Experimental study on dynamic nanoindentation on structural weld zone

Ngoc-Vinh Nguyen¹ and Thai-Hoan Pham²

¹ Dept. of Civil and Environmental Engineering, Sejong University, 98 Gunja-dong, Gwangjin-gu, Seoul 05006, South Korea.

² Dept. of Faculty of Building and Industrial Construction, National University of Civil Engineering, 55 Giai Phong, Ha Noi, Viet Nam.

E-mail: vinhnguyen@sju.ac.kr (N.V. Nguyen); hoanpt@nuce.edu.vn (T.H. Pham)

Abstract: In this study, dynamic spherical indentation and finite element analysis were used to assess the strain rate sensitivity behavior of the SS400 structural steel weld zone. The influences of the loading rate on both yield strength and hardness of the base metal, heat-affected zone, and weld metal are studied using dynamic spherical nanoindentation. The strain rate sensitivity (SRS) of three microstructural phases in the weld zone was also determined using the hardness model, as a result, the SRS behavior in the weld zone was investigated. The relationship of the SRS to the minimum yield stress of the investigated weld zone was constructed and compared with the general trend reported for several types of structural steel in the literature. To verify the SRS behavior in the weld zone, the tensile loading experiments on the weld specimen and finite element (FE) simulation of the tensile process considering the SRS behaviors of base metal, heat affected zone, and weld metal were conducted. The comparison of the engineering stress-engineering strain curves obtained from the tensile experiment and FE analysis is then constructed. Thus, the SRS behavior of the SS400 structural steel weld zone was validated through experimental verification. The present study provided a basic methodology to dynamic nanoindentation on the weld zone, and the experimental results of this study can be used in the practical designs and to understand the strain rate sensitivity behavior of microstructural phases in the weld zone.

1. Introduction

Plastic flow of metals at high loading rates has recently attracted renewed interest due to the strong influences at very high loading rates and the importance of these influences on the dynamic failure mechanisms [1]. Early interest in the issue is stimulated by the applications in the military, for example, the armor penetration. Another application of this issue is in the road infrastructure of transportations. Stopel and Skibicki [2] investigated the dynamic behavior of support elements of road infrastructure during an impact at a speed of 100 km/h by considering the Johnson-Cook model (a visco-plastic model for ductile metals), which was used to consider the strain rate effects on the material behavior and fracture. Although these applications stimulate the research, understanding plastic flow at high loading rates is recognized to be critical importance in wide applications, consisting of high-speed machining, high-rate forming, the crash-worthiness of vehicles to the
retention of flying pieces of broken turbine blades, and explosive welding. From the perspective of failure mechanisms, plastic flow at high loading rates shows an important role in the shear strain localization and dynamic ductile rupture since the high loading rates occur near the shear band and the crack tip, respectively. Plastic flow of metals at high loading rates can be represented by the term strain rate sensitivity, which shows the influences of strain rate on the mechanical properties of the material. Furthermore, the strain rate sensitivity is also an important input parameter of the engineering designs or static/dynamic analyses of the structures [3].

There are several methods to estimate the strain rate sensitivity values of the material, for example, tensile loading experiment, indentation experiment, creep indentation experiment, strain rate jump experiment, stress relaxation experiments, and so on [1,3]. Chatfield and Rote [4] investigated the strain rate effect on the properties of high strength, low alloy steels using dynamic tensile experiments. The research indicated that the ferrous alloys exhibited the SRS behavior in the following ways: First, yield strength (or tensile strength) increased with the further increase of strain, while the uniform elongation showed a decrease. Second, the absorbed energy tended to increase with strain rate. Luecke et al. [1] collected and determined the data of SRS for many types of structural steel to construct the simple relationship between the SRS and the minimum yield strength. The results of their research exhibited that the SRS seemed to depend on the minimum yield stress, and the values of SRS tended to decrease with the further increase of strain rate. Alkorta et al. [5] proposed the simple method to estimate the SRS from the creep indentation response, while a new method for reliable determination of SRS of low-dimensional metallic materials using nanoindentation was proposed by Liu et al. [6]. Nguyen et al. [7] applied the indentation into the determination of SRS of structural steel by performing the nanoindentation tests at different strain rates. However, the SRS behavior of the SS400 structural steel weld zone has not been well investigated so far. Thus, in this study, the SRS behaviors of base metal (BM), heat-affected zone (HAZ), and weld metal (WM) of SS400 structural steel weld zone were characterized using spherical nanoindentation and finite element analysis. The effects of loading rate on three microstructural phases were also investigated, and the SRS behavior of the tested weld zone was then validated through experimental verification.

2. Methods

2.1 Method to extract the material properties from the indentation curve

Recently, nanoindentation testing is attributed to a promising method to investigate the influences of loading rate on mechanical properties of the materials since this experiment can be performed on both displacement and load controls, and the loading rate can be easily changed during the testing process. Thus, the methodology to determine elastic modulus \(E\), indentation hardness \(H\), and yield stress \(\sigma_y\) is briefly described as follows. It can be seen from the loading/unloading curves in figure 1 that the loading curve can be depicted using a power-law formula, \(P = C h^k\), [8–10], while the loading stage is also described as a function of displacement as \(P_u = B(h - h_D)^q\), where \(C\) and \(B\) are the loading curvature and the constant parameter, and \(k\) and \(q\) are the exponent parameters.
The stiffness of the contact ($S$) is determined as $S = \left. \frac{dP}{dh} \right|_{h=h_m} = qB(h_m - h_f)^{q-1}$ [3]. Based on $S$, a maximum load ($P_m$), a maximum depth ($h_m$), a final depth ($h_f$), a contact depth ($h_c$), and $C$, reduced modulus ($E_r$), $E$, and $H$ can be determined using equations (1), (2), and (3), respectively [11,12].

$$E_r = \frac{\sqrt{\pi S}}{2B\sqrt{A_c}}$$  \hspace{1cm} (1)

$$\frac{1}{E_r} = \frac{1-\theta^2}{E} + \frac{1-\theta_i^2}{E_1}$$  \hspace{1cm} (2)

$$H = \frac{P_m}{A_c}$$  \hspace{1cm} (3)

In equation (3), the contact area ($A_c$) is defined as a function of $h_c$ as $A_c = 24.5h_c^2$, where $\epsilon$ is a constant factor [13,14]. Finally, yield strength can be also estimated from the characteristics of the indentation curve using two dimensionless functions as [15]

$$\frac{E_r h_m^2}{W_t} = \sum_{i=1}^{4} a_i(n, \alpha) \left( \frac{E_r}{\sigma_y} \right)^{i-1},$$  \hspace{1cm} (4)

$$\frac{E_r}{\sigma_y} = \sum_{i=1}^{4} b_i(n, \alpha) \left( \frac{W_c}{W_t} \right)^{i-1}.$$  \hspace{1cm} (5)

2.2 Estimation of SRS

There are several methods to determine the strain rate sensitivity ($m$) of the material. First, the tensile loading experiments are attributed to a reliable method to estimate the SRS from the yield stress at different strain rate levels at a constant temperature as

$$\frac{\sigma}{\sigma_0} = \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^m.$$  \hspace{1cm} (6)

This method is widely applied to determine the SRS values of the material. As shown in figure 2, the crosshead velocity is forced to change from $V_1$ to $V_2$, there is an increase in the corresponding load. If
straining is continued for a few percent to eliminate the transient effects, a load comparison can be made. The lower velocity curve is extrapolated to establish a common strain for measurement. Figure 2 shows a schematic load-time diagram representing a velocity change from \( V_1 \) to \( V_2 \). If \( m \) is assumed to be nearly independent of the strain rate in the range covered by the velocity increase, then

\[
m = \frac{\ln(P_A/P_B)}{\ln(V_2/V_1)}
\]  

(7)

**Figure 2.** Schematic of the strain rate change method

Another method to determine the SRS of the material is the nanoindentation technique. Nanoindentations are performed at several loading rates to observe the variation of indentation hardness under loading rate conditions, and then the \( m \) values can be obtained by drawing the log(hardness)-long(indentation strain rate) curve and performing the regression analysis as

\[
m = \frac{\delta \ln(H)}{\delta \ln(\dot{\varepsilon})}.
\]  

(8)

Recently, the nanoindentation technique has also been developed to determine the SRS values from single load-depth curve (so-called strain rate jump test) as [16,17]

\[
m = \frac{\delta \ln(\sigma)}{\delta \ln(\dot{\varepsilon})}.
\]  

(9)

Creep indentation is also applied to determine the SRS values of the material via the creep indentation response during the holding stage as

\[
m = 2 \frac{\Delta \ln h}{\Delta \ln e_{\text{creep}}}
\]  

(10)

Finally, the \( m \) can be well estimated from the stress relaxation experiment using the following equation as

\[
\ln \sigma_t = C + \frac{m}{m-1} \ln(t + D).
\]  

(11)

In equation (11), \( t \), \( C \), and \( D \) are the testing time and the constant factors, and \( \sigma_t \) is the stress at time \( t \).

3. Experimental procedure

In this study, SS400 structural steel weld zone was selected to investigate the strain rate sensitivity behavior in the weld joint. Steel plates with 12 mm in thickness were employed to weld each other
(Figure 3a), in which the ER 70S-6 electrode and the manual metal arc welding method were employed to establish the double V groove butt welding. The rectangular specimens with a size of 20 mm x 12 mm x 8 mm were cut out from the welded steel plate as shown in figure 3b. These rectangular specimens were mounted into the epoxy mode with 2.5 cm in diameter and polished with several poly diamond particles to achieve seven stages of increasing fineness. The preparation of the nanoindentation specimen complied with the ASTM standard [18].

The results from the spherical nanoindentation experiments are shown in figure 4. All the microstructural phases show the loading rate-dependent behavior. It can be recognized that loading speed influences not only the shape but also the magnitude of the loading/unloading curves. When the loading rate increases from 4 mN/s to 28 mN/s, the maximum load shows an increase, while the displacement is kept being constant leading to the increase of loading curvature as illustrated in figure 4.
4. It can be recognized from Equation 3 that indentation hardness is proportional to loading curvature, and hardness tends to increase as presented in figure 5a. Another property, yield strength, also shows the loading rate-dependent behavior. Since the characteristics of the indentation curves in figure 4 can be easily extracted, as a result, the yield strength is well estimated using two non-dimension equations, which show the basic relations between the constitutive parameters and the indentation curves. The results show that yield strength of BM, HAZ, and WM increases with the further increase of loading rate as illustrated in figure 5b. The power formula, $\sigma_y = ae^{bL}$, is then used to describe the mechanical properties-strain rate relationship. It can be seen that this power-law formula is described well the experimental data of yield strength with the change in strain rate indentation.

![Indentation responses from the spherical indenter tip for a) BM, b) HAZ, and WM](image)

**Figure 4.** Indentation responses from the spherical indenter tip for a) BM, b) HAZ, and WM
The hardness model is then employed to estimate the SRS values of BM, HAZ, and WM in the SS400 structural steel weld zone using Equation (8). For this purpose, the plot of the logarithm (Hardness)-logarithm (strain rate) was constructed in figure 5a, as a result, the SRS values of 0.057, 0.052, and 0.045 were well reported for BM, HAZ, and WM, respectively. It can be seen that BM has the highest value of SRS, while the value of WM is lower than those in the SS400 structural steel weld zone. To observe the SRS behavior in the weld zone, the relationship between the SRS and the
minimum yield stress was plotted as shown in figure 6a. It should be noted that the minimum yield stress is estimated from the quasi-static strain rate of 0.0001 s⁻¹. It can be seen that the SRS seems to decrease with a further increase in yield stress. These values of SRS in this study were compared with the general trend reported for structural steel in the literature [1,4,21–25]. The comparison in figure 6b indicates that the present SRS behavior of SS400 structural steel weld zone is in good agreement with those reported in the literature [1,4,21–25].

To demonstrate the accuracy of the present results, the tensile loading experiments on the welded specimens were carried out. The specimen for tensile specimens complied with the ASTM standard [20]. FE analysis is also conducted to simulate the tensile process as shown in figure 8. The input material properties and the SRS behavior of BM, HAZ, and WM used in the FE simulation are presented in figure 7. It should be noted that the FE model considers the SRS behavior by using the yield stress ratio method, and more details of the FE model are carefully illustrated in figure 8. As a result, the comparison of the load-strain curves obtained from both experiments and FE analysis was well constructed as shown in figure 9.

![Elastic/plastic material properties and strain rate sensitivity behavior used in the FE analysis](image)

Figure 7. Elastic/plastic material properties and strain rate sensitivity behavior used in the FE analysis a) BM, b) HAZ, and c) WM
As seen, the applied load-engineering strain curve from FE analysis considering the SRS behaviors of BM, HAZ, and WM closely matches those measured from the tensile loading experiment with a slight difference. The slight difference may come from the imperfection of the specimen in the tensile loading experiment. Furthermore, the average mechanical properties and the average strain rate sensitivity value used in the FE simulation might cause a difference in figure 9. Since the SRS values were obtained from three different series of indentations, as a result, the SRS values of 0.057, 0.052, and 0.045 were reported for BM, HAZ, and WM, respectively. These average values were then employed to consider the influence of strain rate on the constitutive equation of the material as shown in figure 7. Finally, the upper/lower limits of the true stress-true strain data were extrapolated via the experimental data obtained from the indentation results since the indentation testing was performed in the loading rate range of 4-28 mN/s. Although the comparison showed the slight difference of the strain-strain curve, however, the FE results are in good agreement with the experimental data, which demonstrates that the strain rate sensitivity behaviors in the weld zone are valid.

5. Conclusions

In this study, the strain rate sensitivity behavior of the SS400 structural weld zone was investigated by using nanoindentation, tensile experiments, and finite element analysis. The experimental and analysis results support the following conclusions.

1) Loading rate influences on not only the shape but also the magnitude of the indentation curves.

2) Both yield stress and indentation hardness show the loading rate-dependent behavior, in which yield strength tends to increase with the further increase of loading rate.
3) The SRS values of 0.057, 0.052, and 0.045 were well reported for BM, HAZ, and WM, respectively. BM has the highest value of SRS, while the value of WM is lower than those in the weld zone.

4) The relationship between the SRS values and the minimum yield stress was plotted, and SRS seems to decrease with the further increase of yield stress at the semi-static strain rate.

5) The strain rate sensitivity behavior of BM, HAZ, and WM in the weld zone are validated through experimental verification.

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