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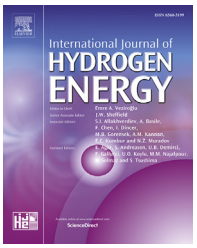

Strengthening mechanism and hydrogen-induced crack resistance of AISI 316L stainless steel subjected to laser peening at different power densities

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ABSTRACT

Microstructural response of AISI 316L stainless steel to laser peening (LP) was examined by means of optical microscopy (OM) and transmission electron microscopy (TEM) in order to analyze the effects of LP on hydrogen-induced cracking (HIC) resistance. Depth profiles of near-surface microhardness and surface compressive residual stress (CRS) of LP treated specimens were presented respectively. Slow strain rate tensile tests were performed on the hydrogen-charged samples and their corresponding stress-strain curves as well as fracture morphologies were finally investigated in detail. The results demonstrated that LP induced a grain refinement effect on the treated surface while a maximum refining rate of 56.18% was achieved at the laser power density of 10 GW/cm^2. The near-surface microhardness also exhibited an attenuation trend with the increasing depth. The surface CRS positively correlated with power density before it reached a threshold value. A special U-shaped dislocation tangle band was observed in the LP treated specimen which served as hydrogen trapping sites. The LP treated samples exhibited better toughness after hydrogen charging from both macro mechanical properties and micro fracture morphologies. LP-induced grain refinement and CRS are believed to be the main contributing factors towards inhibiting the diffusion of hydrogen atoms which ultimately leads to the reduction of the hydrogen embrittlement sensitivity of AISI 316L stainless steel.

Introduction

AISI 316L stainless steel as a typical austenitic stainless is widely used in deep-sea equipment, oil transportation pipelines, reactor vessels and hydrogen storage tanks due to its excellent properties. However, AISI 316L stainless steel is faced with the obstacle of low resistance to HIC during its long-term service life in hydrogen containing mediums [1–3]. Therefore, how to improve the HIC resistance of AISI 316L

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stainless steel and extend its service life in extreme environmental conditions is of great importance to researchers.

Much research has been focused on using chemical methods such as cathodic protection [4–6], coating technology [7–9] and addition of elements [3,10] to improve the HIC resistance of alloy materials. Compared with other techniques, plastic deformation strengthening process (PDSP) utilizes induced surface CRS and refined grains to achieve hydrogen atoms penetration resistance, and its avoidance of failure risk due to interface effect has currently received a great deal of attention [11]. Takemoto et al. [12] found that shot peening could effectively enhance the strain threshold of martensitic aging steel after non-severe hydrogen permeation, thus reducing the possibility of delayed fracture. Takakuwa et al. [13,14] concluded that the CRS induced by cavitation peening could reduce the hydrogen invasion on the surface of austenitic stainless steel. However, it has also been found that an increase in surface roughness after conventional shot peening could be defective, thereby promoting hydrogen adsorption [15]. In addition, the residual stress layer generated on the near-surface was shallow and easy to relax in extreme service environments [16], which weakens the strengthening effect and limits its application in HIC resistant fields.

Laser peening (LP) utilizes high energy short pulse laser beam to generate a super-high shock wave and creates severe plastic deformation on the surface of metals; thereby inducing much higher and deeper CRS compared to that of conventional PDSP [17]. Grain refinement effect produced by LP treatment could be another potential factor to HIC resistance of metals. However, research on the effects of LP on HIC resistance is still in its early stages. Zaleski et al. [18] investigated the influence of LP on hydrogen-charged stainless steel. Hydrogen induced microvoids were observed in the near-surface layer of the non-LPed hydrogenated specimen, while such microvoids were obviously not seen in the LPed specimen. This result initially confirmed the inhibiting effect of LP process on hydrogen penetration. However, the above mentioned research was silent on the effects of the LP induced CRS on HIC. In 2010, Hackel et al. [19] initiated an investigation into the HIC resistance mechanism of LPed titanium alloy. It was revealed that LP could increase the dislocation density of the near-surface in metals, which in turn improves the chemical stability of the material surface, inhibits the infiltration of harmful chemical atoms and molecules, especially hydrogen atoms. However, this study did not make a further discussion on the microstructural response mechanism of the material induced by the high-strain-rate dynamic plastic deformation under the action of LP, and also did not pay attention to the relationship between the LP induced CRS field and the plastic damage behavior at the tip of HICs. In addition, the mechanical and chemical properties of AISI 316L stainless steel are obviously different from that of titanium. Their HIC resistance mechanism also varies.

Our research group conducted an initial study on the role of LP in promoting the hydrogen embrittlement resistance of AISI 316L stainless steel, and compared the tensile properties of hydrogen-charged specimen with and without LP treatment [20]. But it did not include detailed TEM observations to reveal the strengthening mechanism of LP. In fact, the microscopic characteristics of material dislocation configuration, dislocation slip mode and grain size all have important effects on its HIC. Furthermore, our previous study also lacked the analysis of how laser parameters such as laser power density affected the HIC resistance of the alloy.

With the aforementioned challenges in mind, this study aims to determine the redistribution of CRS and the microstructural evolution of LPed AISI 316L stainless steel at different laser power densities. In addition, a slow strain rate tensile test was performed on the hydrogen-charged samples to verify the effects of different laser power densities LP treatment on hydrogen-induced plasticity loss. The mechanism of HIC resistance of LP at different power densities was also discussed.

Experimental and procedure

Material and specimen preparation

Commercial AISI 316L austenitic stainless steel was used as the study material in this paper. Its chemical composition is as listed in Table 1.

As-received substrates were subjected to solution treatment at 1050 °C for 6 min followed by water cooling to room temperature. Rectangular specimens with a dimension of 20 mm × 20 mm × 3 mm were cut from the substrates for metallographic etching, CRS and microhardness tests, as shown in Fig. 1. The dimension of the specimen used for the slow strain rate tensile test is also as presented in Fig. 2. Tensile specimens were pre-machined from plates and tensile axes were parallel to the rolling direction. All the samples were initially sanded and grinded with SiC papers (500# – 2000#) and then mechanically polished to possess a surface roughness of 0.05 μm. The specimens were cleaned ultrasonically with acetone and then preserved in a drying box in order to reduce the residual stress caused by machining to its barest minimum level.

Experimental setup

The LP experiments were carried out on a Q-switched Nd: YAG (Neodymium doped Yttrium Aluminium Garnet) laser system (as shown in Fig. 3) operating at 1064 nm wavelength, with about 10 ns in pulse width. During LP, all the specimens were submerged in a water bath, and a uniform water layer with a thickness of 1 mm was used as the transparent confining layer. The 3M professional aluminium tape with a thickness of 120 μm was used as an ablation medium for plasma initiation to protect the specimen surfaces from the thermal damage of high-temperature plasma.

Fabbro et al. [21] estimated the peak pressure of shock waves in the presence of constraints, as shown in Eq. (1)

$$p(\text{kbars}) = 0.10\left(\frac{\alpha}{2\alpha+3}\right)^{1/2} Z^{1/2}(\text{g/cm}^2\text{s}) \times I_0^{1/2}(\text{GW/cm}^2), \quad (1)$$

where Z is the acoustic impedance, which can be obtained by

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2}, \quad (2)$$

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