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Dependence of hydrogen-induced lattice defects and hydrogen embrittlement of cold-drawn pearlitic steels on hydrogen trap state, temperature, strain rate and hydrogen content

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Abstract

The effects of the hydrogen state, temperature, strain rate and hydrogen content on hydrogen embrittlement susceptibility and hydrogen-induced lattice defects were evaluated for cold-drawn pearlitic steel that absorbed hydrogen in two trapping states. Firstly, tensile tests were carried out under various conditions to evaluate hydrogen embrittlement susceptibility. The results showed that peak 2 hydrogen, desorbed at temperatures above 200 °C as determined by thermal desorption analysis (TDA), had no significant effect on hydrogen embrittlement susceptibility. In contrast, hydrogen embrittlement susceptibility increased in the presence of peak 1 hydrogen, desorbed from room temperature to 200 °C as determined by TDA, at temperatures higher than −30 °C, at lower strain rates and with higher hydrogen content. Next, the same effects on hydrogen-induced lattice defects were also evaluated by TDA using hydrogen as a probe. Peak 2 hydrogen showed no significant effect on either hydrogen-induced lattice defects or hydrogen embrittlement susceptibility. It was found that hydrogen-induced lattice defects formed under the conditions where hydrogen embrittlement susceptibility increased. This relationship indicates that hydrogen embrittlement susceptibility was higher under the conditions where the formation of hydrogen-induced lattice defects tended to be enhanced. Since hydrogen-induced lattice defects formed by the interaction between hydrogen and strain were annihilated by annealing at a temperature of 200 °C, they were presumably vacancies or vacancy clusters. One of the common atomic-level changes that occur in cold-drawn pearlitic steel showing higher hydrogen embrittlement susceptibility is the formation of vacancies and vacancy clusters.

Keywords: Hydrogen embrittlement; Lattice defect; Vacancy; Hydrogen state; Cold-drawn pearlitic steel

1. Introduction

Hydrogen embrittlement of high-strength steel is caused by two principal types of factors: microstructural factors that originate in the steel itself and environmental factors that originate in the external environment. As examples of microstructural factors, it has been shown that grain size [1,2], stability of dislocations [3–5] and hydrogen states [6] affect hydrogen embrittlement. One of the authors has found that not all the hydrogen present in cold-drawn pearlite steels is directly related to hydrogen embrittlement. Specifically, only diffusive hydrogen trapped weakly (peak 1 hydrogen) and desorbed from room temperature to 200 °C, as determined by thermal desorption analysis (TDA), contributes to hydrogen embrittlement. In contrast, non-diffusible hydrogen trapped strongly (peak 2 hydrogen) and desorbed at temperatures above 200 °C, as determined by TDA, is not involved in hydrogen

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embrittlement [6]. As examples of environmental factors, other studies have concluded that temperature [7], strain rate [5] and hydrogen content [6] affect hydrogen embrittlement. Regarding the effect of temperature, it is reported that ductility loss is the largest at 220 K [7]. Investigations on the effect of the strain rate have revealed that ductility loss decreases with increasing strain rate [5]. In other words, it is known that not all hydrogen embrittlement occurs when hydrogen is absorbed into high-strength steels, but that it can take place under certain particular conditions. However, few studies have attempted to clarify the common atomic-level changes in steels under each condition where hydrogen embrittlement occurs [8].

Nagumo et al. reported that plastic deformation at room temperature in the presence of diffusion hydrogen in pure iron markedly enhanced the formation of lattice defects, i.e., hydrogen-induced lattice defects, compared with plastic straining without hydrogen, even though the strain level was the same [9]. One of the authors has recently shown that plastic deformation at room temperature in the presence of diffusion hydrogen in Inconel 625 with a face-centered cubic (fcc) lattice, as well as in pure iron with a body-centered cubic (bcc) lattice, also markedly enhanced the formation of hydrogen-induced lattice defects [10]. Furthermore, the pure iron and Inconel 625 specimens having the hydrogen-induced lattice defects exhibited direct ductility loss, even though hydrogen was not present in the materials [10]. Using hydrogen as a probe and a positron probe microanalyzer, two of the authors have also previously found that the amount of lattice defects and the mean positron annihilation lifetime in tempered martensitic steel increased gradually with increasing time of applied constant elastic tensile stress during hydrogen charging. The defects were especially numerous and longer in the near-fracture area. In addition, the mean positron annihilation lifetimes of the fractured specimen in the near-fracture area were more than approximately 200 ps. These results clearly indicated that the newly formed lattice defects corresponded to larger-size vacancies or vacancy clusters [4]. The authors have also clarified the amount of hydrogen-induced lattice defects formed by applying cyclic pre-stress with hydrogen in tempered martensitic steel as well as by applying constant elastic tensile stress [8]. However, few studies have attempted to investigate the effects of four factors, i.e., hydrogen state, temperature, strain rate and hydrogen content, on the formation of lattice defects, or even the relationship between the formation of lattice defects and hydrogen embrittlement susceptibility.

This paper clarifies the effects of these four factors on hydrogen embrittlement susceptibility for cold-drawn pearlite steel specimens that absorbed hydrogen in two trapping states. The same effects on hydrogen-induced lattice defects were also evaluated by TDA using hydrogen as a probe. The ultimate goal of this work was to clarify the relationship between hydrogen embrittlement susceptibility and hydrogen-induced lattice defects.

2. Experimental

2.1. Material

In the present study, specimens were prepared of cold-drawn pearlitic steel corresponding to JIS SWRS 82B. Specimens were cold-drawn from 13 to 5 mm in diameter, after austenitization at a temperature of 930 °C for 5.4 min and isothermal transformation in a lead bath at a temperature of 530 °C for 3.3 min. Fig. 1 shows the microstructure observed by field emission scanning electron microscopy. The microstructure was pearlite, consisting of a ferrite/pearlite lamellar structure elongated along the cold-drawing direction. The chemical composition was 0.84 mass% C, 0.25 mass% Si, 0.73 mass% Mn, 0.017 mass% P and 0.005 mass% S. Tensile test specimens were machined to 3 mm in diameter and 20 mm in gauge length. Tensile strength at room temperature was 1838 MPa.

2.2. Hydrogen charging and hydrogen analysis

Prior to hydrogen charging, the specimen surface was polished with #1000 emery paper to remove the oxide film. Hydrogen charging of specimens was conducted by immersion in a 20 mass% NH_4SCN solution kept at a temperature of 30 °C.

In order to determine the time needed for the hydrogen concentration to reach equilibrium at the center of the specimens, the specimens immersed for 0–120 h in a 20 mass% NH_4SCN solution at 30 °C were subjected to hydrogen analysis. The TDA profiles of hydrogen and the relationship between the hydrogen charging time and hydrogen content are shown in Fig. 2a and b, respectively. As shown in Fig. 2a, hydrogen was present in the cold-drawn pearlitic steel specimens in two states. One was a weakly trapped state of hydrogen that desorbed at room temperature and disappeared at 200 °C, denoted here as

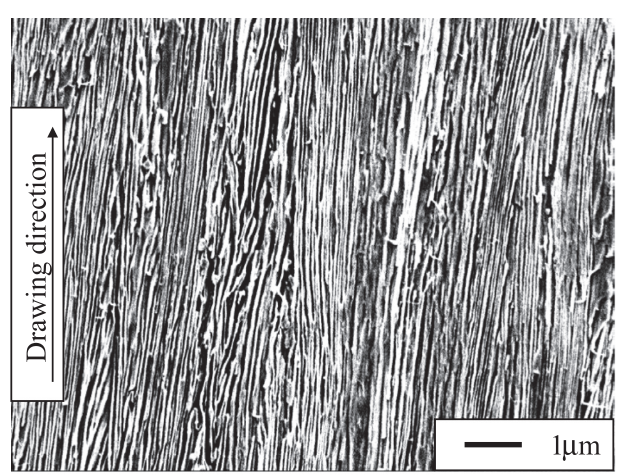

Fig. 1. Scanning electron micrograph of cold-drawn pearlitic steel.