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The Role of Martensite and Delta Ferrite in the Austenitic Stainless Steel Weldments

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Hydrogen embrittlement for SUS316L weld metal is investigated in this work by analyzing the failure mechanism of slow strain rate tensile specimens tested in a high-pressure hydrogen environment. Tungsten inert gas (TIG) weld metal (WM) specimens, which showed delta ferrite and austenite in the microstructure, were pre-strained in the helium environment at 4 K to induce α-martensite before testing in hydrogen. Shielded metal arc welding (SMAW) and submerged arc welding (SAW) WM specimens were tested in the condition of the most severe case, without pre-strain, to clarify the participation of martensite and delta ferrite in the loss of ductility and in the failure process induced by hydrogen. The degradation and failure modes were assessed using a scanning electron microscope, electron back scattered diffraction, and energy-dispersive x-ray spectroscopy. The loss of ductility by the hydrogen embrittlement (HE) at low temperatures was more significant on the TIG WM specimens, and this was mainly promoted by a higher content of delta ferrite and martensite, which served as paths for the hydrogen to induce crack propagation in a quasi-cleavage pattern. Delta ferrite and martensite competed to cause higher degradation in the TIG WM, with delta ferrite being the predominant crack path, and α-martensite as a booster of the HE. SMAW WM showed a better HE resistance, which can be related to the lower Md30 temperature and the negligible presence of delta ferrite.

INTRODUCTION

Hydrogen storage systems are required by society's carbon-neutral goals. In Japan and other countries, there is an interest in storing a huge amount of hydrogen using less space in the most efficient and cost-effective way. Large liquified hydrogen storage tanks or a combination of liquid hydrogen and compressed hydrogen gas storage systems can be a feasible solution, as mentioned in Andersson and Grönkvist (2019) and Rong et al. (2023). However, it is challenging to store a huge amount of hydrogen using carbon steel since very low-temperature conditions and the hydrogen embrittlement phenomenon pose difficulties in this process.

To make this possible, an assessment of commercial steels has been conducted. Investigation of hydrogen embrittlement (HE) in the material needs to consider the behavior of different microstructures as well as the chemical compositions. Moreover, the cryogenic temperature requires a material with excellent toughness. Taking this into account, this project considers the SUS316L as the first candidate for the cylindrical type of large liquefied hydrogen storage tank, as mentioned in Kawabata (2023).

This steel and its welded joints were assessed before for the same purpose by Horiya et al. (1996), and many studies have investigated it in different ways (Herms et al., 1999; Fukuyama et al., 2003; San Marchi et al., 2008; Michler et al., 2009; Jackson et al., 2012; Michler et al., 2015; Álvarez et al., 2023; Park et al., 2023; Yun et al., 2023). Fukuyama et al. (2003) showed that HE susceptibility changes for the 316 series austenitic stainless steels according to the test temperature. As the temperature increases from –253°C to −50°C, the hydrogen embrittlement becomes more prominent, as shown in Fukuyama et al. (2003) and Park et al. (2023). Furthermore, Michler and Naumann (2008) reported the importance of Nickel (Ni) content and the homogeneous distribution of elements in the HE resistance. However, the increase in Ni concentration in the steel makes it more expensive. Thus, it is important to identify the root cause of the HE to allow the application of cheaper materials in these kinds of storage systems.

When the SUS316L is subjected at very low temperatures to large plastic strain, transformation-induced plasticity (TRIP) occurs, promoting the transformation of austenite, a face-centered cubic (FCC) cell structure, into martensite, a body-centered tetragonal (BCT) cell structure. A more detailed explanation for this transformation process can be found in Li et al. (2024). The relationship between martensitic transformation and hydrogen embrittlement was indicated by Izawa et al. (2019), while by Michler et al. (2012), TRIP was not enough to be considered as the cause of HE. Nevertheless, TRIP raises concerns about HE. Depending on the welding process, its parameters and consumables, austenitic stainless steels (ASS) weld metal (WM) can experience the TRIP phenomenon when subjected to plastic deformation at low temperatures.

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