-1} is greater than the increment of yield strength when strain rate value changes from 0.1 s^{-1} to 0.2 s^{-1}. Similar to the hardness, the change of yield strength in individual region with respect to different strain rate levels seem to be obeyed an exponential function, as can be seen in Fig. 5. Considering the correlation between the yield strength values in each region, the yield strength in BM is lowest in the weld zone, while the yield strength in HAZ at a certain strain rate level is higher than the corresponding one in WM. This result indicates that the chosen weld material in this case eventhougth satify the requirements for the weld, it is still should be chosen better in order to avoid the failure of the weld due to the weld material. However, these obtained results are consistent with the reported trends for the same structural steel weld zone in the previous works [3].

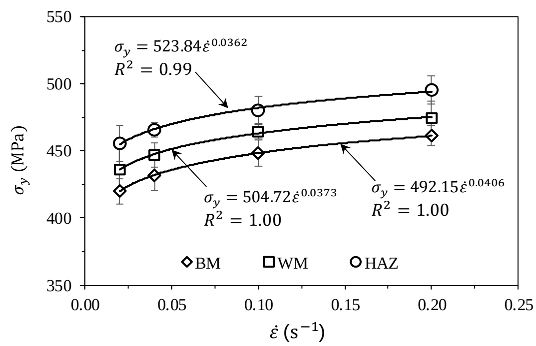


Figure 5. Strain rate effect on yield strength in the weld zone

For the validation of reliability and accuracy of the present results, the obtained hardness and yield strength at a certain strain rate of 0.02 s^{-1} were compared with the corresponding values in the same weld zone, which are available in the literature [3], as listed in Table 4. It is obvious that hardness and

Table 4. Comparison of mechanical properties at strain rate of 0.02 s^{-1} between present and previous works [3]

	Yield strength (MPa)			Hardness (MPa)		
	Present work	Previous work [3]	Error %	Present work	Previous work [3]	Error %
BM	420.08	426.41	−1.48	2950	3064	−3.72
HAZ	455.61	470.92	−3.25	3110	3185	−2.35
WM	436.18	434.57	0.37	3380	3475	−2.72

yield strength values at strain rate of 0.02 s^{-1} in this work match well with corresponding reported ones [3]. The relative error in case of hardness is within ± 3.72%, while it is even smaller in case of yield strength with the error within ± 3.25%. The observation and comparison indicates that the obtained results in this work are accurate and reliable.

5. Conclusions

In this study, the influences of strain rate on the hardness and yield strength of a typical structural steel (SM520) weld zone was investigated using indentation. The following conclusions can be withdrawn:

- Strain rate during influences on both the shape and magnitude of the indentation applied load-depth curves. For all the regions in the weld, the loading curvature increase as the strain rate during indentation increases, leading to the higher maximum applied load with the higher strain rate level due to the applied constant maximum displacement in all the tests.

- Strain rate level has strong effect on the hardness for all regions in the weld zone. The trend is that the hardness values quite rapidly increase as strain rate value increases from 0.02 s^{-1} to 0.04 s^{-1} and the increment of hardness reduces when strain rate value change from of 0.1 s^{-1} to 0.2 s^{-1}. The trend seems to be obeyed an exponential function.

- Strain rate level has strong effect on the yield strength for all regions in the weld zone. The trend is that the increment of yield strength values when strain rate value changes from 0.02 s^{-1} to 0.04 s^{-1} is greater than the increment of yield strength when strain rate value changes from 0.1 s^{-1} to 0.2 s^{-1}. Similar to the hardness, the change of yield strength in individual region with respect to different strain rate levels seem to be obeyed an exponential function.

In conclusion, the mechanical properties in the investigated structural steel weld zone are strongly influenced by indentation strain rate and the relationships between hardness and yield strength with strain rate obtained in present study provide an assessment of these mechanical properties in the weld zone at a specific strain rate level without conducting any additional tests.

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References

[1] Pham, T.-H., Kim, J. J., Kim, S.-E. (2014). Estimation of microstructural compositions in the weld zone of structural steel using nanoindentation. *Journal of Constructional Steel Research*, 99:121–128.

[2] Pham, T.-H., Kim, S.-E. (2015). Nanoindentation for investigation of microstructural compositions in SM490 steel weld zone. *Journal of Constructional Steel Research*, 110:40–47.

[3] Pham, T.-H., Kim, S.-E. (2017). Characteristics of microstructural phases relevant to the mechanical properties in structural steel weld zone studied by using indentation. *Construction and Building Materials*, 155:176–186.

[4] Tamboli, A. R. (1999). *Handbook of structural steel connection design and details*. McGraw-Hill, New York.

[5] Bayraktar, E., Kaplan, D., Devillers, L., Chevalier, J. (2007). Grain growth mechanism during the welding of interstitial free (IF) steels. *Journal of Materials Processing Technology*, 189(1-3):114–125.

[6] Pham, T.-H., Kim, S.-E. (2016). Microstructure evolution and mechanical properties changes in the weld zone of a structural steel during low-cycle fatigue studied using instrumented indentation testing. *International Journal of Mechanical Sciences*, 114:141–156.

[7] Boumerzoug, Z., Derfouf, C., Baudin, T. (2010). Effect of welding on microstructure and mechanical properties of an industrial low carbon steel. *Engineering*, 2(07):502.

[8] Lee, C.-H., Shin, H.-S., Park, K.-T. (2012). Evaluation of high strength TMCP steel weld for use in cold regions. *Journal of Constructional Steel Research*, 74:134–139.

[9] Boyer, H. E. (1990). *Atlas of stress–strain curves*. ASM International, Metals Park, Ohio 44073, USA.

[10] Nagarajarao, N., Lohrmann, M., Tall, L. (1966). Effect of strain rate on the yield stress of structural steel. *ASTM Journal of Materials*, 1(1).

[11] Luecke, W. E., McColskey, J. D., McCowan, C. N., Banovic, S. W., Fields, R. J., Foecke, T., Siewert, T. A., Gayle, F. W. (2005). *Mechanical properties of structural steels*. NIST NCSTAR1-3D.

[12] Wei, Q. (2007). Strain rate effects in the ultrafine grain and nanocrystalline regimes—influence on some constitutive responses. *Journal of Materials Science*, 42(5):1709–1727.

[13] Nguyen, N.-V., Pham, T.-H., Kim, S.-E. (2018). Characterization of strain rate effects on the plastic properties of structural steel using nanoindentation. *Construction and Building Materials*, 163:305–314.

[14] Nguyen, N.-V., Pham, T.-H., Kim, S.-E. (2019). Microstructure and strain rate sensitivity behavior of SM490 structural steel weld zone investigated using indentation. *Construction and Building Materials*, 206:410–418.

[15] Lu, Y. C., Tandon, G. P., Putthanarat, S., Schoeppner, G. A. (2009). Nanoindentation strain rate sensitivity of thermo-oxidized PMR-15 polyimide. *Journal of Materials Science*, 44(8):2119–2127.

[16] Nguyen, N.-V., Pham, T.-H., Kim, S.-E. (2019). Strain rate-dependent behaviors of mechanical properties of structural steel investigated using indentation and finite element analysis. *Mechanics of Materials*, 137.

[17] Oliver, W. C., Pharr, G. M. (1992). An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of Materials Research*, 7(6):1564–1583.

[18] Pham, T.-H., Phan, Q.-M., Kim, S.-E. (2018). Identification of the plastic properties of structural steel using spherical indentation. *Materials Science and Engineering: A*, 711:44–61.

[19] Antunes, J. M., Fernandes, J. V., Menezes, L. F., Chaparro, B. M. (2007). A new approach for reverse analyses in depth-sensing indentation using numerical simulation. *Acta Materialia*, 55(1):69–81.

[20] Kang, J. J., Becker, A. A., Sun, W. (2012). Determining elastic–plastic properties from indentation data obtained from finite element simulations and experimental results. *International Journal of Mechanical Sciences*, 62(1):34–46.

[21] Pham, T.-H., Kim, J. J., Kim, S.-E. (2015). Estimating constitutive equation of structural steel using indentation. *International Journal of Mechanical Sciences*, 90:151–161.

[22] Pham, T.-H., Kim, S.-E. (2015). Determination of mechanical properties in SM490 steel weld zone using nanoindentation and FE analysis. *Journal of Constructional Steel Research*, 114:314–324.

[23] ASTM E3-01 (2007). *Standard guide for preparation of metallographic specimens*. ASTM International, West Conshohocken, PA.

[24] Miller, M., Bobko, C., Vandamme, M., Ulm, F.-J. (2008). Surface roughness criteria for cement paste nanoindentation. *Cement and Concrete Research*, 38(4):467–476.

[25] ASTM E2546-07 (2007). *Standard practice for instrumented indentation testing*. ASTM International, West Conshohocken, PA.