

Evaluation Method for Hydrogen Embrittlement under Atmospheric Corrosion Environments, HeTsACE™

1. Introduction

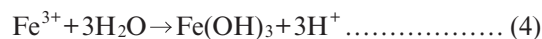
In the automotive field, high-strength steel sheets have been widely applied to improve crash safety and reduce vehicle weight. However, one of the issues associated with their application is hydrogen embrittlement (delayed fracture). Although it is well known that the factors causing hydrogen embrittlement are material strength, applied stress and hydrogen content, the amount of absorbed hydrogen under actual automobile moving environments remained unclear. To address this issue, JFE Steel developed an innovative hydrogen absorption monitoring system to quantitatively measure the absorbed hydrogen in actual environments¹⁾.

This report presents the development of an evaluation method for hydrogen embrittlement, HeTsACE™ (Hydrogen embrittlement Test to simulate Actual Corrosion Environment), which reproduces the occurrence of hydrogen embrittlement under actual environmental conditions in a laboratory setting, based on the hydrogen concentration obtained using the aforementioned hydrogen monitoring system.

2. Concept of the Hydrogen Embrittlement Evaluation Method

2.1 Mechanism of Hydrogen Absorption in Steel under Atmospheric Corrosion Environments

Automotive body parts are generally painted, but due to chipping and gradual degradation of the paint coating over time, portions of the steel sheet are exposed to corrosive environments. Corrosion reactions occur when moisture and chlorides, which act as corrosive agents, adhere to the exposed steel surface. In bare steel, the fundamental reaction steps involved in these processes are as follows:



Iron ions generated by the dissolution reaction of iron, as shown in Eq. (1), undergo the oxidation reaction described in Eq. (3), followed by the hydrolysis reaction in Eq. (4), during which hydrogen ions are produced in the process of rust formation. These hydrogen ions are then reduced to hydrogen atoms via the cathodic reaction in Eq. (5) and adsorb on the steel surface, and a portion of those atoms are subsequently absorbed into the steel sheet.



Here, H_{ad} denotes the hydrogen atoms adsorbed on the steel surface, and H_{ab} indicates the hydrogen atoms absorbed into the steel sheet.

The hydrolysis reaction shown in Eq. (4), which produces hydrogen ions, is accelerated by Fe^{3+} species existing as chloro complexes when the chloride ion concentration increases²⁾. In actual corrosion environments, the chloride ion concentration increases when a thin water film forms as the relative humidity of the atmosphere approaches the deliquescence humidity of the deposited salts. This means that hydrogen generation in atmospheric corrosion environments is influenced by factors affecting the moisture amount, the temperature (which governs the reaction rates), and the extent of salt deposition, which accelerates the hydrolysis reaction contributing to hydrogen production.

2.2 Evaluation Test Conditions for Hydrogen Embrittlement

Based on the hydrogen absorption mechanism described in Section 2.1, a hydrogen embrittlement evaluation method, HeTsACE™, was developed to simulate actual environments by controlling the factors that influence hydrogen generation under the test conditions.

Figure 1 illustrates the test cycle, which includes a high-humidity stage that promotes corrosion of the

[†] Originally published in *JFE GIHO* No. 57 (Feb. 2026), p. 102–104

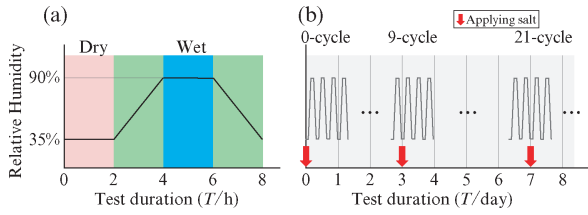


Fig. 1 Test cycle of HeTsACE™ (a) 1 cycle (b) 1 week

steel sheet and a drying stage during which the water film disappears. The test cycle also includes an appropriate humidity transition process to induce the hydrolysis reaction associated with the formation of a thin water film during the transition between the wet and dry stages. The temperature is maintained constant throughout the test duration, and salt deposition is controlled by applying a fixed amount of salt twice weekly after washing the steel surface with water. These conditions were found to create a hydrogen embrittlement environment consistent with the hydrogen absorption mechanism.

3. Behavior of Hydrogen Absorption under HeTsACE™ Test Conditions

3.1 Effect of Temperature and Salt Load

To investigate the hydrogen absorption behavior in HeTsACE™, 1 470 MPa grade martensitic steel was used, and changes in the hydrogen permeation current were measured using the hydrogen monitoring system¹⁾. **Figure 2** shows the typical time variation of the hydrogen permeation current in one cycle under conditions of 30°C and a salt deposition amount of 3 g/m². Two current spikes were observed at times corresponding to changes in humidity. This observation suggests that, as described in Section 2.1, the formation of a thin water film led to an increased chloride ion concentration, which accelerated the hydrolysis reaction and generated a larger amount of hydrogen ions, thereby increasing hydrogen absorption in the steel sheet.

To investigate the effects of temperature and salt load on hydrogen absorption, the maximum amount of absorbed hydrogen was measured under three temperature conditions and three salt deposition levels during a 4-week test period. The amount of absorbed hydrogen was calculated from the hydrogen permeation current using Eq. (7), which is based on Fick's diffusion equation.

$$C_{ab} = \frac{J_{max} \cdot L}{D \cdot F \cdot d} \dots \dots \dots (7)$$

Here, C_{ab} represents the amount of absorbed hydrogen (ppm), J_{max} is the maximum hydrogen permeation

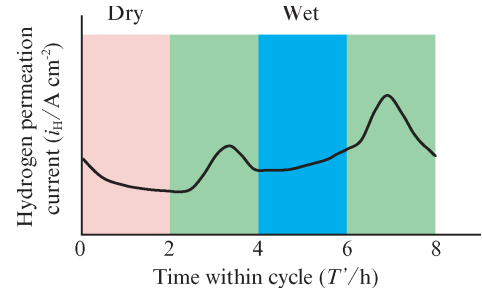


Fig. 2 Changes in hydrogen permeation current within a cycle of HeTsACE™

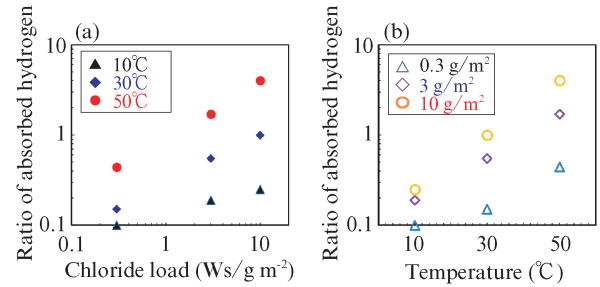


Fig. 3 Influence of environmental factors on amount of absorbed hydrogen (a) Chloride load (b) temperature

current during the test period, D is the hydrogen diffusion coefficient, F is the Faraday constant, and d is the density of the steel sheet. **Figure 3** shows the ratio of the hydrogen amounts normalized to the value obtained under the conditions of 30°C and a salt deposition amount of 10 g/m². As shown in the figure, consistent with the hydrogen absorption mechanism described in Section 2.1, the hydrogen content increased with increasing salt deposition and temperature. These results demonstrate that testing by the HeTsACE™ method can reproduce hydrogen absorption behavior consistent with the mechanism observed in atmospheric corrosion.

3.2 Comparison of Hydrogen Absorption Amounts with Behavior in Actual Environments

Field exposure tests were conducted at three locations with distinct climatic characteristics: Ishikari City in Hokkaido, Kasaoka City in Okayama (Setouchi region), and Uruma City in Okinawa. Hydrogen monitoring systems were installed at each site. The test period was one year, during which the steel specimens were periodically retrieved to measure the amount of salt deposition on their surfaces. The maximum hydrogen amount obtained during the test period was calculated, and the temperature and salt load at the time of this maximum value were correlated. The hydrogen concentrations obtained from the field exposure tests were then compared with those obtained in the HeT-

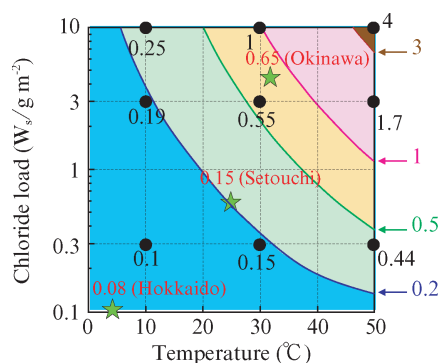


Fig. 4 Influence of environmental factors on amount of absorbed hydrogen

sACE™ tests. **Figure 4**, which is based on the results shown in Fig. 3, illustrates the influence of environmental factors on hydrogen absorption in atmospheric corrosion environments. The numbers annotated with the ● symbol in the figure indicate hydrogen absorption ratios obtained from HeTsACE™. Contour lines of the hydrogen concentration as functions of the temperature and salt load can be drawn based on these results. The hydrogen absorption ratios obtained from the field exposure tests are indicated by ★, and show good agreement with the results obtained from HeTsACE™. Based on these results, the developed hydrogen embrittlement evaluation method HeTsACE™ demonstrated hydrogen absorption behavior consistent with the actual hydrogen absorption mechanism and accurately reproduced the hydrogen concentration corresponding to the temperature and salt deposition levels

in the actual environments. Thus, HeTsACE™ provides a means of replicating the hydrogen embrittlement characteristics observed under actual conditions in a laboratory setting.

4. Conclusion

The hydrogen embrittlement evaluation method HeTsACE™ introduced here is characterized by the ability to experimentally reproduce the hydrogen absorption factors of corrosive environments in a laboratory setting. Therefore, this method can be applied not only to cold-rolled steel sheets but also to Zn-coated steel sheets and other types of metals. Accurate evaluation of hydrogen embrittlement characteristics is expected to support expanded application of ultra-high-strength steels to automotive bodies, contributing to vehicle weight reduction and improved crash safety.

References

- 1) Ootsuka, S.; Mizuno, D.; Matsuzaki, A. Development of Monitoring System for Hydrogen Absorption into Steel Under an Actual Vehicle Environment. *JFE GIHO*. 2018, no. 41, p. 62–67.
- 2) Omura, T.; Kushida, T.; Kudo, T.; Nakasato, F.; Watanabe, S. Environmental Factors Affecting Hydrogen Absorption into Steels. *Zairyo-to-Kankyo*. 2005, vol. 54, no. 2, p. 61–67

For Further Information, Please Contact:

Corrosion Evaluation & Analysis Center, Materials Characterization & Analysis Division, JFE Techno-Research Corporation
Phone (81) 44-322-6206 FAX (81) 44-322-6528