Effect of hydrogen on creep properties of SUY-1 pure iron

Kentaro Wada[1], Ryosuke Komoda[1,2], Toshihiro Tsuchiyama[1,3] Arnaud Macadre[1,4]
Masanobu Kubota[1], Petros Sofronis[1,5], Mohsen Dadfrnia,[1,6], Aleksandar Staykov[1]
Cynthia A. Volkert[1,7], Reiner Kirchheim[1,7], Lin Tian[7]

[1] I2CNER, Kyushu University
[2] Kyushu Institute of Technology
[3] Dept. Mater. Sci., Kyushu University
[4] Yamaguchi University
[5] University of Illinois at Urbana Champaign
[6] Seattle University
[7] University of Gottingen

Abstract

High temperature hydrogen technologies such as SOEC, SOFC, hydrogen gas turbine, hydrogen boiler, hydrogen internal combustion engine and so on, are being developed to achieve carbon neutrality by 2050. When structural materials are subjected to high-temperature hydrogen, understanding of the degradation of structural materials under ambient conditions is not enough. Particularly, creep deformation dominates the failure of materials at high temperature. The objective of this study is to characterize the hydrogen effect on the creep properties of pure iron and elucidate the mechanisms of how hydrogen affects creep deformation. This study will be done within the framework of an interdisciplinary and international collaboration between I2CNER and the University of Gottingen with the financial support by JRP-LEAD with DFG program.

The material was JIS SUY-1 industrial pure iron. Although this material is not used for the advanced high-temperature hydrogen technologies, its simple chemical composition and pure single phase may facilitate considerations about the mechanism.

Creep testing was carried out in argon and hydrogen gases at 873 K. The absolute gas pressure at which the creep tests were performed was 0.12 MPa. The hydrogen concentration in the specimen at the relevant conditions was estimated to be 0.70 mass ppm with reference to Yamabe et al [1].

Hydrogen accelerated the minimum creep strain rate, resulting in a significant reduction in the creep life over the entire stress range in which we carried out the experiments. The fracture profiles and fracture surfaces were examined to consider the mechanism of the hydrogen effect. It was found that the fracture profile was double cup fracture for both environments, and the fracture surface morphology was dimples for both argon and hydrogen environments. These observations provided very important confirmation that hydrogen doesn’t change the creep deformation mechanism but

accelerates the deformation. In addition to the examinations of the fracture profiles and fracture surface, the analysis of the creep life based on the minimum creep strain rate clarified that the creep life was dominated by the minimum strain rate, $\dot{\varepsilon}$, regardless of the environment. In other words, the relationship between $\dot{\varepsilon}$ and creep life is the same in hydrogen and argon. This also supports the assertion that hydrogen accelerates the deformation without changing the creep deformation mechanism.

According to the creep deformation mechanism map produced by Frost and Ashby [2], the creep deformation mechanism in these experiments was estimated to be power-law creep. In the power-law creep region, the creep strain rate is analytically formulated in terms of the applied stress. The analysis of our creep data based on that expression showed that a plausible role of hydrogen was to decrease the creep activation energy. Interestingly, this inference for the BCC steel is the same for an FCC steel in another of our experiments [3].

Creep deformation in the power-law creep region is dominated by dislocation climb, in which vacancy diffusion takes an important role. According to the literatures, hydrogen reduces vacancy formation energy in alpha iron [4,5]. If hydrogen causes an increase in vacancy concentration, it can promote dislocation climb. Henceforth, we will investigate the hydrogen effect on the atomic scale defects such as vacancies and dislocations through a scale-bridging approach.

1) Yamabe, J., Tohru A., and Saburo M., Investigation of hydrogen transport behavior of various low-alloy steels with high-pressure hydrogen gas, International Journal of Hydrogen Energy, Vol. 40 No.34 (2015) pp. 11075-11086.
2) Frost, H.J., and Ashby, M.F., Deformation-mechanism maps: the plasticity and creep of metals and ceramics, Oxford: Pergamon Press (1982) pp. 60-70.
3) Takazaki, D., Tsuchiyama, T., Komoda, R., Dadfarnia, M., Somerday, B. P., Sofronis, P., and Kubota, M., Effect of Hydrogen on Creep Properties of SUS304 Austenitic Stainless Steel, Corrosion, Vol. 77, No. 3 (2021) pp. 256-265.
4) Fullarton, M. L., Voskoboinikov, R. E., and Middleburgh, S. C., Hydrogen accommodation in α-iron and nickel, Journal of Alloys and Compounds, Vol. 587, No. 25 (2014), pp. 794-799.
5) Matsumoto, R., Nishiguchi, N., Taketomi, S., and Miyazaki, N., First-Principles Calculation of Hydrogen Effects on the Formation and Diffusion of Vacancies in Alpha Iron: Discussion of the Hydrogen-Enhanced Strain-Induced Vacancy Mechanism, Journal of the Society of Materials Science, Japan, Vol. 63, No. 2 (2014), pp. 182-187.