Engineering Failure Analysis 49 (2015) 49–56

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Investigation of high-temperature hydrogen embrittlement of sensitized austenitic stainless steels

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ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form 24 November 2014
Accepted 26 November 2014
Available online 30 December 2014

Keywords:
Hydrogen embrittlement
Austenitic stainless steels
Fracture

ABSTRACT

Several new hydrogen production methods are currently being developed for commercialization. These new production methods, such as gasification of various feedstocks, operate in the temperature range from 973 K to 1173 K. There are concerns regarding potential hydrogen embrittlement and sensitization occurring in the stainless steel process components. In the current study, burst test specimens were fabricated from AISI stainless steel types 310S, 316/316L, and 321. Each specimen was sensitized and charged with hydrogen. The burst strength of the specimens was determined using nitrogen gas. Both burst strength and ductility were compared with typical values for each grade available from the literature. It was determined that both the burst strength and the ductility were reduced by exposure to hydrogen in the conditions used in this study. These results indicate that care should be used in the design of hydrogen production facilities using stainless steel alloys even at temperatures not typically associated with hydrogen embrittlement.

1. Introduction

Heightened interest in fuel cells has increased the demand for concentrated hydrogen, necessitating the development of new production methods for the gas. Many of these processes require much higher temperatures than current methods. Austenitic stainless steels can potentially resist both the elevated temperatures and chemical environments associated with hydrogen production. However, it has recently been discovered that austenitic stainless steels are not as resistant to embrittlement as previously thought [1]. Little data currently exists on hydrogen embrittlement at temperatures over 400 K (127 °C), but there is interest in the gasification field regarding how these stainless steels will react to the combination of high temperature and hydrogen exposure. This interest is driven mainly by the fact that many production methods fall in the temperature range above 700 K (427 °C), e.g. steam methane reforming which occurs between 1023 and 1073 K [1]. Engineers at the University of North Dakota Energy and Environmental Research Center (EERC) have developed gasification technologies for the production of hydrogen from several different feedstocks, such as waste wood chips and railroad ties, that operate between 973 K and 1173 K (700–900 °C). Some premature failure of austenitic stainless steel process components has been observed and the current study was undertaken to determine if hydrogen embrittlement played a role.

Stainless steel components can also undergo sensitization at elevated temperatures. Sensitization occurs when the chromium in the steel alloy segregates to the grain boundaries and forms chromium carbides [2–4]. The chromium-depleted grain matrix is more susceptible to intergranular corrosion. Sensitization is a potential concern due to the fact that the

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http://dx.doi.org/10.1016/j.engfailanal.2014.11.023
1350-6307/

sensitization temperature range and the operating temperature range of several hydrogen production methods overlap. Sensitization has been observed to enhance the effects of hydrogen embrittlement [e.g. 5].

Hydrogen embrittlement can manifest in multiple ways. One of the oldest and most commonly measured manifestations of hydrogen embrittlement is loss of tensile ductility [6,7]. Lower strength steels and other alloys commonly demonstrate this effect when exposed to hydrogen. Loss of tensile ductility is characterized by a significant decrease in tensile elongation and reduction in fracture area, but has no effect on strength [6,7]. Other categories of hydrogen embrittlement include a decrease in tensile elongation and reduction in area at failure accompanied by a decrease in strength. Loss of tensile ductility is very sensitive to strain rate and hydrogen content, increasing with decreases in strain rate and with increases in hydrogen concentration [6,7]. It has been found that as embrittlement effects get more severe, the fracture mode of steels can change from dimple rupture or quasi-cleavage transgranular fracture in unexposed steels to intergranular decohesion in embrittled steels [8]. The change in fracture mode may not occur over the entire fracture surface, but is usually more evident at the place where the fracture has originated [8].

Previously observed effects of hydrogen on metallic materials typically reach a maximum near ambient conditions and decrease as temperature is increased or decreased [9]. At room temperature, hydrogen is mobile enough in steels to jump from normal interstitial sites within the lattice ("dissolved" hydrogen) to defect sites ("trapped" hydrogen), in which the residence time for hydrogen is dependent upon the size of the site [10]. As defect sites are typically larger than normal interstitial sites, hydrogen has longer residence times in defects [10]. As the temperature decreases, hydrogen mobility is reduced within the microstructure of the material and local equilibrium between trapped and dissolved hydrogen cannot be maintained [10]. At lower hydrogen mobility the hydrogen atoms cannot relocate from normal interstitial lattice sites to defect sites, thus reducing the effects of hydrogen embrittlement [10,11]. As the temperature increases, the mobility [10,11] and solubility of hydrogen in the material increase [10] and the material's ability to trap hydrogen is reduced [11]. With increasing hydrogen mobility, the difference in residence times between defects and normal interstitial sites becomes negligible [10]. This means that more hydrogen can be dissolved into the material at higher temperatures. As more hydrogen is dissolved into the material, the distribution of hydrogen in the material becomes more uniform; hydrogen is no longer segregated to the grain boundaries or defects within the material. The increased hydrogen mobility also means that the residence times for normal and defect sites are adjusted to be essentially the same which also reduces the effects of hydrogen embrittlement [10].

Most previous studies on hydrogen embrittlement have only been conducted up to about 400 K, at which point the effects of hydrogen embrittlement were diminished, but not entirely mitigated, in meta-stable grades (e.g. AISI types 304L and 316). This is in contrast to observed full mitigation of embrittlement approaching 400 K in stabilized grades (e.g. AISI type 310), which are not as severely affected by hydrogen in the first place [1,11]. The general trend for meta-stable stainless steels is for embrittlement to be further diminished as the temperature continues to increase. This effect can be seen in Fig. 1 [11]. One purpose of the current work is to determine if hydrogen embrittlement is of concern at higher temperatures than previously investigated.

2. Materials and methods

2.1. Materials

The materials to be studied in detail in this research are AISI types 310S, 316/316L, and 321. Alloy 316H was also used to determine whether the experimental apparatus could produce embrittlement when tested at room temperature. Table 1 shows the composition of each alloy as specified on the mill data sheet provided by the supplier.

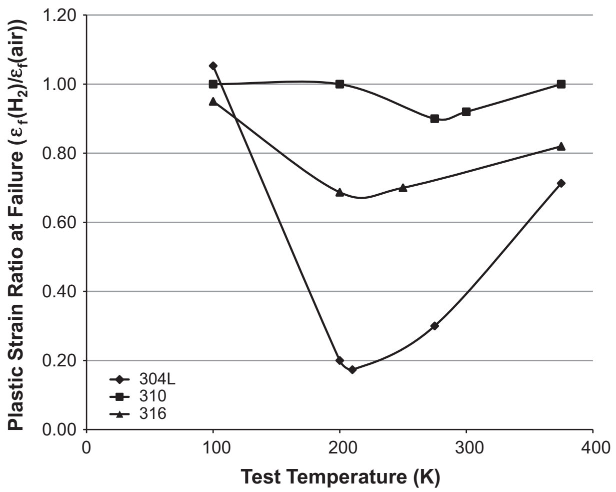

Fig. 1. Effect of temperature on hydrogen embrittlement of stainless steels from [11].