Journal of Alloys and Compounds 773 (2019) 168–179

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Effects of laser shock peening with different coverage layers on fatigue behaviour and fractural morphology of Fe-Cr alloy in NaCl solution

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ARTICLE INFO

Article history:
Received 12 June 2018
Received in revised form
10 September 2018
Accepted 13 September 2018
Available online 22 September 2018

Keywords:
Laser shock peening
Fe-Cr alloy
Fractural morphology
Corrosion fatigue
Stress corrosion

ABSTRACT

Effects of massive laser shock peening (LSP) treatment as a function of coverage layer on surface residual stress, microstructure, and corrosion fatigue (CF) resistance of Fe-Cr alloy were studied by X-ray diffraction technique, scanning electron microscope observations, and corrosion fatigue crack growth (CFCG) testing. Special attention was paid to the details of compressive residual stress and fracture morphology, and the influence mechanism of coverage layer on CF behaviour was also determined. Results indicated that LSP generated deeper compressive residual stress and effectively decreased the CFCG rate, and increased coverage layers further improved the corrosion fatigue life of notched specimens.

1. Introduction

Fe-Cr alloy, such as 2Cr13 martensitic steel, 3Cr13 martensitic steel, and 4Cr13 martensitic steel, are commonly used as a structural material for components such as steam turbine blades, impellers, and hydraulic press valve plates owing to its relatively high strength, excellent oxidation and corrosion resistance [1,2]. Most of these components are applied to heavy machinery that operates in aggressive conditions, such as high stress loading and corrosive environments. In engineering applications, corrosion fatigue (CF) fracture usually occurs during the interaction between cyclic loading and a corrosive environment [3], including seawater environment, liquid droplet erosion environment and cavitation erosion environment. Therefore, in the above corrosive environment, the service life of Fe-Cr alloys depends mainly on the surface properties. At present, the traditional surface treatment technologies, including tempering [4], low temperature plasma nitriding [5], and ultrasonic shot peening [6], have proven to be powerful tools for improving corrosion fatigue resistance. However, the parts prepared by low temperature plasma nitriding cannot withstand too much contact stress and high impact loading; and the compressive residual stress layer induced by tempering and ultrasonic shot peening is relatively shallow.

Compared with these methods mentioned above, laser shock peening (LSP), an effective surface-strengthening technology, has been widely used to refine the coarse grain and improve the mechanical performance of alloys and metals [7,8]. It is well known that LSP can induce ultrahigh-strain-rate plastic deformation and high-amplitude compressive residual stress in the surface layer, which is beneficial to reducing the fatigue crack growth rate [9,10] and improving fatigue life [11–13]. The author's previous research [14] revealed that LSP effectively causes a significant improvement in ultimate tensile strength (UTS), stress corrosion cracking (SCC) resistance, and electrochemical corrosion resistance of American Iron and Steel Institute (AISI) 304 stainless steel in a 0.598 mol/L sodium chloride (NaCl) solution. Meanwhile, the corresponding corrosion resistance can be gradually improved by increasing the pulsed energy of a laser beam. Correa et al. [15] investigated the relationship between the advancing direction of the laser scanning path and the fatigue resistance of 316L stainless steel, showing that the high-cycle fatigue (HCF) life of the LSP treated (LSPed) specimens was improved from +166% to +471% by the optimization of pulsed sequence. Ge et al. [16] investigated the effects of LSP treatment on AZ31B magnesium alloy and demonstrated that an obviously lower fatigue crack growth (FCG) rate occurred for LSP-

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https://doi.org/10.1016/j.jallcom.2018.09.147
0925-8388/

treated samples owing to the combined effect of surface nanocrystalline and deeper compressive residual stress. Bergant et al. [17] investigated the effects of LSP without a protective coating on the HCF crack propagation rate and fracture ductility of 6082-T651 Al alloy. In regard to the initiation of fatigue microcracks, a lower number of cycles were needed and faster fatigue crack propagation emerged in the state of tensile residual stress of LSPed specimens. Compared with the as-machined specimen, the threshold of the crack propagation was reduced by 60% after massive LSP treatment.

The above-mentioned investigations mainly focused on the effects of massive LSP treatment on SCC performance and FCG behaviour of austenitic stainless steel, magnesium alloy, and aluminum alloy [18]. In fact, the coverage layer and the concentration of corrosive solution are significant factors affecting the CF life of metallic components. However, few researchers have explored the effect of the coverage layer and the concentration of corrosive solution on CF behaviour of LSPed Fe-Cr alloy. Therefore, the need for a systematic investigation into the effect of the coverage layer and the concentration of corrosive solution on the CF behaviour of LSPed Fe-Cr alloy is of the essence.

The purpose of this paper is to report on an investigation into the relationship between the CF behaviour of Fe-Cr alloy and the coverage layer of massive LSP treatment in 0.598 mol/L (3.5 wt.%) and 1.71 mol/L (10 wt.%) NaCl solutions. The effects of LSP on the corrosion fatigue crack growth (CFCG) rate and fatigue life were investigated, and surface residual stresses along the notched tip of three kinds of notched specimens were characterized and analyzed before and after a three-point bending CFCG experiment. In particular, the fracture morphologies and the corrosive products of the as-machined and LSPed specimens were characterized and compared after the CFCG experiment. Finally, the influence mechanism of coverage layer on the CF resistance of Fe-Cr alloy was determined.

2. Material and experimental work

2.1. Experimental material and LSP parameters

The selected Fe-Cr alloy in the present work was 2Cr13 martensitic stainless steel, and its chemical composition was 0.20 wt.% C, 0.45 wt.% Si, 0.41 wt.% Mn, 0.021 wt.% P, 0.060 wt.% S, 0.53 wt.% Ni, 12.61 wt.% Cr, 0.12 wt.% Cu, and balanced Fe. Its Vickers hardness and yield strength are 202–210 HV and 440 MPa, respectively. The CFCG tests were conducted with a three-point, single-edge notched bending structure [19], as shown in Fig. 1a. All of the three-point bending specimens were machined into a cuboid with dimensions of 140 mm (length) × 30 mm (width) × 15 mm (height) from a same sheet. The corresponding dimensions are shown in Fig. 1b. And a notch with a length of 11 mm was made in the middle of the specimen using wire cutting technology, as shown in Fig. 1d. Both sides of all specimens were gradually ground using different silicon carbide (SiC) papers (varying from 240- to 2000-grit) and then cleaned using the deionized water. After grinding, the average surface roughness (Ra) was less than 0.8 μm. Specimens were then immersed in ethanol and cleaned by ultrasonic wave. Subsequently, the specimens were subjected to a massive LSP treatment with different coverage layers after preparation.

A massive LSP treatment was performed using a Q-switched Nd: YAG laser system operating at an irradiation wavelength of 1064 nm. The laser spot diameter is 3 mm, whereas the pulse duration, repetition rate and pulse energy is 10 ns, 5 Hz and 5 J, respectively. To obtain a uniform strengthening effect, the overlapping rates between the two neighbouring laser spots in the transverse and longitudinal directions were maintained at 50%. The function and selection of the absorbing layer and the confining medium are discussed in the authors' previous publication [20].

In order to study the effects of the LSP coverage layer on CF behaviour, a 2 mm preexisting crack was fabricated by cold extrusion. Its location and direction are shown in Fig. 1d. Both square regions, with dimensions of 21 mm × 21 mm below the notch at both sides, were selected for massive LSP treatment, called "the LSPed region." The starting point, end point, and scanning path are schematically shown in Fig. 1c.

There were three kinds of three-point, single-edge notched bending specimens. The untreated specimen was called the as-machined specimen, and the LSPed specimens with one and two coverage layers were defined as the LSP-1 specimen and the LSP-2 specimen, respectively.

2.2. CFCG test

The CFCG tests were carried out on an MTS810 electro-hydraulic servo fatigue testing system at room temperature in the NaCl solution and included the corrosion fatigue fixture, corrosive environment test box, and a self-developed machine, as shown in Fig. 2a. The centerline of the upper and lower chucks of the specimen was the same as that of the testing machine's main shaft when the specimen was installed. The maximum deviation of the centerline of the upper and lower chucks was checked by the concentric test standard rod, the allowed values of which were less than 5%. The centerline deviation of the main shaft and specimen center were less than 0.125 mm. Fig. 2b shows the schematic diagram of the CFCG test. The specimens were fixed by the upper chucks, and the cyclic load was generated by the lower chuck during the CFCG test.

In the CFCG test, the compliance method was used to measure the length of the preexisting crack and, indirectly, the cycle curve, as shown in Fig. 2a. To avoid corrosion of the extension gauge, the single-edge notch of the three-point bending specimen was placed upward; and the extension gauge was installed above the notch. The crack tip was covered by the corrosive solution to ensure that the crack growth region could be fully immersed in the corrosive solution, as shown in Fig. 2b.

During the CFCG test, two kinds of corrosive environments, 0.598 mol/L and 1.71 mol/L NaCl solutions, were chosen. The load ratio $R = P_{min}/P_{max}$ was kept at 0.1, and the loading frequency of 8 Hz with a triangular waveform was used. A preexisting 2 mm fatigue crack was created on each specimen before the LSP treatment and CFCG test, per ASTM E647:1995, as shown in Fig. 1d. To ensure the reliability of the measurements, two specimens were measured in each group. The crack increment interval was set to 0.05 mm, and the cycle number N and the corresponding crack length a were recorded. After the CFCG test, all fractural surfaces were cut from the failed specimens and then cleaned in ultrasonic acetone and dried by cold air.

2.3. Residual stress measurement

Residual stress measurement was carried out by X-ray diffraction (XRD) with Cr-Kα radiation in an X-350A X-ray diffractometer with the $\sin^2\psi$ method [21]. The X-ray beam diameter was set to approximately 1 mm. The initiating scan angle and terminating angle were 161° and 152°, respectively. The β phase (220) plane was used for measuring the residual stress, and the X-ray elastic constant used to calculate residual stresses was 220 GPa. As shown in