Effect of Microstructure on Fracture Toughness of Linepipe Steels in 21MPa Gaseous Hydrogen

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ABSTRACT

Linepipe manufactured from the plates rolled by the Thermo-Mechanical Controlled Processing (TMCP) have been giving tremendous benefit in obtaining higher strength and superior toughness. ASME B 31.12-2019 “Hydrogen Piping and Pipeline” is a current design code for a hydrogen pipeline, and low carbon Nb microalloyed TMCP steels with homogeneous fine grain microstructure are recommended in Non-Mandatory Appendix G. In this study, the effect of microstructure on fracture toughness in 21MPa gaseous hydrogen was investigated. The results show that bainitic steel that meets Appendix G exhibited excellent fracture toughness, while the ferrite-pearlite steel simulating a lower grade old pipe steel had inferior fracture toughness.

KEY WORDS: hydrogen embrittlement; linepipe; SSRT; fracture toughness.

INTRODUCTION

Pipeline transportation systems were introduced to improve the efficiency of oil transportation and have gradually expanded their transportation media. In particular, pipelines play a significant role as a system for the mass transportation of natural gas. Demand for hydrogen is expected to increase in the future to achieve carbon neutrality. Regarding the transportation of hydrogen using pipelines, it is predicted that 23000 km of hydrogen transportation pipelines will be established in Europe by 2040, of which 75% will be converted from natural gas pipelines (Enagás et al., 2020). Low alloy steels may deteriorate their mechanical properties under hydrogen environment due to hydrogen embrittlement. For linepipe steel, for example, it has been reported that fracture toughness deteriorates in high pressure gaseous hydrogen (Robinson et al., 1981; Cialone et al., 1988). It is important to clearly understand fracture properties of linepipe steel in hydrogen because the failure of pipe can lead to serious damage to pipeline system. Ronevich et al. have reported that fracture toughness in 21 MPa gaseous hydrogen tends to deteriorate with increasing yield strength, including results from previous literature (Ronevich et al., 2021). On the other hand, in Marchi et al.’s study using linepipe steels with strength of X60 and X80 grades, the higher strength material had better fracture toughness in 5.5 MPa and 21 MPa hydrogen gas (Marchi et al., 2010). These different tendencies suggest that there are other factors other than strength that govern fracture toughness. In other words, the fracture toughness would change if the microstructures were different. A relatively simple method for evaluating material properties in hydrogen environment is a slow strain rate tensile (SSRT) test according to ASTM G142 (“Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both”; ASTM, 2022a). SSRT can be broadly divided into two methods: one is performed in a hydrogen gas environment (Nguyen et al., 2020), and the other is a cathode-charging method, in which a desired amount of hydrogen is added to steel by controlling voltage and other factors using an aqueous solution containing ammonium thiocyanate, which promotes hydrogen entry. For conventional cathodic charging, SSRT was performed after hydrogen was introduced into the specimen beforehand by electrochemical charging and then electroplated to prevent hydrogen release (Wang et al., 2005). Therefore, specimens with uniform hydrogen distribution were subjected to SSRT in air. On the other hand, in recent years, there have been studies in which SSRT was performed while cathode-charging to simulate continuous hydrogen entry in a high-pressure gas atmosphere (Tsurumi et al., 2018), but there have been few applications in linepipe steel.

ASME B 31.12 is a current design code for a hydrogen pipeline (“Hydrogen piping and pipelines”; ASME, 2019). Regarding the material selection for hydrogen pipeline, low carbon Nb microalloyed thermomechanical controlled processing (TMCP) steels with a fine grained microstructure and small center segregation index are recommended in Non-Mandatory Appendix G of ASME B31.12. It has been reported that steel with fine grains has excellent fatigue performance in 21 MPa gaseous hydrogen, which is the upper limit pressure prescribed by ASME B31.12 (Stalheim et al., 2020). However, many of the microstructure of old pipes manufactured before TMCP technology was established consists of coarse ferrite-pearlite structure with lower strength (Slifka et al., 2018). As for the mechanical properties...