INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–14

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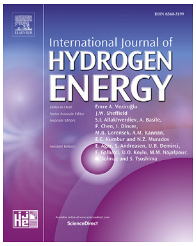

Evaluation of hydrogen permeation through standalone thermally sprayed coatings of AISI 316L stainless steel

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ARTICLE INFO

Article history:
Received 21 September 2017
Received in revised form
11 December 2017
Accepted 7 January 2018
Available online xxx

Keywords:
Hydrogen
Permeation
Diffusion coefficient
Thermally sprayed coating
Stainless steel

ABSTRACT

This research evaluates hydrogen permeation and its diffusion characteristics through standalone thermally sprayed coatings of AISI 316L stainless steel. The effects of various charging currents and other parameters on hydrogen diffusion coefficient were scrutinized using electrochemical hydrogen permeation tests. Hydrogen permeation through the thermally sprayed coatings displayed anomalous behavior such that a maximum pinnacle was observed in the permeation curves, attributed to heavily trapped hydrogen atoms in the delayed surface cracks. Therefore, new diffusion parameters were defined for modeling of the anomalous permeation curves. The fitted diffusion parameters were consistently identified, and hence, the model perfectly explained experimental data. The results showed that the increase in charging current caused fast activation and development of surface cracks. The measured diffusion coefficient of hydrogen in the stainless steel thermally sprayed coating was relatively high because the microstructure of the coating contained some ferritic phases and dense dendritic structure, which configure fast diffusion paths.

Introduction

Hydrogen has attracted growing attention regarding its numerous applications in various industries, and its importance as well has been increased by the significance of green renewable energies. Since hydrogen has the smallest atom, it can easily diffuse through materials and raise some difficulties such as hydrogen embrittlement and permeation in oil, gas and/or nuclear industries [1–3]. The effects of hydrogen on the stainless steels have been evaluated as well. Hydrogen mainly causes reduction of elongation; however, a little increase in its strength has been observed [4–6]. These effects are discernible when a minimum hydrogen concentration of 1–5 ppm introduced in a stainless steel [4].

Protecting coatings of austenitic steels and other hydrogen resistant materials have been used for many years in order to hinder hydrogen embrittlement and leakage [7–9]. However,

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https://doi.org/10.1016/j.ijhydene.2018.01.021

Please cite this article in press as: Moshref-Javadi M, et al., Evaluation of hydrogen permeation through standalone thermally sprayed coatings of AISI 316L stainless steel, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.01.021

thermal spray, which is a fast and adaptable method with many coating capabilities, has been neglected and few evaluations have been reported regarding specifications and properties of the produced coatings against hydrogen degradation. Nevertheless, thermally sprayed coating (TSC) has been shown to have positive effects on the reduction of hydrogen embrittlement [10–12].

There are many inter-dependent parameters in TSC, which can affect hydrogen diffusion. For instance, residual stress [13–15], plastic strain [16–19], oxide layers, and porosities [9,20,21], chemical composition variations, and the possibility of phase transformation [22–24] simultaneously exist in a TSC of stainless steel and affect hydrogen diffusion. Moreover, some external parameters such as hydrogen charging current density (CCD) employed in hydrogen permeation test affects hydrogen permeation, too. A high CCD, until reaching a saturation level, results in more surface concentration of hydrogen, increased permeated hydrogen flux, and more apparent hydrogen diffusion coefficient [25–28].

Severe plastic deformation in thermally sprayed splats of stainless steels in addition to changes in chemical composition and phase stability variations can result in microstructural defects, phase transformation, and residual stress [29,30]. For example, the density of dislocations in TSC is twice of a starting powder of AISI 316 stainless steel [18]. Besides, austenite phase instablility can lead to the development of martensitic and ferritic phases in TSCs of AISI 316 stainless steel [31–33]. Regarding that hydrogen diffusion coefficient (D) in ferritic and martensitic phases is more than that of austenite [34–36] and dislocations can also play the role of diffusion channel for hydrogen [37–39], the presence of these phases and defects in the coating develops fast diffusion paths and depreciates the hindering effect of the austenite phase against hydrogen diffusion [40–42]. Consequently, D of hydrogen in the TSC is drastically affected and amplified. In addition, the shape of the transformed phases is efficacious, and if these phases are continuous across the coating, they are more effective on D increment [43–45].

Besides, TSCs always exhibit a rough surface which renders the coating vulnerable to cracking and increases the actual surface of a membrane [46,47]. When the specific surface of a specimen, on which hydrogen ions are reduced and absorbed, is increased, more hydrogen atoms are produced during a permeation test. Therefore, more hydrogen atoms permeate through a rough membrane and lead to a higher steady state flux for the permeating hydrogen [47,48]. Additionally, because the roughness of a surface leads to deep valleys, the roughness of a membrane decreases the effective thickness and shortens the diffusion path for hydrogen atoms across the specimen [47]. Furthermore, brittle microstructure and weak inter-splat connections in a TSC can increase the risk of surface cracks [49,50] which may propagate into the specimen during hydrogen diffusion [51,52]. All the mentioned factors in addition to the effects of substrate, integrally existing in TSC and manipulating each other, strongly influence hydrogen diffusion behavior in TSCs.

When hydrogen atoms are introduced into a material, they can be solved in the lattice or trapped in hydrogen traps including dislocations, grain boundaries, precipitates, cracks, etc. [7]. Hydrogen is solved much more in the near surface layers than do in other places in a metal [6,34,53]. Accordingly, the new internal surfaces of a developing crack can solve more hydrogen, and hence, they can play the role of high-capacity traps for hydrogen atoms. As a result, it is observed that the surfaces cracks can dramatically reduce hydrogen permeation current and diffusivity [54–56]. Furthermore, the diffused hydrogen into a metal can result in localized plasticity and reduction in the localized yield strength, along with increased residual tensile stress at the surface [57–60]. Thereupon, a metal sensitive to cracking, particularly when bearing residual stresses, could undergo surface cracks. The cracks are promoted by not only high hydrogen concentration which is trapped under the surfaces of the cracks but also the enhanced localized plasticity in front of a crack tip.

Diffusion and permeation of hydrogen through a metal suffering surface cracks, such as TSC, can be affected by the newly developed cracks and traps. These cracks which are activated at a critical hydrogen concentration forcefully trap hydrogen atoms and sink the permeable hydrogen current [56]. Accordingly, curves obtained from hydrogen permeation tests through a layer of a material which experiences surface cracking during hydrogen diffusion demonstrate an anomalous shape and exhibit a maximum peak [61–63]. In this case, the common solutions of the Fick's second law for diffusion, which are widely used in the researches [64,65], is inapplicable and new boundary conditions should be taken into account. As Wu has demonstrated [61], the boundary condition should consider the newly created traps (cracks) at the surface of the specimen.

A few references have described the hindering specifications of TSC on hydrogen diffusion and permeation. The positive effects of TSC on the reduction of hydrogen diffusion has been reviewed by Matějíček [12]. In addition, Vargas et al. [10]. mentioned that metallic TSC of Ni alloys can reduce hydrogen embrittlement of structural steels. It was also observed by Smuga-Otto and Road [66] that the sprayed coating of Cr can save the reduction area of hydrogenated carbon steels due to its inherent layers and porosities [67]. Besides, some researchers perceived that TCS of W exhibited higher resistance to hydrogen permeation than that do its sputtering coatings [11,68]. In addition, a TSC of aluminum over steels succeeded by a heat treatment could produce some diffusive aluminide layers which are known as strong hydrogen diffusion barriers [69]. The barrier effects of TSCs of Al_2O_3 and Al_2O_3–13 wt% TiO_2 ceramics against hydrogen diffusion were proved by Song [70], as well. Future applications of ion releasing amorphous TSC against hydrogen embrittlement and corrosion has been also proposed [34,71].

Furthermore, TSCs have been employed in some hydrogen-related applications in which enhanced hydrogen diffusion or permeation are required. Because TSCs are capable of providing a rough surface and porous structure, they were successfully utilized in fuel cells and hydrogen purification systems in order to improve hydrogen diffusion and permeation [72–75].

Consequently, it seems that even the general diffusion behavior of hydrogen through TSC has not been revealed and explored, yet. On the other hand, detection of the effects of each mentioned parameters involved in TSC on hydrogen diffusion is difficult and requires more spread evaluations.

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