Available online at www.sciencedirect.com

ScienceDirect

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

Hydrogen compatibility of austenitic stainless steel tubing and orbital tube welds

Lauren A. Hughes [1], *Brian P. Somerday*, *Dorian K. Balch*, *Chris San Marchi**

Sandia National Laboratories, 7011 East Ave., Livermore, CA 94550, USA

ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form
6 March 2014
Accepted 28 March 2014
Available online xxx

Keywords:
Hydrogen embrittlement
Austenitic stainless steel
Tubing

ABSTRACT

Refueling infrastructure for use in gaseous hydrogen powered vehicles requires extensive manifolding for delivering the hydrogen from the stationary fuel storage at the refueling station to the vehicle as well as from the mobile storage on the vehicle to the fuel cell or combustion engine. Manifolds for gas handling often use welded construction (as opposed to compression fittings) to minimize gas leaks. Therefore, it is important to understand the effects of hydrogen on tubing and tubing welds. This paper provides a brief overview of on-going studies on the effects of hydrogen precharging on the tensile properties of austenitic stainless tubing and orbital tube welds.

Introduction

Hydrogen manifolds, for example in gaseous hydrogen fuel systems, predominantly use austenitic stainless steel tubing for processing and transporting hydrogen. In assembling a manifold, welding is one way in which potential leaks can be avoided (e.g., leaks associated with compression fittings). However, welds are known to be more sensitive than the base material to environmental effects due to the microstructure of the weld region [1,2]. Since gaseous hydrogen is an environment that embrittles many structural alloys, there is a concern that welds in gaseous hydrogen manifolds may be more severely affected by hydrogen than the tubing base material.

Gaseous hydrogen effects on austenitic stainless steels have been extensively evaluated for many decades [3–9]. Nickel content, for example, affects resistance of austenitic stainless steels to hydrogen-assisted fracture, as demonstrated by the reduction of ductility from both internal and external hydrogen exposure during tensile tests [5,7,8]. The strength of austenitic stainless steels can be controlled by strain-hardening processes, which also affects resistance to hydrogen-assisted fracture [10]. Additional environmental factors, such as temperature exposure, influence hydrogen-assisted fracture as well. Studies show reduction of tensile ductility in the presence of hydrogen reaches a maximum at temperature around 220 K for austenitic stainless steels [4,5]. However, there are relatively few studies analyzing the role of microstructure on hydrogen-assisted fracture, and fewer studies analyzing the hydrogen effects on the weld microstructure [1,2]. Microstructural effects due to processing may also be important to the performance of austenitic stainless steels when exposed to hydrogen. Precipitation of carbides at grain boundaries during thermal exposure (as experienced during welding, for example) is generally referred to as

* Corresponding author.
E-mail address: cwsanma@sandia.gov (C. San Marchi).

[1] now at University of California Davis.

http://dx.doi.org/10.1016/j.ijhydene.2014.03.229

sensitization and has been shown to reduce tensile ductility of austenitic stainless steels exposed to hydrogen [6,11–13].

This manuscript provides an overview of several active studies assessing hydrogen-assisted fracture of austenitic stainless steel tubing and orbital tube welds. The materials and microstructures explored in these studies reflect tubing and tubing welds intended for service with gaseous hydrogen. The studied materials are type 316L and several types of 304/304L austenitic stainless steels. All tubing was tested in tension in the as-received condition and after hydrogen precharging. Additionally, samples of tubing were sensitized prior to tensile testing with and without hydrogen precharging. Specimens with orbital tube welds in the gauge length of two tubing materials were also tested (type 316L and type 304L material 2).

Materials and experimental procedure

All of the materials described in this report are commercially available austenitic stainless steel tubing: one type 316L material, five type 304L materials and one type 304 material (the designation of L-grade in this report is based on carbon content <0.03 wt%, although some of the materials are dual certified to both type 304 and type 304L). The composition of the alloys is given in Table 1. The type 316L tubing was obtained in the nominally annealed condition with nominal outer diameter (OD) of 6.35 mm and nominal wall thickness of 1.24 mm. The six type 304/304L tubing materials all have a nominal OD of 3.18 mm with a nominal wall thickness of 0.71 mm; they are referred to as materials 1 through 6 (Table 1). The type 304 tubing is material 4. Three of the type 304/304L tubing materials were procured in the strain-hardened condition, while the other three were nominally annealed. The measured OD and measured inner diameter (ID) are used for all stress calculations. All six type 304/304L tubing materials were subjected to a sensitization heat treatment at a temperature of 998K for 240 min.

Orbital tube weld specimens were formed by welding together two pieces of tubing, each 50–55 mm long. The welding was performed with automated commercial tube welding equipment using standard vendor recommended practices (single-pass, gas tungsten arc welding). Two sets of welded type 316L tubing were prepared on different equipment with different operators, referred to as weld process A and weld process B. Weld specimens of material 2 were also prepared (the welding equipment and operator for the welded type 304L specimens were different from the type 316L processes). All welded tubing was tested in the as-welded condition without modification or machining of the welds.

Tensile testing was performed using approximately 100 mm long specimens clamped over a length of approximately 25 mm on both ends using wedge grips. The gauge length between the grips was thus approximately 50 mm. To prevent the specimen from being crushed in the grips, round pin inserts were used (refer to ASTM E8); the length of the pin within the tubing specimens was approximately 25 mm, mirroring the length of the gripped section on each end of the specimen. Tests were conducted in laboratory air at room temperature (293 K) on a servo-hydraulic test frame.

An extensometer with a gauge length of 25.4 mm was centered in the gauge section and used to determine strain during testing. All testing was conducted at a constant displacement rate of 2.54 mm/min, which corresponds to a measured strain rate in the extensometer gauge of about 5×10^{-4} s^{-1}. The nickel content, carbon content, 0.2% offset yield strength (YS), and reduction of area (RA) are used to characterize the mechanical properties of the tested materials and conditions. RA values were determined with the aid of digital stereo-images at 30× using commercial software to correct for focal distance. For comparison of the tensile ductility with and without hydrogen the relative reduction of area (RRA) is sometimes used: the RA with internal hydrogen relative to the RA of the same tubing material and condition without hydrogen.

A uniform saturation of hydrogen within the specimens was achieved by thermal precharging: exposure to gaseous hydrogen at a pressure of 138 MPa and a temperature of 573 K for about 10 days. These conditions are used extensively in the literature and produce a hydrogen content of about 140 parts per million by weight [7]. The hydrogen content was verified by inert gas fusion on a number of hydrogen-precharged specimens, representing both type 316L and type 304L materials. Additional details of thermal precharging methods can be found in Refs. [7,14].

Results

Strength

The relationship between reduction of area (RA) and yield strength (YS) is plotted in Fig. 1 for all the tested materials, including the welds (note: hydrogen-precharged materials are

Table 1 – Composition (wt%) of austenitic stainless steels in this report, as specified by the manufacturer, and yield strength, as measured in this study. The ID is the number used to designate the material in the text. Compositional values not provided on the material certification are denoted as *n/r*.

Alloy type	ID	YS (MPa)	Cr	Ni	Mn	Mo	Si	C	S	P
316L	–	286	16.7	12.4	1.7	2.1	0.39	0.018	0.006	0.027
304L	1	–	18.2	9.1	1.0	*n/r*	0.50	0.020	0.004	0.027
304L	2	699	18.6	11.7	1.7	0.08	0.43	0.021	0.0004	0.017
304L	3	296	18.7	11.6	1.6	*n/r*	0.50	0.015	0.026	0.032
304	4	627	18.3	10.2	0.74	0.29	0.33	0.04	0.002	0.033
304L	5	359	18.4	10.2	1.2	*n/r*	0.35	0.01	0.007	0.029
304L	6	763	18.4	8.2	1.1	*n/r*	0.46	0.024	0.003	0.028

Please cite this article in press as: Hughes LA, et al., Hydrogen compatibility of austenitic stainless steel tubing and orbital tube welds, International Journal of Hydrogen Energy (2014), http://dx.doi.org/10.1016/j.ijhydene.2014.03.229