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Effects of laser peening on stress corrosion cracking (SCC) of ANSI 304 austenitic stainless steel

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ABSTRACT

The effects of massive laser peening (LP) impacts on surface residual stress, micro-structure, and stress corrosion cracking (SCC) behaviour of U-bend samples were investigated by X-ray diffraction (XRD) technology, optical microscope (OM) and transmission electron microscope (TEM) observations. Two important factors to influence SCC initiation, residual stress and grain refinement, were discussed in detail by using different types of treatment processes. Results showed massive LP impacts can induce both deep compressive residual stress and refined grains in the surface layer of ANSI 304 stainless steel, and the corrosion mechanism of massive LP impacts on SCC was also analysed and revealed.

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1. Introduction

Laser peening (LP), also known as laser shock processing, is a cold machining process, and is also a novel and promising surface modification technique to improve the fatigue durability, corrosion properties, wear resistance and other mechanical performances of metallic materials and alloys due to the grain refinement in their surface layer [1–4]. The shock wave can induce relatively deep compressive residual stress in the surface layer of the metals and alloys by comparison with the conventional surface treatment techniques, such as shot peening [5,6], surface mechanical attrition treatment (SMAT) [7,8] and equal channel angular pressing (ECAP) [9,10]. Stress corrosion cracking (SCC) is one of the most severe maintenance problems in the power generation industry today, and the investigation on SCC in power generation industry attracts more and more attentions of researchers from the explosion of the nuclear power plant in Japan. Particularly, many crack failures occur as a result of the cyclic stress combined with corrosion [11]. Austenitic stainless steel has numerous industrial applications due to a good combination of mechanical properties and corrosion resistance. However, it is extremely susceptible to localised forms of corrosion like pitting and SCC, and in particular, it is highly vulnerable to chloride SCC [12]. SCC usually occurs when the following three factors superpose simultaneously: a susceptible material, exposure to a corrosive environment, and tensile stresses above a threshold, including residual stress [13].

There have been many reports on the effects of LP on the corrosion resistance of metallic materials. In particular, the effect has been demonstrated through actual applications as preventive maintenance against SCC in the operating nuclear power reactors. After treated by LP, without any other protective coating, water-immersed ANSI 304 exhibits a good capability to prohibit the SCC initiation and the propagation of small pre-cracks in an environment that is more vulnerable to SCC, due to the fact that the surface residual stress was converted from tensile residual stress to the high-level compressive residual stress [14]. The influences of LP on the pitting corrosion behaviour has been investigated and evaluated, and results showed that LP can improve the pitting corrosion behaviour of 316L steel in a NaCl 0.5 M solution [15]. The SCC behaviour of 316L stainless steel subjected to LP has been investigated, and LP can effectively prevent the initiation of SCC cracks in the boiling magnesium chloride ($MgCl_2$) solution [16]. LP has been found to increase the pitting potential of AA 2050-T8 aluminium alloy [17], but has no significant effect on the solubility of hydrogen in alloy 22 [18]. The above investigations focused on either the corresponding experimental results or the improvement of residual stress induced by refined micro-structures during LP.

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In fact, LP can generate relatively deep compressive residual stress and refine the coarse grain in the surface layer of metallic materials [1,3]. Residual stress and micro-structure of metallic materials are two important factors to restrict the SCC initiation. Few studies investigated on the effects of both residual stress and grain refinement on the SCC resistance. In industrial applications, massive LP impacts is an effective method to induce uniform compressive residual stress across the entire surface of the metallic component, and the overlapping rate between the adjacent round spots is usually 50% in both transverse direction and longitudinal direction [19,20]. Compared with conventional surface treatment techniques, the influence process and the improvement mechanism of massive LP impacts on the corrosion resistance of metallic materials are explored to a far less degree, in particular, the effects of residual stress combined with refined micro-structure during massive LP impacts is still not well elucidated. Hence, the corrosion behaviour of metallic materials subjected to massive LP impacts is worth to be investigated.

The purpose of this paper is to investigate the effects of massive LP impacts on the SCC behaviour of ANSI 304 austenitic stainless steel and highlight the distribution of surface residual stress, the SCC initiation and micro-structure on the top surface of three types of U-bend samples. In addition, the mechanism of massive LP impacts on the corrosion resistance of ANSI 304 austenitic stainless steel is also revealed.

2. Experimental procedures

2.1. Sample preparation

The material subjected to LP was commercial ANSI 304 stainless steel with chemical composition of 0.06C–0.48Si–1.54Mn–18.47Cr–8.3Ni–0.3Mo–0.37Cu–0.027Nb–Fe (wt.%). The yield strength of ANSI 304 stainless steel was 205 MPa, and its Vickers-hardness was 200 HV. All original steel plates of $15 \times 75 \times 3\ mm^3$ were cut from the same plate, and the dimensions of the steel plate and the U-bend sample were shown in Fig.1. These steel plates were ground with different grades of SiC paper (from 500 to 1600), and then were followed by cleaning in deionized water. Ultrasonic cleaning was used to degrease the sample surface in ethanol. Subsequently, LP experiments were performed shortly after preparation. The as-processed steel plates were bended to the U-bend samples in accordance with ASTM G36-1994 [21]. In the present study, there are three types of U-bend samples, and each type has seven samples. Fig. 2 shows the schematic diagrams for the three types of the U-bend samples. The first type of sample (the U-bend sample) is bended from the original steel plate, as shown in Fig. 2(a). The second type of sample, the U-bend LPed sample, is bended from plate after the LP treatment, in which the LP impacts treated surface is located in the middle region of the upper surface of the sample (Fig. 2(b)). The third one is the LPed U-bend sample, which is made by first bending the original steel plate into U shape, and followed by LP treatment in the middle region in the upper surface of the U-bend sample (as shown in Fig. 2(c)).

2.2. Experimental parameters

The massive LP impacts were carried out using a Q-switched Nd: YAG (Neodymium doped Yttrium Aluminium Garnet) laser system operating at 1064 nm wavelength and delivering 3 J pulse energy in 10 ns top-hat pulse, with 5 Hz repetition-rate. The laser beam was focused on the sample surface to be treated with a spot diameter of 3 mm. During LP, all samples to be treated were submerged into a water bath, and a uniform water layer with a thickness of 1 mm was used as the transparent confining layer. The 3 M professional aluminium tape with a thickness of 100 μm (Made in USA) was used as an ablation medium for plasma initiation to protect the sample surface from the thermal damage of high-temperature plasma. During the LP experiment, the laser beam was perpendicular to the sample surface all the time, and the overlapping rate between two adjacent spots was 50% in order to ensure no blind area at the shocked region (as shown in Figs. 1 and 2).

The SCC tests were performed in boiling 42% $MgCl_2$ solution, and the test solution was held at a constant boiling temperature of 143 ± 1 °C. The solution was prepared by adding a predetermined quantity of reagent grade $MgCl_2$ to distilled water into the flask. When the $MgCl_2$ solution started boiling, it was adjusted to keep the boiling temperature at 143 ± 1 °C through the addition of distilled water. All the U-bend samples were immersed into

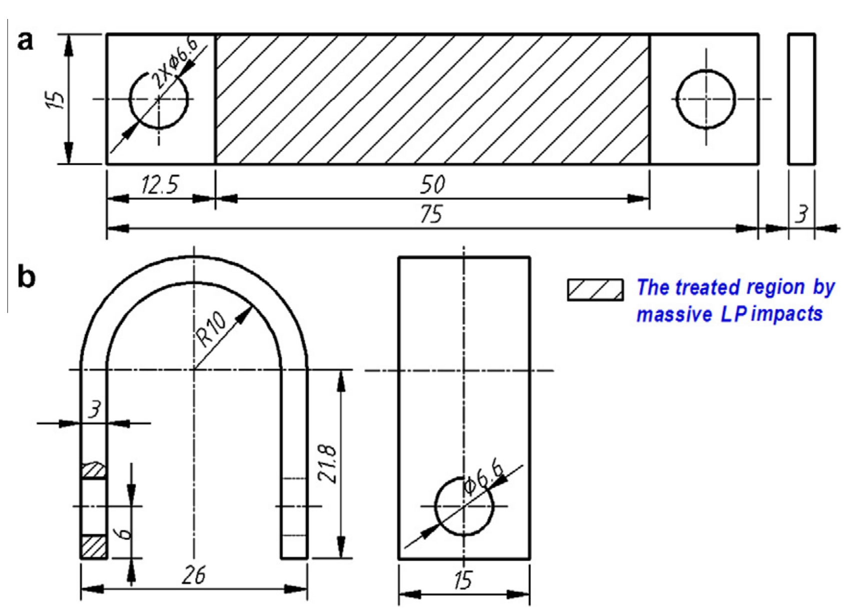

Fig. 1. Dimensions of (a) the steel plate and (b) the U-bend sample (unit: mm).

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