

INFLUENCES OF HYDROGEN ON THE MECHANICAL BEHAVIOR OF WELD HEAT-AFFECTED ZONE IN API STEEL PIPELINE

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Abstract: To prepare the up-coming era of so-called ‘hydrogen economy,’ many researches on the related infrastructures are actively conducted around the world. One of the important issues on the topic is hydrogen transmission. Recently, the use of existing natural gas pipeline is often considered as an cost-effective way of hydrogen transmission. However, while much researches have been performed on the possible hydrogen effects on the mechanical performance of pipeline steels, few study has been reported for the influence of hydrogen on the mechanical behavior of their weld heat-affected zone (HAZ), that is well known to be the weakest in the pipeline. In the present study, various HAZs are simulated, and the hydrogen effects on their mechanical behavior were systematically investigated through indentation, tensile tests, and impact tests.

Keywords: Heat-affected zone, hydrogen embrittlement, nanoindentation, pipeline steel

Facing the 21st century’s major energy-related problems arising from non-renewable nature of fossil fuels and serious environmental pollutions, recently the demands for the use of hydrogen as alternative main energy have been explosively increased. To meet the demands and prepare the up-coming era of so-called ‘hydrogen economy,’ many researches focused on the related topics are actively conducted all around the world.

With a viewpoint of industrial field applications, one of the important topics being studied is an issue of hydrogen transmission (more specifically, ‘hydrogen pipeline’). Today, hydrogen is being transported primarily by railroad cars, cryogenic liquid trucks, gaseous tube trailers, tanker ships and a limited amount of hydrogen pipelines. Among them, pipeline is conceivably the most economic way to consistently and safely transport a large amount of hydrogen over a long distance, which may be strongly requested in hydrogen economy era.

Although hydrogen pipelines have already been operating over the past 50 years, they are still very limited. Construction of a new pipeline system is so expensive that research in peripheral equipment, sensors, control systems, etc. is needed to reduce the cost. It was reported that if the

ratio of hydrogen added to natural gas is less than 30%, use of the existing natural gas transmission pipeline is possible [1]. In this sense, many efforts have been made to examine the possibility of hydrogen induced mechanical degradation (such as hydrogen embrittlement) in the natural gas pipeline steels. However, few study has been focused on the influence of hydrogen on the mechanical behavior of weld heat-affected zones (HAZs) in the steels pipeline, although the HAZs are generally known to be the most brittle region due to both a rapid gradient of microstructures and unusual mechanical environments (such as welding residual stresses and strength mismatch between weld metal and base metal) [2].

In the present study, we produced simulated HAZ specimens with various peak temperatures considering multi-pass welding condition, and investigated the hydrogen effect on deformation and fracture behavior of base metal and simulated HAZ specimen through nano-/macro-indentation test, tensile test, and Charpy impact toughness test.

The material examined in this work is API X70 steel whose chemical composition is Fe-0.08C-1.55Mn-0.25Si-0.25Cu-0.2Ni-0.03Al-0.04Nb-0.03V-0.014Ti-0.004N in weight %. The critical temperatures A_{C1} and A_{C3} were calculated to 732 °C and 887 °C, respectively, according to the empirical formula of Andrew [3].

To simulate various HAZ specimens, the thermal cycle treatment was performed on specimens through a Gleeble1500 thermo-mechanical simulator. During first thermal cycle with a heating to peak temperature (T_{P1}) of 1350 °C at a linear rate of 100 °C/s, the coarse grained HAZ (CGHAZ) is simulated. Then, the specimens were cooled down to 800 °C at a linear rate of 24 °C/s and from 800 to 500 °C for 18 s corresponding to the cooling time of a girth weldment with a heat input of 30 kJ/cm in 17 mm thick plate. According to the peak temperature of subsequent thermal cycle (T_{P2}) in multi-pass welding procedure, the CGHAZ can be divided again into four characteristic regions: Unaltered (UA) CGHAZ with $T_{P2} > 1100$ °C, supercritically-reheated (SCR) CGHAZ with 1100 °C $> T_{P2} > A_{C3}$, intercritically-reheated (IC) CGHAZ with $A_{C3} > T_{P2} > A_{C1}$, and subcritically-reheated (SC, or tempered) CGHAZ with $A_{C1} > T_{P2} > 450$ °C [2].

Among them, SCR CGHAZ can be treated as FGHAZ due to its recrystallized fine grain, while SC CGHAZ is often considered as the same as UA CGHAZ since toughness and microstructure of the former are usually very close to those of the latter. IC CGHAZ is generally considered as a primary local brittle zone (LBZ) because it exhibits very low toughness due to a large portion of martensite-austenite (M-A) constituent in addition to the coarse bainite structure

The surface of as-received and simulated HAZ specimens were mechanically polished with fine SiC paper of grit number 2000 and then electrolytic-polished using Lectropol-5 instrument (Struers, Westlake, OH) in a solution appropriate for steel (ethanol 80%, distilled water 14%, perchloric acid 6%) at room temperature [4]. Specimens were etched with 3% Nital solution for an observation of microstructure by optical microscope.

For measuring macroscopic hardness, a Vickers pyramidal indenter with an indenting load of 9.8 N was applied to the electrolytic-polished specimen that had been subjected to heat cycle. Nanoindentation tests also were carried out to obtain nanohardness using a Nanoindenter-XP (MTS Corp., Oak Ridge, TN) with a three-sided pyramidal Berkovich tip. During the test, the sample was loaded up to the peak load of 5mN under a constant strain rate of 0.05 /s. The tip calibration and the hardness calculation were conducted in accordance with the Oliver-Pharr method [5].

Tensile tests were performed at room temperature using round tensile specimens with a gage diameter of 6 mm and a gage length of 28.6 mm. Specimens are loaded until fracture occurred with a crosshead speed of 0.12 mm/min [6]. And Charpy V-notch impact tests were carried out on the standard V-notch specimens ($10 \times 10 \times 55 \text{ mm}^3$) at different temperatures according to ASTM E23-06 [7]. After Charpy test, fracture morphology of all tested specimens was investigated with scanning electron microscope (SEM).

To investigate the hydrogen effect, we injected hydrogen into both of the electropolished base and simulated HAZ samples by cathodic charging in a 1 N $\text{H}_2\text{SO}_4 + 0.25 \text{ g/L As}_2\text{O}_3$ solution [8]. The charging was made for 24 h under a constant current density of 100 mA/cm². Mechanical tests mentioned above (Vickers hardness, nanoindentation, tensile test, and Charpy impact test) were performed with same testing conditions just after hydrogen charging to minimize the leakage of hydrogen from the samples. In the case of macro-/nano-hardness measurement, since the results are strongly depends on the surface roughness, indentation tests were performed on the surface after gentle polishing.

We will present, at the conference, the analysis of experimental results mentioned above (microstructure, hardness, tensile properties, and fracture toughness and morphology) and the effect of hydrogen on the microstructural and mechanical behavior in as-recieved and simulated HAZ API-X70 steels.

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