Effect of temperature on mitigation of hydrogen embrittlement by oxygen

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Hydrogen embrittlement (HE) is a degradation of material strength caused by the presence of hydrogen. In HE of steels exposed to gaseous H_2, the initial step involves the dissolution of hydrogen into the material. The dissolution process includes the dissociation of hydrogen molecule into hydrogen atoms facilitated by the catalytic action of the iron (Fe) surface. Therefore, when H_2 gas contains certain gas impurities such as oxygen (O_2) and carbon monoxide (CO) that can deactivate the catalytic action of Fe surface, hydrogen uptake into the material is suppressed, leading to mitigation of HE.

If this mitigation effect can be practically implemented, it will improve the safety and reduce the cost of hydrogen equipment. However, achieving this requires a comprehensive understanding of the details of the mitigation effect. As the HE mitigation by gas impurities involves surface chemical reactions, it should be affected by temperature. Therefore, this study investigated the effect of temperature on HE mitigation by O_2. To fulfill it, fracture toughness tests of a low-alloy steel SCM440 were carried out in H_2, H_2 containing 10 or 100 vppm O_2, and N_2. The gas pressure was 1 MPa. The crosshead speed, which is the loading rate, was 2.0×10^{-3} mm. The temperature was 20°C and 4°C. 4°C was assumed the temperature of the submarine pipeline.

In the absence of O_2, the HE in H_2 gas became more significant as the temperature decreases from 20°C to 4°C. The temperature reduction suppresses hydrogen permeation and diffusion, resulting in the mitigation of HE. Also, the decrease in the temperature increases the occupancy of trap site for hydrogen, thereby enhancing the HE. Under the given tenting conditions in this study, the enhance effect became more apparent, resulting in the enhancement of the HE with the decrease in the temperature.

The addition of more than 10 vppm O_2 to H_2 gas completely prevented the HE at 4°C, whereas the addition of 100 vppm O_2 only partially mitigated the HE at 20°C. The temperature reduction enhanced the O_2 mitigation effect. The H_2 adsorption on Fe surface, which involves an activation barrier, is temperature-dependent, whereas O_2 adsorption on Fe surface, which is without an activation barrier, remains unaffected by temperature. Consequently, the decrease in the temperature solely decreases the H_2 adsorption. Furthermore, the increase in the activation barrier for H_2 adsorption due to the presence of O_2 heightens the temperature dependence of H_2 adsorption. Through these dual mechanisms, the decrease in the temperature enhances the O_2 mitigation effect.