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Effect of laser peening on electrochemical properties of titanium stabilized 321 steel

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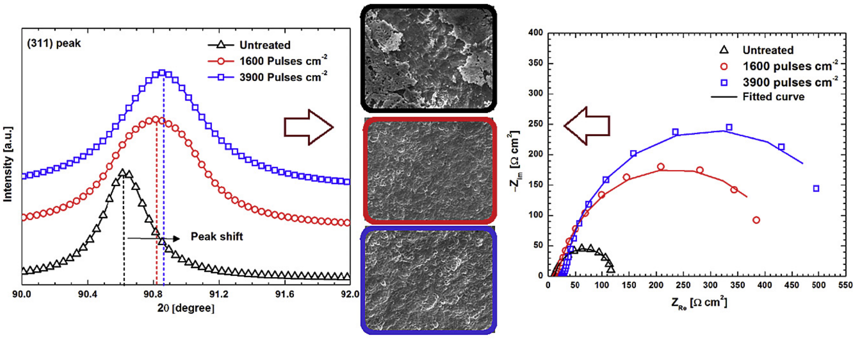
HIGHLIGHTS

- Corrosion rate of Ti-stabilized 321 steel lowered 19 times after laser peening.
- Charge transfer resistance increased 5 times after laser peening.
- Residual stresses (−854 MPa) induced by laser peening increased the corrosion resistance.
- Materials dissolution occurred preferentially at α' martensitic phases.
- Roughness (≤ 1 μm) after peening did not influence the electrochemical properties.

GRAPHICAL ABSTRACT



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ABSTRACT

Influence of deformation induced martensitic (α') phase transformation and compressive residual stresses on electrochemical properties of austenitic (γ) 321 steel laser peened without protective coating in acidic solution was investigated. Peening induced compressive residual stresses lowered the corrosion rate 19 times compared to untreated condition, subdued the deleterious role of α' phase. Presence of dual phases (γ and α') ensued multiple peaks in the active region of the polarization curve and pitting at α' phase sites. Roughness after peening (≤ 1 μm) had no effect on corrosion properties. A fivefold increase in charge transfer resistance observed after peening.

1. Introduction

AISI 321 steel is used for pressure vessel internals in VVER-1000 (Vodo-Vodyanoi Energetichesky Reaktor) type nuclear reactor [1] and as desulfurizers in petroleum refining plants [2] because of its good mechanical strength and moderate resistance. Nonetheless, its poor susceptibility towards stress corrosion cracking [3], inter-granular [4,5] and localized corrosion [6] failures under extreme corrosive environments, for example, simulated petrochemical environment containing hydrogen sulfide and chloride has been reported, and urged a need of an efficient surface modification method to overcome these issues. Over the years, number of such methods, for example, shot peening (SP) [7], supersonic fine

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particles bombarding (SFPB) [8,9] and ultrasonic impact peening (UIP) [10] has been applied to enhance the surface integrity of this alloy against aforesaid failures. Despite the merits of SP, SFPB and UIP like enhancing surface properties for better corrosion resistance, they commonly introduces larger surface irregularities (micro-cracks and increased peaks and valleys), shallower compressive residual stresses (CRS) and higher degree of percentage of cold working; and that would lead rapid relaxation of CRS when processed alloy is exposed to high temperatures. These limitations are the major concerns with above mentioned methods.

As an alternative to these conventional methods, an advanced laser based technique called *laser peening without coating* (LPwC) has been developed in 1995. Unique features of LPwC are: (1) it requires no surface protective coatings, (2) laser pulses can be delivered through a flexible optical fiber for treating materials in this process, (3) it is very suitable to treat water immersed object using water penetrable laser wavelengths and (4) applicable for nuclear reactor facilities and other extreme environments requiring a full remote operation [11]. AISI 321 steel was LPwC treated previously by Mordyuk et al. [12] and by us [13] recently. Mordyuk et al. [12] reported a relatively smaller CRS, no $\gamma \rightarrow \alpha'$ phase transformation (γ−austenitic, α'−martensitic phases) after LPwC as a consequence of smaller laser power density (2 GW cm^{-2}) used which is generally inadequate to imparted appreciable CRS too. In contrast, we noticed [13] larger CRS of ~850 MPa near treated surface (~at 50 μm depth) and $\gamma \rightarrow \alpha'$ phase transformation having α' volume fraction of ~18% through LPwC with appropriate laser power density of ~6 GW cm^{-2}.

In general, the corrosion behaviour of LPwC surface with significant CRS, $\gamma \rightarrow \alpha'$ phase transformation and peening introduced roughness would be different as, (1) the CRS can lower the corrosion current density by forming a highly dense and stable passive film [14], (2) largely introduced surface roughness would enhance the corrosion rate [15] and (3) presence of dual γ and α' phases would lead galvanic coupling effect and in particular, α' phase could accelerate the corrosion rate [16,17]. Considering the surface roughness aspect on corrosion behaviour of laser peened alloys, recent review on LPwC [18] reports appreciable corrosion resistance with surface roughness of ~4 μm after LPwC at laser pulse energy of ≥1 J. On the other hand, Kalainathan et al. [19] observed enhanced corrosion resistance in AISI 316 L steel with surface roughness of ~1.4 μm after LPwC at laser pulse energy of 0.3 J. These results suggest that laser pulse energy of ≤0.3 J would result in smaller surface roughness (≤1 μm) [20], which may have minimal influence on corrosion properties of peened alloys.

Having the peening induced α' phase into account, as it can induce the galvanic coupling effect and enhance the corrosion rate to a larger extent, we observed reversion of α' phase that is $\alpha' \rightarrow \gamma$ transformation after annealing treatment of LPwC treated AISI steel [13]. However, in addition to $\alpha' \rightarrow \gamma$ transformation, CRS was largely relaxed at least in one of the principal axes, which in turn is not favourable considering the mechanical and corrosion properties. Previously, Burstein et al. [21] suggested a technique called electrochemically annealing for $\alpha' \rightarrow \gamma$ transformation without affecting bulk properties of the alloy prior to being subjected to any of the surface modification treatment processes. The present investigation is aimed at studying electrochemical behaviour of LPwC treated AISI 321 steel without any such post treatments considering the practical use of treated material in as peened surface conditions. To the best of our knowledge no such investigations was reported previously with LPwC. It is therefore, in this report, an attempt is made to understand the mutual influence of α' phase, CRS and surface roughness on electrochemical properties of AISI 321 steel using potentio-dynamic polarization, electrochemical impedance spectroscopy (EIS) and scanning electron microscopy equipped with energy dispersive spectroscopy (SEM/EDS) techniques.

2. Materials and methods

2.1. Test specimens

Test specimens of dimension of 20 × 20 mm^2 area were cut using electric discharge machine cutting from commercially purchased AISI 321 steel plate of 5 mm thickness. The elemental composition of this alloy was studied using a Spark Analyzer (Thermo Electron, USA) and the result is shown in Table 1. A stress relief annealing was employed at 700 °C for 2 h on all the specimens which were then ground mechanically up to 2000 grit size, degreased in acetone.

2.2. Laser peening process

A Q-switched and pulsed Nd:YAG laser capable of delivering pulses of wavelength of 1064 nm at pulse duration of 10 ns, pulse repetition rate of 10 Hz was used for peening. Peening was conducted at room temperature (~25 °C) with water layer of 1–2 mm thickness (made) on the specimen's surface as confinement medium. Characteristics of the laser beam utilized in this study are as follows: (1) Guassian beam with pointing stability of less than ± 70 μrad and (2) divergence at output of ≤0.5 mrad [20]. Basic principle of LPwC process has been detailed in our previous study [20]. The spot diameter at specimen's surface and laser pulse energy were set to 0.8 mm and 0.3 J respectively to achieve laser power density of 5.97 GW cm^{-2}. Peening was carried on 10 mm × 10 mm area with pulse densities 1600 and 3900 pulses cm^{-2}. Followed by Peening, specimens were cleaned thoroughly in acetone for few minutes and dried.

2.3. Measurement of residual stresses, phase transformation and roughness

Residual stresses (RS) were measured on (311) peak using X'pert Pro system (PANalytical, Netherlands) equipped with characteristic $CuK\alpha_1$ ray ($\lambda = 1.5406$ Å). Average RS between longitudinal (L) and transverse (T) directions with respect to the specimen dimension (and zigzag type LPwC scan) was obtained from standard XRD $\sin^2\Psi$ method. Further, a high resolution X-ray diffraction instrument (Brucker D8, USA) was operated over a 2θ scan range of 40°−100° with step size of 0.02° to analyze phase transformation, peak broadening and lattice strain effects. Surface roughness was evaluated using an atomic force microscope (AFM) (Nanosurf easyscan2, Switzerland).

2.4. Electrochemical tests

Electrochemical tests were conducted at room temperature (~25 °C) at peened and untreated surfaces. Here, to understand the role of surface roughness, presence of α' phases on electrochemical properties and to avoid any loss of information at as peened surfaces, no post polishing processes were carried out on the peened specimens. A classical three electrodes setup was used to perform potentio-dynamic polarization and EIS studies in

Table 1
Elemental composition of AISI 321 steel.

Element	C	Cr	Ni	Mn	Si	Ti	P	S	Fe
wt%	0.053	17.14	9.09	1.65	0.49	0.34	0.022	0.015	rest