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Applications of Advanced Indentation Technique to Pre-Qualification and Periodic Monitoring of Strength Performance of Industrial Structures

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Keywords: Advanced Indentation Technique, Tensile Properties, In-Service Inspection (ISI),
Pre-Service Inspection (PSI), Pre-Qualification, Periodic Monitoring

Abstract. The demand for new in-field technology which can non-destructively evaluate the key material properties has been increased for safe and economic operations of industrial structures/facilities whose material properties can be significantly degraded during operation in hostile environments. As a promising method to meet the needs, an advanced indentation technique is suggested here. This novel technique can evaluate the true-stress-true-strain relationship and quantitative tensile properties (such as yield strength, tensile strength and work-hardening exponent) non-destructively by analyzing indentation load-depth curve. In this paper, two recent applications of the indentation technique to pre- and in-service-inspection (PSI and ISI) of industrial structures are introduced and discussed. First, pre-qualification of strength performance of welded joint in power plant pipes is successfully performed using this indentation technique while conventional pre-qualification of welded joints through other non-destructive techniques are just focusing on exact crack detection. Second, it was proved that the advanced indentation technique has the strong potential to be used for in-field periodic monitoring of strength change of oil/gas transmission pipeline, which is required by new regulations for safe maintenance and economical repair.

Introduction

To prevent frequent failure of structural components by time-dependent degradation and a severe operating environment, many kinds of non-destructive testing techniques (NDT), most of which are focused on the detection of crack-type damage and microstructural change, have been developed. However, there has been little NDT technique developed for direct measurement of mechanical property change in industrial field. Although portable hardness testing equipments have provided hardness value in field, the obtained hardness values cannot be applied to mechanical-design-based integrity evaluations which need not the empirical value such as hardness but the exact tensile and fracture properties. It is very clear that, if those kinds of the mechanical properties can be measured non-destructively in field, the accuracy level and reliability of structural integrity will be significantly enhanced. With the similar viewpoints, new regulations have been recently established. For example, US-DOT (Department of Transportation)'s 49 CFR 192 specifies that one set of tensile tests have to be done for each 10 unit lengths of pipe for pipelines of more than 100 pipe lengths [1]. But, conventional standard tests for measuring the mechanical properties such as the uniaxial tensile and the fracture toughness tests, which have the requirements of bulky-sized samples, cannot be used for in-service components and local region such as welded joints, known as critical region of welded structures.

As the most promising NDT for measuring mechanical property in industrial fields, an advanced indentation technique is introduced in this study. This technique, one of instrumented indentation techniques, can measure the tensile properties (including the yield strength, work-hardening exponent and ultimate tensile strength) almost non-destructively by analyzing indentation load vs. penetration depth curve obtained during loading and unloading, without direct observation of indent size as like conventional hardness test. This indentation load-depth curve represents the deformation behavior of the test sample beneath the rigid ball indenter [2]. Additionally, the technique has lots of advantages for in-field applications: (i) the indentation system is portable and easily attached to the components in service, (ii) testing procedure is very simple and does not require tedious specimen preparation, (iii) no damage remains after the tests.

In this paper, two interesting examples of the recent applications are introduced and discussed; First, pre-qualification of strength performance of welded joint in power plant pipes under construction, and second, in-field periodic monitoring of strength change of oil/gas transmission pipeline, which is required by new regulations for safe maintenance and economical repair.

Theory of the advanced indentation technique

As the spherical indenter penetrates into material, mechanical deformation is divided as three stages of elastic, elastic/plastic and fully plastic [3]. A reversible deformation occurs at low load indentation. When the indentation stress fields satisfy the yield criterion, plastic zone occurs inside the material and expands to free surface. And, the mean contact pressure beneath the spherical indenter rapidly increases in this elastic/plastic region. Finally, the expanded hemi-spherical plastic zone grows into the surrounding elastic zone with a constant velocity as the indentation depth increases. The mean contact pressure slightly increases in this fully plastic region. These deformation stages are similar to the work-hardening behavior of the uniaxial tensile test except for non-homogeneity.

Research for predicting the uniaxial flow properties from indentation-induced deformation was performed as described below. The raw data from the advanced indentation test is the indentation load-depth curve as shown in fig. 1.

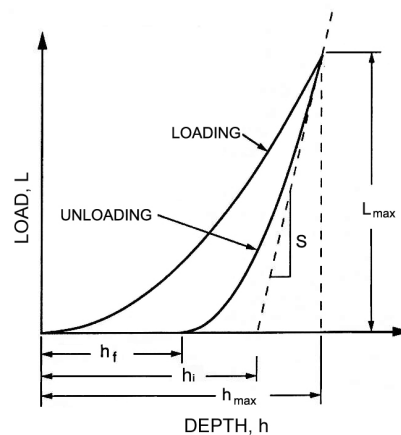


Fig. 1. Schematic graph of the indentation load-depth curve.

The equivalent stress and strain were defined in terms of the measured indentation contact parameters such as contact depth, h_c^* , indenter shape and the morphology of the deformed sample surface. And, real contact properties were determined by considering both the elastic deflection and the material pile-up around the contacting indenter.

First, a contact depth at maximum indentation load can be evaluated by analyzing the unloading curve with the concept of indenter geometry and elastic deflection as shown in Eq. (1) [4].

$$h_c^* = h_{max} - \omega(h_{max} - h_f) \quad (1)$$

where h_i is the intercept indentation depth as shown in Fig. 1 and indenter shape parameter, ω is 0.75 for the spherical indenter. Second, the material pile-up around indentation enlarges the contact radius from the analysis of elastic deflection. The extent of this pile-up is determined by a constant c and the work-hardening exponent, n for steels in Eq. (2) [5, 6].

$$c^2 = \frac{a^2}{a^{*2}} = \frac{5(2-n)}{2(4+n)} \quad (2)$$

where a is the real contact radius and a^* is the contact radius without considering the pile-up around the indent. Using the geometrical relationship of the spherical indenter, the real contact radius is expressed as Eq. (3) in terms of indenter radius, R and h_c^* .

$$a^2 = \frac{5(2-n)}{2(4+n)} (2Rh_c^* - h_c^{*2}) \quad (3)$$

The contact mean pressure, P_m is expressed as Eq. (4).

$$P_m = \frac{L_{max}}{\pi a^2} \quad (4)$$

An equivalent strain, ϵ_R of indentation is defined from the material displacement beneath the indenter along the indentation axis direction. The equivalent strain is expressed in Eq. (5) at the position of the contact radius by multiplying a fitting constant α . The value of α is used as 0.1 for various steels [2].

$$\epsilon_R = \frac{\alpha}{\sqrt{1-(a/R)^2}} \frac{a}{R} \quad (5)$$

In the case of metals including structural steels, the elastic and elastic/plastic deformation stages occurred at very low indentation load. Therefore, we considered only the plastic deformation region in this study. The equivalent stress, σ_R can be evaluated using the relationship with contact mean pressure as shown Eq. (6) [2, 7].

$$\frac{P_m}{\sigma_R} = \psi \quad (6)$$

where ψ is a constraint factor for plastic deformation and the upper limit is about 3 for fully plastic deformation of steels. The exact value of work-hardening exponent, equivalent stress and strain is calculated by iteration process [2].

Both equivalent stress and strain values are determined from the analysis of each unloading curve. The stress and strain relation is fitted as the Hollomon equation expressing work-hardening behavior. The fitted curve was extrapolated to initial yield and ultimate tensile regions. Then, yield strength was evaluated by inputting yield strain to the Hollomon equation. The ultimate tensile strength was evaluated using the concept that uniform elongation is equal to work-hardening exponent [8].

Experimental conditions

A portable instrumented indentation system, AIS-2000TM (Frontics, Inc., Seoul, Korea) was used in this study for measuring tensile properties in field. Generally, 15 times loading-unloading sequences were made at 0.3 mm/min. During indentation, load-displacement curves were continuously obtained and converted to true stress-true strain curves.

The applied accuracy of the sensors used was 300 gf for load and 0.2 μm for displacement. The LVDT is installed next to the indenter. The spherical WC indenter was an integrated part of the WC stem which makes it possible to eliminate brazing of the WC indenter to the steel stem. With this type of arrangement, the system compliance can be minimized. Since unreliable attachment of the system to the pipeline could result in significant errors in load and displacement measurements, a pair of curved magnets, along with mechanical chain or u-block, were used to firmly attach the system to the pipe against the maximum load.

Results and Discussion

Application to Pre-service Inspection (PSI). In general, mechanical properties of weld joints have been evaluated by only procedure qualification records (PQR), in which tensile tests at laboratory were made using sample specimens with the same welding conditions as in-field. But it is difficult for PQR to consider various constrain conditions and environments of in-field weldments during construction. Therefore advanced indentation tests were applied to inspect the strengths of pipeline welded joints non-destructively at the fossil power plant under construction.

The indentation system was attached and could obtain indentation load-depth curves of each local regions including weld metal, heat affected zone(HAZ), and base metal. Tested materials was ASTM A335 P91 pipeline steel with chemical composition of 0.1C - 0.3Si - 0.4Mn - 0.02 P- 0.4Ni - 9Cr - 1Mo - 0.2V - 0.05N. Considering grain size and thickness of pipeline, spherical indenter with 0.5mm diameter was used, and indentation loads with multiple loading-unloading cycles were applied to the materials at the speed of 0.3 mm/min up to maximum indentation depth of 0.3 mm. Also several indentations were performed in array from weld metal through HAZ to base metal to analyze local strengths distributions.

In fig. 2(a) and (b), indentation load-depth curves and the indentation-derived flow curves were shown. Yield strengths and ultimate tensile strengths increased in order of base metal, HAZ, and weld metal as shown in Table 1. Also load-depth curves had the same trend of strengths distributions since indentation loads for indenting to constant depth (0.3mm) increased with the same order. On the other hands, the strengths of HAZ had the sudden changes with testing positions although the strengths of weld metal and base metal were almost constant individually. It means that HAZ had various types of microstructures during multi-pass welding.

The obtained tensile properties were compared with PQR, in which the reported strength was tensile strength of weld joint specimen and fracture occurred in base metal, in Table 1. It was found that the strengths of base metal were different with PQR value significantly.

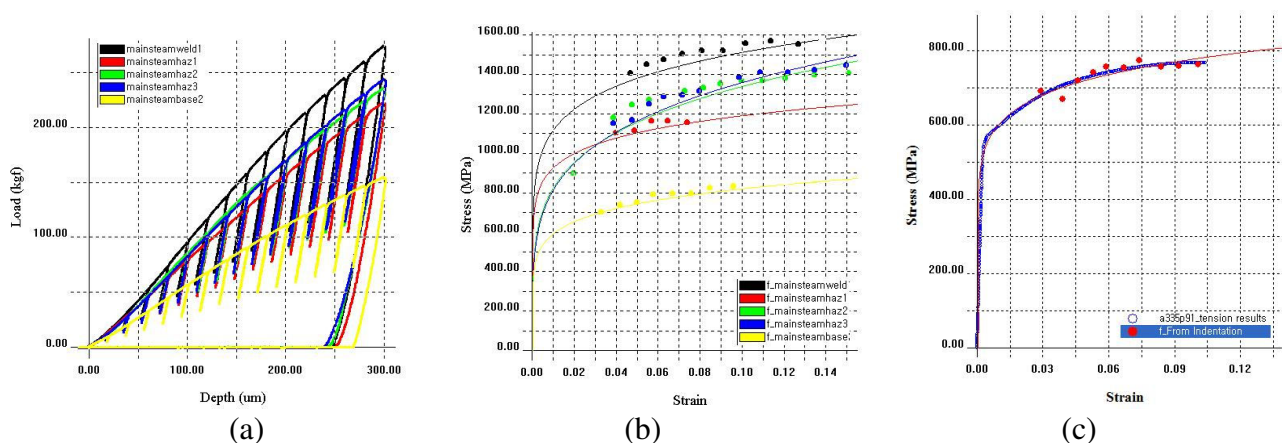


Fig. 2. Indentation for A335 P91 pipeline in fossil power plant; (a) indentation load-depth curves, (b) Indentation-derived flow curves of weld metal, HAZ and base metal, and (c) comparisons of flow curves from uniaxial tensile test (thick line) and indentation test (solid circle and thin line).

Table 1. Indentation-derived tensile properties of ASTM A335 P91 pipeline.

Position	YS[MPa]	UTS[MPa]	PQR strength [MPa]
Weld(Average)	1128(±80)	1501(±104)	1041 1031
HAZ 1	927	1175	
HAZ 2	826	1417	
HAZ 3	815	1455	
Base(Average)	598(±35)	810(±57)	

To verify the reason, the base metal of tested position was cut and machined to standard tensile test specimen, and tensile tests were also performed in accordance with ASTM E8. Also indentation tests were made on the same specimen for comparison. Tensile curves obtained from two testing methods were shown in fig. 2(c). From uniaxial tensile test, yield strength and ultimate tensile strength were 568 MPa and 769 MPa, respectively as average values of 3 tests. They agreed well with indentation-derived yield strength and ultimate tensile strength of 577 ± 12 MPa and 780 ± 26 MPa in laboratory, and also were very similar with 598 ± 35 MPa and 810 ± 57 MPa in field during being attached to pipeline. From the results, it was concluded that indentation could be used effectively as a direct inspection method of welded joint considering various in-field environments and constraint factors.

Application to In-service Inspection (ISI). As one of NDT methods to satisfy the requirement of the new regulation of US-DOT (department of transportation) mentioned before [1], the advanced indentation technique was used. Tested pipeline material for the verification of applicability was API-X60-graded pipelines of outer diameter 762 mm and thickness 17.5 mm, which are generally used as natural gas transmission pipelines. The chemical composition of the material is 0.08C – 0.31Si – 1.45Mn – 0.019P – 0.003S. Because the pipeline has been used for over 15 years, it could be affected by the various environmental conditions such as corrosion, mechanical shock, and other material degradation factors by long-term operation. Accordingly, materials could have mechanical properties different from those of new materials. To inspect the safety and the degree of degradation of this old pipeline, the indentation technique was applied. Main purpose of in-field application in this work was to verify whether the pipeline meets the minimum strength requirements (YS: 413 MPa, UTS: 517 MPa) on the mill sheet.

Considering microstructure variations in the pipe, 3~4 indentations were made and averaged tensile properties were obtained. The distance between indentation marks was 3 mm to avoid the superposition of plastic deformation fields. In this case, the spherical indenter with diameter 0.5 mm was used, and indentation load was applied to make the maximum depth of 0.15 mm with the same loading rate and multiple cycles.

The results from the advanced indentation method were shown in fig. 3(b). Yield strengths in weld metal were lower than those in HAZ and base metal, but all strengths in base metal met the requirement of minimum specifications of API X60. Also the strengths were not different significantly with those from a new API X60 pipeline. Fig. 3(c) shows the comparison between indentation-derived flow curve and uniaxial tension curve of a new API X60 pipeline. It was found that indentation stress-strain points agreed well with tensile test results. However, API X60 had Lüders strain as inhomogeneous yielding phenomena after elastic deformation. At that case, Lüders strain has to be added to pre-determined indentation yield strain as shown in fig. 3(c) to determine yield strength from indentation-derived flow curve. Lüders strain values could not be directly determined by indentation load-depth curve because it could be evaluated only through the residual indent observation with optical microscope [9]. Actually, all the yield strengths in this study were evaluated by considering yield strain with Lüders strain correction of 2 %. From the results, it was concluded that the pipeline could be operated continuously in terms of mechanical properties.

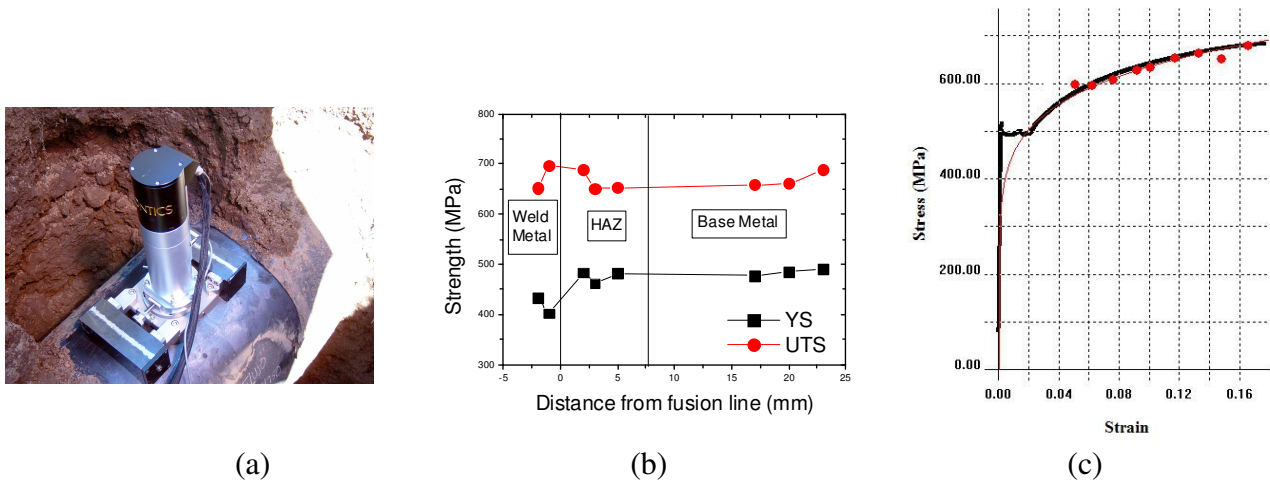


Fig. 3. Indentation results of API X60 pipeline under ground; (a) testing equipment attached to pipeline, (b) strength distributions of the pipeline along with the distance from fusion line, (c) flow curves (solid circle and thin line) compared to the uniaxial tension curve with Lüders strain (think solid line) for new API X60 in laboratory.

Concluding remark

In this study, the two interesting examples proving in-field applicability of newly developed indentation technique were introduced; (1) pre-qualification of strength performance of welded joint in fossil power plant pipes under construction, and (2) in-field periodic monitoring of strength change of oil/gas transmission pipeline. The true stress-true strain curves of the pipelines, especially their welded joint, were obtained based on the analysis of equivalent stress and strain considering the deformation behavior beneath the spherical indenter and indentation stress field. From the results, it can be understood that the technique is very useful for both PSI and ISI, and thus it is hoped that this work will be valuable in providing a better direction of structural integrity evaluation to related industry.

Acknowledgement

The authors with Seoul National University (Y. Choi and D. Kwon) wish to thank the Korean Ministry of Science and Technology for providing financial support for this work under the National Research Laboratory (NRL) Program.

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