INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2015) 1–9

Available online at www.sciencedirect.com

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

Effect of hydrogen on the hardness of different phases in super duplex stainless steel

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ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form
4 October 2015
Accepted 26 October 2015
Available online xxx

Keywords:
Super duplex stainless steel
Austenite
Ferrite
Electrochemical nanoindentation
Nano hardness
Residual stress

ABSTRACT

Despite its superior corrosion resistance, super duplex stainless steels (SDSS) are prone to hydrogen embrittlement. In this paper, a novel in situ electrochemical nanoindentation technique is used to investigate the hydrogen effect on the nanomechanical response of the existing phases in SDSS, i.e. ferrite and austenite. A systematic change in electrochemical (EC) charging potential revealed the interconnected nature of the hydrogen effect on the nanomechanical properties of SDSS. It is shown that the hydrogen effects in each phase are very different and are strongly coupled with the existing residual stresses in the microstructure induced during the manufacturing and/or induced by EC hydrogen charging.

Introduction

Super duplex stainless steels (SDSS) are two-phase highly alloyed steels with excellent resistance against localized corrosion [1–3]. They are used in especially demanding environments like the oil and gas industry and the chemical industry. However, despite the very favorable properties of SDSS, they tend to fail when exposed to hydrogen, due to hydrogen embrittlement [4–13]. In spite of much research into hydrogen embrittlement (HE) in SDSS, its mechanism in this alloy is still not completely understood [14]. This is mainly because HE is the result of the interaction of a material under a mechanical load with its environment, as shown in Fig. 1. Numerous circumstances can result in the ingress of hydrogen into the metal. Mechanical loading can manifest itself in different ways, e.g. residual stresses, cyclic loading, static loading, etc. The third aspect, beside the environmental and mechanical ones, addresses the wide range of intrinsic and extrinsic variables within the material itself.

In the case of SDSS, we are dealing with a two-phase material comprised of austenite (γ) and ferrite (α) with different physical properties. Specifically, from the HE point of view, these differences are crucial, e.g. austenite has a high H

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http://dx.doi.org/10.1016/j.ijhydene.2015.10.106

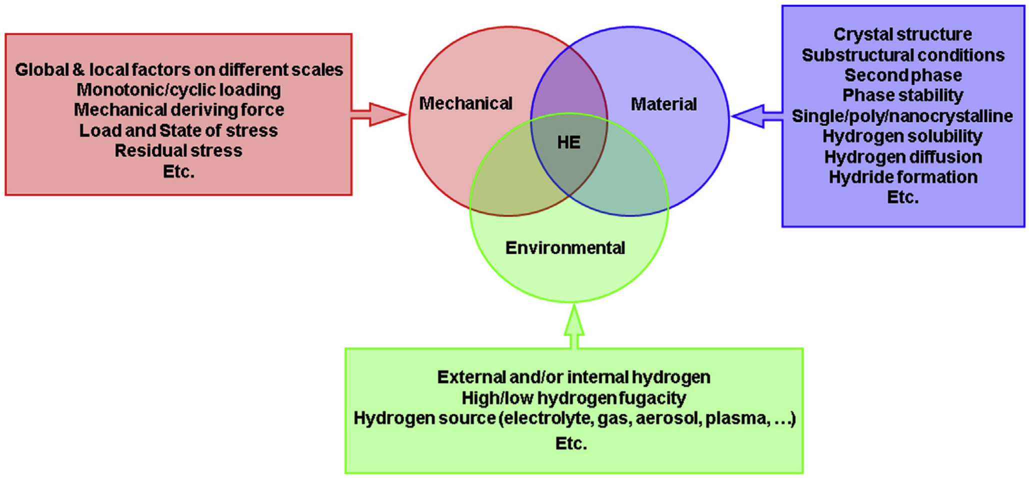

Fig. 1 – Different aspects of hydrogen embrittlement and complication.

solubility and low diffusivity, while ferrite is vice versa. The glide resistances to dislocations, widely referred to as Peierls–Nabarro resistance, which results from the pulsing distortions of the dislocation core as it moves through the discrete lattice, are also different for γ austenite and α ferrite [15]. The Peierls–Nabarro resistance often affects edge and screw dislocations differently, and at very distinct levels in different crystal structures can also be affected by hydrogen differently. Therefore, it is necessary to study the HE on similar scales in the individual phases. For the purpose of local mechanical testing, instrumented nanoindentation is the most appropriate tool. The measured load–displacement (L–D) curves of nanoindentation (Fig. 2) can be analyzed to extract hardness and elastic moduli according to the well-known Oliver–Pharr method, as given in Eqs (1) and (2) [16].

$$H = \frac{P_{max}}{A_c} \quad (1)$$

$$E_r = \frac{S\sqrt{\pi}}{2\beta\sqrt{A_c}} \quad (2)$$

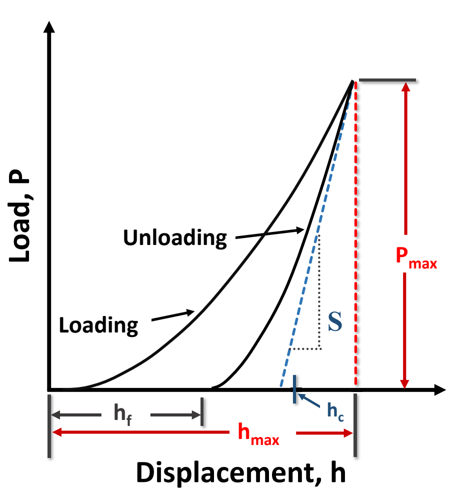

Fig. 2 – Typical nanoindentation loading and unloading curve.

Here, S is the slope of the load–displacement curve at the initial unloading, as shown in Fig. 2, A_c is the projected contact area evaluated from the contact depth h_c shown in Fig. 2 and the tip area function. β is a correction factor dependent on the tip geometry (1.034 for the Berkovich indenter used in this study).

In order to probe the hydrogen effect during nanoindentation, the best practice is achieved by combining nanoindentation with in situ hydrogen charging (H-charging) [17–19]. It has been shown that the presence of hydrogen in a metal can alter the nanomechanical footprint registered in the form of the L–D curve [20–25]. Hydrogen can affect the hardness, elastic modulus, and/or the elastic to plastic transition load (pop-in load). The purpose of this paper is to examine and understand the effect of EC H-charging at different conditions separately on the phases present in SDSS.

Experimental

Material

The SDSS sample was a SAF 2507 provided by OUTOKUMPU. This grade is comparable to the American UNS S32750 and European EN 1.4410 grades. The composition of the sample provided by the supplier is given in Table 1. The sample was in the solution-annealed condition, i.e. heat treated at 1120° for 45 min and quenched in water. The ferrite content of the sample was 46% according to the supplier's test results. The chemical composition of the main alloying elements in the sample was measured by using energy-dispersive X-ray spectroscopy (EDS) and is shown in Table 2. As expected, the ferrite stabilizing elements, chromium and molybdenum, are

Table 1 – Composition of SDSS used in this study provided by the supplier.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
wt.%	0.016	0.23	0.79	0.021	0.001	25	6.98	3.82	0.32	0.27

Please cite this article in press as: Kheradmand N, et al., Effect of hydrogen on the hardness of different phases in super duplex stainless steel, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.10.106