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Effect of laser shock peening on stress corrosion sensitivity of 304 stainless steel C-ring weld specimens

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Abstract

As a new surface treatment technology, laser shock peening (LSP) can improve the corrosion resistance and fatigue performance of the metal surface with the help of a high-power density laser beam. In this work, 304 stainless steel C-ring weld specimens were treated with four laser power densities, and the effect of LSP on the surface properties of the specimens was investigated by microhardness measurement, grain size analysis and residual stress test. The research shows that LSP can improve the surface microhardness, produce grain refinement, and transform the residual tensile stress into residual compressive stress in the surface layer of 304 stainless steel. Electrochemical corrosion test and the constant strain corrosion test in boiling magnesium chloride solution were carried out. The results show that the crack initiation time of the C-ring weld specimens treated with LSP is significantly longer than that of the specimens without LSP. As the laser power density of LSP increases, the corrosion current density and the corrosion rate are decreased greatly, the polarization resistance is increased significantly, and the crack initiation time is increased evidently.

1. Introduction

It is known that 304 stainless steel has many excellent properties such as good corrosion resistance, high temperature (or low temperature) resistance and good weldability, it has good strength and plasticity in the temperature range of −196 °C−600 °C, so it is widely utilized in various fields [1–4]. However, 304 stainless steel is easy to cause stress corrosion cracking in severe conditions of corrosive environments of chloride solution. For the 304 stainless steel welded pipe, there are high stresses caused by internal pressure and welding temperature field, and the composition, organization and performance are non-uniform in the welded joint, so it is more likely to cause stress corrosion cracking. 304 stainless steel welded pipes are currently widely used in chemical equipment and nuclear industry equipment, and stress corrosion cracks in welded components can lead to severe consequences. Therefore, studying the method and mechanism for improving the stress corrosion resistance of 304 stainless steel welded pipes is of great significance. In this study, the loaded C-ring weld specimens were selected to simulate the welded pipe under internal pressure and welding residual stress.

There are many methods to improve the stress corrosion resistance of 304 stainless steel welds. For example, improving the structure of welded joints to reduce stress concentration, performing post-weld heat treatment to eliminate welding residual stress, using surface modification techniques to improve stress corrosion resistance. The usual surface modification techniques include high energy shock peening [5], ultrasonic shock peening [6], surface mechanical attrition treatment [7], and laser shock peening (LSP) [8], etc.

LSP is an innovative surface treatment technology that has been proven to be capable of refining the surface grains [9] and inducing high magnitude residual compressive stress [10]. Compared with other surface modification technologies, LSP can more effectively improve the performance of the metal surface layers, such as microhardness [11, 12], wear resistance [13, 14], and stress corrosion resistance [15, 16]. Lu et al [15] treated 304 stainless steel by LSP and carried out slow strain rate test and potentiodynamic polarization test. Results showed that LSP can induce residual compressive stress, refine grains, and improve the stress corrosion...
resistance of 304 stainless steel. Wang et al [17] studied the effect of LSP on the stress corrosion behavior of 7075 aluminum alloy laser welded joints. The research indicated that the static toughness of samples with LSP was two times higher than that of samples without LSP, the elastic modulus ultimate tensile was increased by about 30%, and the elongation of the base alloys showed an increase from 7.62% to 11.13%, the stress corrosion cracking resistance of 7075 aluminum alloy laser welded joints was improved by way of LSP treatment. However, there is almost no research on the stress corrosion resistance of 304 stainless steel welded pipes with LSP treatment.

The main stress corrosion test methods include the constant displacement test method [18–20], the slow strain rate tensile test method [21, 22], and the constant strain test method [23, 24]. The constant displacement test method is based on linear elastic fracture mechanics, which is suitable for crack growth test of high-strength steel at low-stress levels ($\sigma/\sigma_s \leq 0.5$), and large size is needed for its specimen to maintain the plane strain state, so there are many restrictions on the application of this method. The slow strain rate tensile test method is used by many researchers, the test must be carried out on a special testing machine, and only the qualitative sensitivity index can be calculated, the quantitative crack growth rate of stress corrosion cannot be gotten from the test results. Compared with the above two methods, the requirements of testing machine and specimen processing are relatively low for the constant strain test method, the specimens can be loaded by themselves, the crack growth rate of stress corrosion can be quantitatively measured, and the crack morphology and crack initiation time can be obtained. So the constant strain test method for C-ring weld specimens was adapted.

In this work, the C-ring weld specimens of 304 stainless steel were treated with four laser power densities by the LSP method. Through microhardness measurement, grain size analysis, and residual stress test, the enhanced effects of LSP on surface properties have been studied. The constant strain corrosion tests of C-ring weld specimens were carried out in 42% boiling magnesium chloride solution, the electrochemical corrosion tests of 304 stainless steel C-ring welds were done in saturated magnesium chloride solution at room temperature, and the crack microscopic morphology was observed by a metallurgical microscope. The effect of LSP on stress corrosion resistance of 304 stainless steel C-ring weld specimens has been studied.
2. Materials and methods

2.1. Specimens and LSP experimental procedure

The C-ring weld specimens were first cut from 304 austenitic stainless steel pipes, and then welded by argon arc welding (welding current 110–130 A, welding voltage 10–11 V, welding speed 130–180 mm min⁻¹), the schematic diagram of the specimens is shown in figure 1 (The data in the figure is in mm units). Specimens were loaded to a stress level of 80% yield stress with 304 austenitic stainless steel nuts and bolts according to the standard GB/T 15970.5–1998 Corrosion, Stress Corrosion Test of Metals and Alloys Part 5: Preparation and Application of C-ring Specimens [25], the yield strength of specimens at room temperature is about 205 MPa. The required displacement for the 80% yield stress can be calculated according to the following equation:

\[ \Delta D = \frac{\sigma d^2}{4EZ} \]  \hspace{1cm} (1)
where \( \Delta D \) is the required displacement (mm), \( \sigma \) is the stress to be applied (MPa), \( d \) is the average diameter of the C-ring (mm), \( t \) is the wall thickness of the C-ring (mm), \( E \) is the elastic modulus (MPa), \( Z \) is the bending beam correction coefficient which can be obtained from figure 2. The stress of the C-ring specimen was simulated by finite element method, the maximum stress was located in the central area of the welding, the value is 164.51 MPa, as shown in figure 3.

The Nd:YAG nanosecond laser (wavelength 1064 nm, pulse width 10 ns, repetition rate 5 Hz) was utilized for LSP treatment. Refer to the parameters adopted in correlation studies \([26, 27]\), specimens were treated with four laser power densities: 3.537 GW \( \text{cm}^{-2} \), 4.244 GW \( \text{cm}^{-2} \), 4.951 GW \( \text{cm}^{-2} \) and 5.659 GW \( \text{cm}^{-2} \), respectively.

The laser spot diameter was 3 mm, the overlapping rate was 50%, and the U-shaped scanning path of LSP was adapted, as shown in figure 4. For comparison, the specimens without LSP were set as the reference group. In order to increase the peak pressure of the shock wave and prolong the action time, 1–2 mm thick flowing water was used as the transparent constrained layer during the LSP process. A 1 mm thick aluminum foil was adopted.

**Table 1.** Process parameters of laser shock peening.

| Specimens No | Pulse energy \( E_n \) (J) | Power density \( I \) (GW \( \text{cm}^{-2} \)) | Lap rate (%) | Spot diameter \( D \) (mm) | Pulse width \( \tau \) (ns) | Absorption layer | Constrained layer |
|--------------|-----------------------------|----------------------------------|---------------|--------------------------|-------------------|-----------------|-------------------|
| S1           | 2.5                         | 3.537                            | 50%           | 3                        | 10                | Aluminum foil   | Water             |
| S2           | 3                           | 4.244                            | 50%           | 3                        | 10                | Aluminum foil   | Water             |
| S3           | 3.5                         | 4.951                            | 50%           | 3                        | 10                | Aluminum foil   | Water             |
| S4           | 4                           | 5.659                            | 50%           | 3                        | 10                | Aluminum foil   | Water             |

**Figure 5.** The microhardness measurement points along the depth direction.

**Figure 6.** The distribution of the residual stress measurement points.
as the absorption layer to promote the absorption of laser energy and reduce thermal damage due to heat and vaporization on the surface of the material, the process parameters of LSP are listed in table 1.

2.2. Characterization of the specimens
The microhardness of the surface layer was measured with an HMV-2TADWXY automatic Vickers hardness tester. The indenter load and the dwell time were set to 0.49 N and 10 s. The measurement points along the depth direction are shown in figure 5 (The distance in the figure is in µm units).

The microstructure in the near-surface layer was observed with a metallographic microscope. Before the microstructure observation, the specimens were corroded with 10% oxalic acid solution, corrosion current density and corrosion time were set to 1 mA cm$^{-2}$ and 40–60 s, respectively.

The residual stress in the subsurface layers of the specimen was measured by an x-350A X-ray diffraction according to the sin$^2$ψ-method. The diffraction angle 2θψ of the X-rays at different off-axis angles ψ are measured, and the residual stress can be calculated based on the slope of the 2θψ-sin$^2$ψ line [28, 29]. Additionally, the measurement points are shown in figure 6 (The data in the figure is in mm units), points 1 and 2 are in the welding area, and points 3 and 4 are in the heat-affected zone and the base material zone, respectively.

2.3. Corrosion tests
2.3.1. Electrochemical corrosion tests
Electrochemical corrosion tests were carried out on a CS350 electrochemical workstation, and electrochemical characteristics of specimens were measured by dynamic potential scanning method in saturated magnesium chloride solution at room temperature. Prior to the electrochemical test, the argon gas was injected into the solution to remove the oxygen. The electrical potential was measured with a three-electrode system consisting of a working electrode (the test specimen), a counter electrode (the platinum mesh) and a reference electrode (the saturated calomel electrode). The tests were conducted at a scanning rate of 3 mV s$^{-1}$, and Tafel curves were generated from the potentiodynamic polarization experimental data.
2.3.2. Constant strain corrosion tests

Constant strain corrosion tests were conducted in boiling 42% magnesium chloride solution. The test device is composed of a test container, heating device and condensing unit, as shown in figure 7. The magnesium chloride solution was heated to the boiling point, and then specimens were immersed in the solution. Specimens were taken out regularly, cleaned with deionized water, and observed with a magnifying glass. The time when the cracks were observed was taken as the crack initiation time, which was used as a characteristic parameter of stress corrosion sensitivity.

After constant strain corrosion tests, Specimens with cracks were polished and corroded with 10% oxalic acid, and the microscopic morphology of cracks was observed with a metallographic microscope.

| Measuring point | Without LSP | 3.537 GW cm\(^{-2}\) | 4.244 GW cm\(^{-2}\) | 4.951 GW cm\(^{-2}\) | 5.659 GW cm\(^{-2}\) |
|-----------------|-------------|-----------------|----------------|----------------|----------------|
| 1               | 239.2       | −77.7           | −188.4         | −131.2         | −357.5         |
| 2               | 123.8       | −81.7           | −139.9         | −254           | −297.4         |
| 3               | −11.1       | −117            | −107.4         | −320.9         | −287.3         |
| 4               | 241.2       | −62.4           | −214           | −132           | −259.7         |

Figure 8. Residual stress distribution under different laser power densities.

Figure 9. Optical observation of the microstructure in the near-surface layer of the 304 stainless steel without laser shock peening.

Table 2. Results of residual stress tests.
3. Results and discussion

3.1. Surface residual stress
The measurements of residual stresses are shown in table 2 and figure 8. It can be seen from figure 8 that the residual stress on the surface layer of the specimen without LSP treatment was mainly tensile stress, which was attributed to the non-uniform temperature distribution of the welding area, and the maximum tensile stress was formed in the weld zone. After LSP treatment, the residual tensile stress was transformed into residual compressive stress ranging from $-62.4$ to $-357.5$ MPa, its distribution was more uniform than that of the specimen without LSP. With the increase of laser power density, the value of residual compressive stress on the sample surface gradually increases. When the laser power density increased to $5.659$ GW cm$^{-2}$, the residual compressive stress magnitude was about $357.5$ MPa which exceeds the yield strength of the material, it is helpful to improve the stress corrosion resistance.

3.2. Microstructure
The microstructure of the welding area of the specimen without LSP is shown in figure 9, the equiaxed grains were mainly observed. The grains were distributed uniformly, the grain size was large, and the diameter of grains varied from a dozen microns to tens of microns. The microstructure of the welding area of the specimens treated with different laser power densities is shown in figure 10, the grains were refined, the micron-level grains and sub-grains can be observed clearly (figure 10(a)–(d)). The twin structure with a size of only a few microns can be found at 100 microns from the surface of the specimen (figure 10(a)). With the increase of laser power density, the grain size of the surface layer decreases significantly. After LSP treatment, the surface layer underwent severe plastic deformation, numerous dislocations and twins were formed, and the original coarse grains were refined. The accumulation of dislocation lines led to the formation of multi-directional stacking faults and plane dislocation arrays. The grains were further refined as the multi-directional twins and plane dislocation arrays intersected with each other, and the mechanical twins were transformed into sub-grains. The strength of the material with randomly distributed refined grains is increased, the crack growth is inhibited, and the stress corrosion resistance of specimens is improved.

Figure 10. Optical observations of the microstructure in the near-surface layer of the 304 stainless steel with four laser power densities: (a) $3.537$ GW cm$^{-2}$, (b) $4.244$ GW cm$^{-2}$, (c) $4.951$ GW cm$^{-2}$, (d) $5.659$ GW cm$^{-2}$. 
The average Vickers hardness of the surface layer of specimens is shown in Table 3 and Figure 11. It can be seen from Table 3 that the microhardness of the surface layer increases significantly with increasing laser power density. When the laser power density increased to 5.659 GW cm\(^{-2}\), the hardness value of the welding surface increased to about 236.8 HV0.05, which is about 16% higher than that of the weld without LSP treatment. The microhardness of the specimens without LSP was distributed uniformly, the microhardness values in the near-surface layer were almost the same as that in the deep area from the surface. The microhardness of the specimens treated with four laser power densities tends to decrease with increasing depth. When the distance from the surface layer is more than 800 \(\mu\)m, the microhardness gradually stabilizes. It indicates that the influence depth of LSP on 304 stainless steel is about 800 \(\mu\)m under the adopted laser power density, which agrees well with the research results of Luo [30].

As mentioned above, the grains in the near-surface layer were refined after LSP treatment. Numerous dislocations were generated inside the grains, and they intersected with each other. According to the Taylor relationship of strength (\(\sigma\)) and dislocation density (\(\rho_T\)) [31]:

\[
\sigma = \alpha \mu b^2 \sqrt{\rho_T}
\]

where \(\mu\) is the shear modulus, \(\alpha\) is the empirical constant, \(b^2\) is the burgers vector. The strength (microhardness) of the material increases with the increase of dislocation density. In addition, the crystal defects such as twins will be formed with the effect of laser shock waves, and the microhardness of the defect area can also be improved. As the microhardness increases, the fatigue resistance increases, but there is no significant effect on the stress corrosion performance.

### Table 3. Microhardness (The average values) in the near-surface layer of 304 stainless steel with different laser power densities.

| Depth from surface (\(\mu\)m) | Vickers hardness (HV0.05) |
|-----------------------------|---------------------------|
|                             | Without LSP 3.537 GW cm\(^{-2}\) | 4.244 GW cm\(^{-2}\) | 4.951 GW cm\(^{-2}\) | 5.659 GW cm\(^{-2}\) |
| 0                           | 203.253                  | 217.592                  | 214                    | 232.288                  | 236.758                  |
| 100                         | 199.713                  | 216.591                  | 215.612                | 219.599                  | 224.189                  |
| 200                         | 199.552                  | 223.706                  | 227.96                 | 231.177                  | 215.569                  |
| 300                         | 203.072                  | 216.605                  | 216.538                | 207.896                  | 208.558                  |
| 400                         | 204.555                  | 223.32                   | 227.929                | 212.664                  | 206.994                  |
| 500                         | 203.253                  | 218.585                  | 220.606                | 207.916                  | 204.215                  |
| 600                         | 203.137                  | 206.039                  | 204.215                | 201.51                   | 200.315                  |
| 700                         | 202.641                  | 202.693                  | 202.427                | 196.259                  | 212.623                  |
| 800                         | 207.856                  | 203.928                  | 205.111                | 198.846                  | 206.961                  |
| 900                         | 206.618                  | 202.345                  | 204.568                | 197.181                  | 209.57                   |

**Figure 11.** Surface microhardness of the 304 stainless steel specimens with different laser power densities.
3.4. Electrochemical corrosion tests

The Tafel curves obtained for the as-received and LSP treated specimens in saturated magnesium chloride solution are shown in figure 12. From these polarization curves, corresponding values of corrosion current density ($I_{corr}$), corrosion potential ($E_{corr}$), corrosion rate ($\nu$), anodic Tafel constant ($\beta_a$) and cathodic Tafel constant ($\beta_c$) were extrapolated and are listed in table 4.

The polarization resistance ($R_P$) can be calculated according to the Stern-Geary equation (table 4) [32]:

$$R_P = \frac{\beta_a \beta_c}{2.303 I_{corr} (\beta_a + \beta_c)}$$

It can be seen from table 4 that the $I_{corr}$ of the specimen without LSP treatment is the highest, the $\nu$ is the fastest, and the $R_P$ is the lowest. After LSP, the magnitudes of $I_{corr}$ and $\nu$ were significantly reduced, while the $R_P$ value was significantly increased. When the laser power density was 5.659 GW cm$^{-2}$, compared with the specimens without LSP, the $I_{corr}$ and $\nu$ both were reduced by three orders of magnitude, and the $R_P$ value was increased by two orders of magnitude. With the increase of laser power density, the $I_{corr}$ and $\nu$ decrease, and the $R_P$ increases. According to the relationship between $I_{corr}$ and $\nu$ [33]:

![Figure 12. Potentiodynamic polarization curves of the as-received and laser shock peening treated specimens in saturated magnesium chloride solution.](image)

![Figure 13. Cracks of the specimens without laser shock peening: (a) 100 X, (b) 400 X.](image)

**Table 4.** Electrochemical parameters of the as-received and laser shock peening treated specimens in saturated magnesium chloride solution at room temperature.

| Specimens       | $E_{corr}$ (V) | $I_{corr}$ (A cm$^{-2}$) | $\beta_a$ (mV) | $\beta_c$ (mV) | $\nu$ (mm a$^{-1}$) | $R_P$(Ω cm$^2$) |
|-----------------|----------------|--------------------------|----------------|----------------|---------------------|-----------------|
| Without LSP     | $-0.27946$     | $4.0725 \times 10^{-5}$  | 374.37         | 1864.2         | 0.44649             | 3324052.18      |
| 3.537 GW cm$^{-2}$ | $-0.35727$     | $1.3447 \times 10^{-3}$  | 136.64         | 706.85         | 0.14743             | 3697480.01      |
| 4.244 GW cm$^{-2}$ | $-0.40432$     | $6.035 \times 10^{-6}$   | 202.01         | 828.3          | 0.066165            | 11684803.21     |
| 4.951 GW cm$^{-2}$ | $-0.43487$     | $2.6432 \times 10^{-7}$  | 575.12         | 457.14         | 0.0028978           | 418401265.2     |
| 5.659 GW cm$^{-2}$ | $-0.26964$     | $3.5852 \times 10^{-8}$  | 35.136         | 134.93         | 0.00039307          | 337626103       |

3.5. Laser shock peening treatment

LSP treatment can significantly improve the surface properties of the magnesium alloy, such as the hardness, microstructure, and corrosion resistance. The laser shock peening process involves the conversion of laser energy into kinetic energy, which is then transferred to the material surface through the formation of shock waves. The shock waves cause microscopic plastic deformation and surface roughness, which can lead to an increase in the surface hardness and a decrease in the metal fatigue life. The microscopic plastic deformation also leads to a decrease in the surface porosity, which can reduce the metal fatigue life. The laser shock peening process also causes microscopic plastic deformation and surface roughness, which can lead to an increase in the surface hardness and a decrease in the metal fatigue life. The microscopic plastic deformation also leads to a decrease in the surface porosity, which can reduce the metal fatigue life.
where \( n \) is the number of metal ions, \( F \) is the amount of charge carried by 1 mol of metal ions. The \( I_{\text{corr}} \) is proportional to the \( \upsilon \); the lower value of \( I_{\text{corr}} \) implies lower \( \upsilon \) of the tested specimens in saturated magnesium chloride solution.

\[
I_{\text{corr}} = nF\upsilon 
\]  

(4)
3.5. Stress corrosion sensitivity

The crack initiation time of the specimens in 42% boiling magnesium chloride solution is listed in table 5. It can be seen that the crack initiation time in the welding area of the specimens treated with LSP was significantly longer than that of the specimens without LSP. The crack initiation time of the specimens treated with 4.951 GW cm$^{-2}$ was 262 h, which is about 3.7 times that of the specimens without LSP. In addition, after 354 h of testing, no macroscopic crack was observed in the welding area of the specimens treated with the laser power density of 5.659 GW cm$^{-2}$. The crack initiation time increases obviously with the increase of laser power density. These results indicate that the stress corrosion resistance of C-ring weld specimens in chloride solution is effectively improved by LSP, and the stress corrosion resistance is positively correlated with the laser power density of LSP.

The microstructure of cracks is shown in figures 13–16. The main crack can be observed on the welding surface, the fine bifurcation cracks with dendritic shape and the secondary cracks were originated from the main crack during the propagation process. It can be seen from the metallographic diagrams 400 X that some cracks propagated along the grain boundary (figure 14(b)), and others propagated through the grains (figure 15(b), figure 16(b)). Therefore, the cracks of C-ring weld specimens propagate in the transgranular and intergranular mixed way, which is a typical characteristic of stress corrosion cracking.

The improvement of the stress corrosion resistance of C-ring weld specimens is mainly attributed to grain refinement and residual compressive stress induced by LSP. Surface grains have been refined after LSP treatment because of the serious plastic deformation. According to the relationship between $I_{\text{corr}}$ and grain size ($gs$) given by Ralston et al [34]:

$$I_{\text{corr}} = (A) + (B)gs^{-0.5}$$  

(5)

where $A$ is a function of the corrosive environment, $B$ is the material constant, $gs$ is the grain size. When $gs$ decreases, $I_{\text{corr}}$ decreases. Firstly, the surface refined grains can produce more grain boundaries, and the high grain boundary density makes the surface easier to passivate, then the corrosion resistance is increased [35]. Secondly, during the crack initiation stage, there are more grains to bear the crack driving force, so that the stress concentration is reduced and the crack initiation is delayed. During the crack propagation stage, the propagation of microcracks will suffer greater resistance and consume more energy due to the increase of grain boundaries when microcracks propagate along or across the grain boundaries. In addition, due to the generation of the extremely refined grain layer, the surface dislocation slips and dislocation slip steps are reduced, and the origination of pitting is limited. In this way, the corrosion resistance is improved, and the crack propagation rate is decreased.

The residual stress is an extremely important factor affecting the stress corrosion cracking. The residual compressive stress has been recorded to be favorable to delay the crack initiation [36, 37]. With the increase of the residual compressive stress, the metal corrosion current density caused by plastic deformation decreases [38]. Due to the residual compressive stress induced by LSP, the threshold of the stress corrosion crack propagation is increased, and the crack propagation rate is reduced, so that the stress corrosion resistance of 304 stainless steel can be improved.

4. Conclusions

The surface properties of 304 stainless steel C-ring weld specimens were tested after LSP treatment. Electrochemical corrosion tests and constant strain corrosion tests were conducted in magnesium chloride solution. The main conclusions are itemized as follows:

1. The microhardness of the welding surface was significantly increased by the laser-induced strain hardening effect. The surface microhardness of the specimens treated with LSP decreases with the increase of depth and increases with the increase of laser power density. The influence depth of LSP on 304 stainless steel is about 800 μm under the adopted laser power density.

2. With the high-energy impact of LSP, the severe plastic deformation was caused, the original coarse grains were effectively refined, numerous dislocations, micron-level grains and sub-grains structures were formed on the surface layer. With the increase of laser power density, the grain size of the surface layer decreases significantly.

3. The residual tensile stress on the welding surface was transformed into residual compressive stress ranging from −62.4 to −357.5 MPa, the residual stress was more uniformly distributed after LSP treatment. The value of the residual compressive stress increases with the increase of laser power density.
4. The constant strain corrosion tests shown that the crack initiation time of the C-ring weld specimens treated with LSP was significantly longer than that of the specimens without LSP. The dynamic potential polarization curves shown that the corrosion current density and corrosion rate were significantly reduced, and the polarization resistance was significantly increased after LSP treatment. With the increase of laser power density, the corrosion current density and corrosion rate decrease, the polarization resistance increases, and the crack initiation time increases. The improvement of the stress corrosion resistance of the 304 stainless steel C-ring weld is mainly attributed to grain refinement and residual compressive stress induced by LSP.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

[1] Ji S, Liu C, Li Y, Shi S and Chen X 2019 Mater. Sci. Eng. A 746 50–7
[2] Hou B, Li X, Ma X, Du C, Zhang D, Zhang M, Xu W, Lu D and Ma F 2017 npj Mater. Degrad. 1 4
[3] Tomashchuk I, Sallamand P, Andriezowski H and Grevey D 2011 Intermetallics 19 1466–73
[4] Gardner L, Insuasti A, Ng K T and Ashraf M 2010 J. Constr. Steel Res. 66 654–47
[5] Wang H, Yuan X, Wu K, Xu C, Jiao Y, Ge W and Luo J 2018 J. Mater. Process. Technol. 255 76–85
[6] Mordyuk B N, Prokopenko G I, Vasylyev M A and Iefimov O M 2007 Mater. Sci. Eng. A 458 253–61
[7] Liu S, Gao S Y, Zhou Y F, Xing X L, Hou X R, Yang Y L and Yang Q X 2014 Mater. Sci. Eng. A 617 127–38
[8] Prabhakaran S, Kulkarni A, Vasanth G, Kalainathan S, Shukla P and Vasudevan V K 2018 Appl. Surf. Sci. 428 17–30
[9] Lainé S J, Knowles K M, Doorbar P J, Cutts R D and Rugg D 2017 Acta Mater. 123 350–61
[10] Umaphathi A and Swaroop S 2016 Surf. Coatings Technol. 307 38–46
[11] Zhang H, Cai Z, Wan Z, Peng P, Zhang H, Sun R, Che Z, Guo C, Li B and Guo W 2020 Mater. Sci. Eng. A 788 139486
[12] Spadaro I, Hereñu S, Strubbia R, Gómez Rosas G, Bolmaro R and Rubio González C 2020 Opt. Laser Technol. 122 105892
[13] Yin M, Cai Z, Li Z, Zhou Z, Wang W and He W 2019 Trans. Nonferrous Met. Soc. China 29 1439–48
[14] Wang H, Ning G, Huang Y, Cao Z, Chen X and Zhang W 2017 Opt. Lasers Eng. 90 179–85
[15] Lu J, Qi H, Luo K Y, Luo M and Cheng X N 2014 Corros. Sci. 80 53–9
[16] Wei X, Zhang C and Ling X 2017 J. Alloys Compd. 723 237–42
[17] Wang J T, Zhang Y K, Chen J F, Zhou J Y, Ge M Z, Lu Y L and Li X L 2015 Mater. Sci. Eng. A 647 1–14
[18] ASTM 1997 ASTM G30-97, Standard Practice for Making and Using U-Bend Stress Corrosion Test Specimens (West Conshohocken, PA: ASTM International)
[19] ASTM 2001 ASTM G38-01, Standard Practice for Making and Using C-ring Stress Corrosion Test Specimens (West Conshohocken, PA: ASTM International)
[20] ASTM 2011 ASTM G39-99, Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test (West Conshohocken, PA: ASTM International)
[21] Ge M Z, Xiang J Y, Yang L and Wang J T 2017 Surf. Coatings Technol. 310 157–65
[22] De Assis K S, Schuabbi C G C, Lage M A, Gonçalves M P P, Dias D P and Mattos O R 2019 Corros. Sci. 152 45–53
[23] Al-Obaid Y F 1995 Eng. Fract. Mech. 51 19–25
[24] Xia H, Yang M J, Dong T D, Zhao W J, Qiao J S, Zhang H and Duan R F 2013 Nonferrous Metals (Extractive Metallurgy) 10 51–5
[25] Former Ministry of Metallurgical Industry 1998 GB/T 15970.5-1998 Corrosion, Stress Corrosion Test of Metals and Alloys Part 5: Preparation and Application of C-ring Specimens (China: National Bureau of Quality and Technical Supervision)
[26] Peyre P, Fabbros R, Merrien P and Lieurade H P 1996 Mater. Sci. Eng. A 210 102–13
[27] WARREN A, GUO Y and CHEN S 2008 Int. J. Fatigue 30 188–97
[28] Luo Q and Jones A H 2010 Surf. Coatings Technol. 205 1403–8
[29] Ruud C O 1982 NDT Int. 15 15–23
[30] Luo K Y, Lu J Z, Zhang Y K, Zhou J Z, Zhang L F, Dai F Z, Zhang L, Zhong J W and Cui C Y 2011 Mater. Sci. Eng. A 528 4783–8
[31] Nix W D and Gao H 1998 J. Mech. Phys. Solids 46 411–25
[32] Haycock EW 1957 J. Electrochem. Soc. 104 751
[33] Cao CN 2008 Principle of Corrosion Electrochemistry (China: Chemical Industry Press)
[34] Ralston K D, Birbilis N and Davies C H J 2010 Scr. Mater. 63 1201–4
[35] Argade G R, Panigrahi S K and Mishra R S 2012 Corros. Sci. 58 145–51
[36] Sano Y, Obata M, Kubo T, Mukai N, Yoda M, Masaki K and Ochi Y 2006 Mater. Sci. Eng. A 417 334–40
[37] Luong H and Hill M R 2008 Mater. Sci. Eng. A 477 208–16
[38] Lv Y, Ding Y, Cai H, Liu G, Wang B, Cao L, Li L, Qin Z and Lu W 2020 Mater. Charact. 164 11035