Effects of laser shock peening on corrosion fatigue behavior of 2Cr13 stainless steel

Yue Kou *, Yaling Du
School of Management, Tianjin University of Technology, Tianjin 300384, China

*Corresponding author’s e-mail: kouyue2016tj@163.com

Abstract. Effects of laser shock peening (LSP) with different coverage layers on corrosion fatigue (CF) resistance of 2Cr13 stainless steel were investigated by residual stress measuring, corrosion fatigue testing and fatigue fracture morphology observing. The results show that LSP can induce high compressive residual stress on the surface of 2Cr13 stainless steel, and the value of surface compressive residual stress increases with the increase of LSP coverage layer. The CF life of LSP specimens is much larger than that of as-machined specimens, and it increases with the increase of LSP coverage layers; the CF crack growth rate of LSP specimens decrease compared with that of as-machined specimens, and it decreases with the increase of LSP coverage layers. After the analysis, we can conclude that the fatigue fracture surface of as-machined specimens is flat and contains few secondary cracks. However, for LSP specimens, due to high surface compressive residual stress induced by LSP, the growth of corrosion fatigue crack is effectively restrained, resulting in a river pattern morphology.

1. Introduction
2Cr13 martensitic stainless steel has a wide range of applications, mainly used for manufacturing steam turbine blades, impeller, hydraulic turbine valves and other parts [1-2]. These 2Cr13 steel parts are mostly used in heavy machinery, which is subject to multiple damage effects such as high strength cyclic load and corrosive environment erosion. Corrosion fatigue fracture often occurs in practical application [3]. However, the emergence of corrosion fatigue often occurs on the surface of workpiece, so it is necessary to finish the surface of 2Cr13 stainless steel workpiece to improve its anti-corrosion fatigue performance. Conventional enhancement techniques include tempering [4], Surface chemical coating [5], ultrasonic shot peening [6], zhao weimin [7-8] et al. studied the influence of chemical coating on the corrosion fatigue properties of X80 steel. Prolong corrosion fatigue life. However, these conventional surface enhancement techniques have disadvantages such as high energy consumption, low processing efficiency and environmental pollution.

Laser shock processing (LSP) is a new surface strengthening technology, under the action of high pressure pulse wave can produce obvious plastic deformation in the surface layer material and high residual compressive stress layer, can effectively improve the mechanical performance of materials [9], strengthen material microstructure [10], reduce the fatigue crack growth rate, improve the corrosion resistance of metallic materials [11]. Ren xudong [12] et al. studied the effect of LSP on fatigue performance of 00Cr12 alloy. The test results showed that laser impact can effectively improve the fatigue life of 00Cr12 alloy, and the fatigue life of 00Cr12 alloy LSP sample after fatigue test is 1.6
times that of untreated sample. Zhou jianzhong et al. [13] studied the influence of LSP coverage rate on the residual stress and fatigue crack growth performance of ti-6al-4v titanium alloy. LSP coverage has a significant impact on the fatigue crack growth performance of Ti -- 6Al -- 4V titanium alloy. With the increase of LSP coverage, the fatigue crack growth rate decreases. Ge maozhong et al. [14] studied the effect of LSP on microstructure and crack growth rate of AZ31B magnesium alloy. After LSP, nanocrystals were formed on the surface of the sample. Grain refinement, residual compressive stress and surface nanocrystals were the main reasons for the reduction of crack growth rate of AZ31 magnesium alloy. Zhao weimin [7] et al. studied the influence of thermal spraying aluminum coating on the corrosion fatigue performance of X80 pipeline steel in NaCl solution with a mass fraction of 3.5%. Although thermal sprayed aluminum coatings can significantly increase the corrosion fatigue life of X80 steel substrates, but thermal sprayed aluminum coatings corrosion fatigue crack propagation rate of sample but slightly higher than the untreated sample, but the final results show that the thermal spraying aluminum coating on the corrosion fatigue crack initiation of X80 steel inhibition is far greater than its of X80 steel corrosion fatigue crack propagation. It can be found from the summary that the current researches on the corrosion fatigue property of materials at home and abroad are mostly limited to the coating, changing the corrosion medium and the stress ratio [15-16], etc., while the influence of laser impact reinforcement on materials is mostly on the fatigue property [20-22], rather than studying the influence of LSP on the corrosion fatigue property. Therefore, it is of great significance to study the effects of laser shock intensification and corrosion medium of different layers on the corrosion fatigue properties of 2Cr13 stainless steel.

Based on 2 cr13 martensitic stainless steel as the research object, through to the different processing states of corrosion fatigue tests were carried out, the change of the surface residual stress before and after the contrast analysis of LSP and fracture morphology of the corrosion fatigue life, the influence of impact mainly studied the different layers of the LSP affect the performance of 2 cr13 stainless steel corrosion fatigue mechanism.

2. Test materials and test methods

2.1. Test materials

The materials selected in this paper are 2Cr13 martensite stainless steel. The chemical composition and mechanical properties are shown in table 1 and table 2 respectively. The single-side notch three-point bending SNE(B) sample was selected for testing. The specific size of the three-point bending sample was designed according to the requirements in GB/ t6398-2000 test method for fatigue crack growth rate of metal materials. The size of the sample and the area of laser impact enhancement are shown in figure 1.

| Table 1. Chemical composition of the 2Cr13 stainless steel (mass fraction, %) |
|-----------------|---|---|---|---|---|---|---|---|
| Ingredient      | C  | Si | Mn | P  | S  | Ni | Cr | Cu |
| Content         | 0.20 | 0.45 | 0.41 | 0.021 | 0.006 | 0.53 | 12.61 | 0.12 |
|                 |    |    |    |    |    |    |    | Bal. |
2.2. Test method
Laser shock processing experiment using laser research institute of Tianjin university Nd: YAG high power laser, laser pulse energy of 5 J, spot diameter is 3 mm, flare lap rate was 50%, the pulse width of 10 ns, impact frequency of 5 Hz, the wavelength of 1064 nm, constraint layer is about 1 mm thickness for water, absorb the protection layer with thickness of 0.1 mm aluminum foil. The laser impact intensification area and the speckle impact path are shown in figure 1, and the tetrahedral area of 21 mm x 21 mm under the sample notch is respectively subjected to double-sided laser impact intensification with the number of impact layers of 1 and 2. The samples to be processed are divided into three groups, among which the as-machined samples are those that have not been strengthened by laser impact, and the lsp-1 ones are those that have not been strengthened by laser impact. Lsp-2 specimen (lsp-2 specimen) is a two-layer specimen strengthened by laser shock.

The corrosion fatigue crack growth (CFCG) test was carried out on the MTS810 fatigue test machine. The maximum load applied in the test was P max = 8 kN, stress ratio R=0.1, triangular wave loading, and frequency was 8 Hz. The 2 mm corrosion fatigue crack was prefabricated before the corrosion fatigue test. Therefore, the initial length of the crack is 13 mm, including the linear cutting notch of 11 mm and the prefabricated crack of 2 mm. LSP samples with different impact layers were subjected to corrosion fatigue tests in mass fraction of 3.5% and 10% NaCl solution, respectively. The compliance method was used to indirectly measure crack length and cycle number N, and the data was recorded in real time during the test. After the failure of the sample, the fracture was cut and cleaned by ultrasonography for subsequent observation. The field emission scanning electron microscopy (SEM) of jsm-6700f was used to observe the fracture microstructure.

The residual stress measurement equipment is x-350a type X-ray stress measurement instrument. The residual stress is measured by tilting fixed star method. The pipe pressure is 20 KV, the pipe flow is 5 mA, the collimated pipe is 1 mm, and the diffraction crystal surface is (220). Scan the starting Angle and ending Angle 159 ° and 151 ° respectively. As shown in the black point below the notch of the
sample in FIG. 1, residual stress on the surface is measured at 3 mm intervals along the center line below the notch after LSP. There are 7 points in total. The surface residual stress after the corrosion fatigue test is measured every 3 mm along the surface fatigue crack growth path of the sample, a total of 7 points.

3. Test results

3.1. Residual stress test results

Fig.2 shows the residual stress distribution of LSP-1 and LSP-2 samples after the laser impact enhancement test, and the corresponding data is shown in table 3. Can be seen from the figure 2 and table 3, the improved sample of the notch tip about 48 MPa residual stress value, residual stress away from the gaps of compressive stress, the residual compressive stress stabilized at about 430 MPa, the area of the residual compressive stress is produced in the process of preparation of sample (in the process of corrosion fatigue test will quickly released, little influence on the result of the corrosion fatigue test [17]). The residual stress distribution of LSP samples was similar to that of unreinforced samples. The residual compressive stress values of LSP-1 and LSP-2 samples at the notch tip were -643 MPa and -685 MPa, respectively, and finally stabilized around -750 MPa and -795 MPa, respectively. The reason for the variation of the residual stress value is that the tensile stress is produced in the prefabricated crack. The residual compressive stress on the surface of the LSP sample offset the tensile stress generated by the prefabricated crack. The mean values of residual compressive stress on the surface of LSP-1 and LSP-2 samples increased by 317 MPa and 364 MPa, respectively, 73.2% and 84%, compared with the unreinforced samples. Compared with the LSP-1 sample, the residual compressive stress value of the LSP-2 sample was further improved, but the increase was not large.

![Figure 2. Residual stresses distribution of as-machined, LSP-1, and LSP-2 specimens along the center line after LSP impacts](image)

| Specimen     | 0mm   | 3mm   | 6mm   | 9mm   | 12mm  | 15mm  | 18mm  |
|--------------|-------|-------|-------|-------|-------|-------|-------|
| As-machined  | 48    | -317  | -428  | -432  | -425  | -437  | -443  |
| LSP-1        | -643  | -667  | -747  | -742  | -745  | -750  | -761  |
| LSP-2        | -685  | -709  | -790  | -795  | -793  | -799  | -812  |

Table 3. Residual stress values of specimens subjected to LSP with different coverage layers. (Unit: MPa)

Figure 3 shows the surface residual stress distribution of the samples of LSP-1 and LSP-2 along the crack growth direction without strengthening after the corrosion fatigue crack growth test. The residual
stress data are shown in table 4. It can be found that after the corrosion fatigue test, the surface residual compressive stress along the crack growth direction is released to different degrees. The residual compressive stress is basically completely released from the notch tip, and the residual compressive stress is relatively small, and its value is around -25 MPa. The stress at the notch tip of the unstrengthen sample is still the residual tensile stress, while the LSP sample still has high residual compressive stress at the gap. The residual compressive stress of lsp-1 and lsp-2 samples at the notch tip was 36 MPa, -271 MPa and -318 MPa, respectively. This is because in the CFCG test process, the expansion of the corrosion fatigue crack actually starts from the bottom of the prefabricated crack, so the residual compressive stress is completely released from the region of 3-18 mm away from the notch tip. The residual compressive stress in the area within 3 mm from the notch tip is partially released under the action of external cyclic loading.

![Figure 3. Residual stresses distribution of as-machined, LSP-1, and LSP-2 specimens along the crack growth direction after CFCG test](image)

3.2. Corrosion fatigue life
And LSP has not improved sample, LSP-1 and LSP-2 sample in different concentration of NaCl solution corrosion fatigue life as shown in table 5, not improved sample in 3.5% NaCl solution corrosion fatigue life for 57961 times, and the sample and LSP-1 and LSP-2 sample of corrosion fatigue life of 75839 times and 85211 times respectively, compared with the not improved sample, corrosion fatigue life is increased by about 30.8% and 47% respectively. The corrosion fatigue life of the unenhanced sample in 10% NaCl solution was 52,637 times, while that of the lsp-1 and lsp-2 samples was 73,100 times and 80,325 times respectively. Compared with the unreinforced sample, the corrosion fatigue life of the unreinforced sample was increased by 38.8% and 52.6% respectively. The corrosion fatigue life of samples under the same LSP treatment state in 3.5% NaCl solution was greater than that in 10% NaCl solution. Compared with 3.5% NaCl solution, the corrosion fatigue life of samples under 10% NaCl solution decreased by 9.2%, that of unenhanced samples decreased by 3.6%, that of lsp-1 samples decreased by 3.6%, and that of lsp-2 samples decreased by 5.7%. It can be seen that the corrosion fatigue life of LSP samples in NaCl solution with the same concentration is significantly higher than that of unenhanced samples. The corrosion fatigue life was further improved with the increase of LSP impact layer number. NaCl solution concentration is inversely proportional to the corrosion fatigue life of the sample. The higher the concentration, the lower the corrosion fatigue life.

4. Conclusion
The corrosion fatigue property of 2Cr13 stainless steel is mainly affected by the sample, external force and corrosion solution. Based on the above test results, this section analyzes and discusses the influence
of laser shock reinforcement on the corrosion fatigue property of 2Cr13 stainless steel from three aspects of microstructure, residual stress and corrosion solution concentration.

First, laser-impact-enhanced surface nanorization can improve the corrosion resistance of 2Cr13 stainless steel in NaCl solution. On the one hand, on the surface of grain refinement, the refined grain produces more grain boundaries to effectively resist the corrosion process [23]. Therefore, the anti-corrosion performance of 2Cr13 stainless steel in NaCl solution was improved due to the refined grain induced on the surface of 2Cr13 stainless steel by laser impact enhancement. On the other hand, in the process of corrosion fatigue test, refining the grain layer can effectively prevent dislocation slip, so as to prevent the surface layer of 2Cr13 stainless steel sample from sliding steps (which will lead to passivating film rupture, which will lead to corrosion first), and 2Cr13 stainless steel has enhanced corrosion resistance. In addition, refining the grain can enhance the sliding deformation resistance of materials, to strengthen the corrosion fatigue crack extension resistance [17], in the process of corrosion fatigue crack propagation, increased grain boundary due to grain refinement, dislocation movement is blocked, crack extension need through the more grain boundary, so use more energy, make the corrosion fatigue crack extension is restrained, improve the anti-corrosion fatigue property of materials.

Secondly, the study shows that [21-22], LSP can produce significant plastic deformation and high residual compressive stress on the material surface. As shown in figure 9(b), the residual compressive stress induced by laser shock on the two surfaces of the 2Cr13 stainless steel sample can balance the external loading of the corrosion fatigue test. It effectively delays the rupture of the passivating film on the surface of the 2Cr13 stainless steel sample, and finally significantly improves the anti-corrosion fatigue performance of the sample in NaCl solution. In addition, in the process of corrosion fatigue crack propagation, the crack tip under the effect of residual compressive stress will produce closed effect, reduce the crack tip stress intensity factor range, thereby reducing corrosion fatigue crack propagation rate [24], effective prevent the corrosion fatigue crack initiation and propagation, improving the corrosion fatigue life 2 cr13 stainless steel sample.

Third, the corrosion solution concentration also has an important effect on the corrosion fatigue properties of 2Cr13 stainless steel. As shown in figure 9(c), in different concentrations of NaCl solutions, the higher concentration of corrosive solutions means more Cl- intrusion. In the crack initiation stage, a large number of Cl-intrusions on the surface of the sample lead to more rupture of the passivated film and more fatigue corrosion sources. At the initiation stage of crack, more Cl- invades into the fracture, accelerating the damage effect of corrosion solution on crack growth and increasing the growth rate of corrosion fatigue crack. In this paper, laser shock intensification generates high amplitude residual compressive stress on the surface of 2Cr13 stainless steel, and the residual compressive stress further increases with the increase of LSP impact layer number. The surface grain can be further refined by multilayer laser impact enhancement. Therefore, under the combined effect of residual compressive stress and grain refinement, the anti-corrosion fatigue performance of 2Cr13 stainless steel in 3.5% NaCl solution was significantly improved with the increase of LSP impact layer number. However, with the increase of Cl- fatigue corrosion rate in 10% NaCl solution, the anti-corrosion fatigue performance of 2Cr13 stainless steel in 10% NaCl solution is lower than that in 3.5% NaCl solution.

(1) Laser shock reinforcement induces high amplitude residual compressive stress on the surface of the sample, and further increases with the increase of LSP layer number. Compared with the unstrengthen samples, the residual compressive stress values of the lsp-1 and lsp-2 samples increased by 317 MPa and 364 MPa, respectively, and increased by 73.2% and 84%. Compared with the lsp-1 sample, the residual compressive stress on the surface of lsp-2 sample was further increased, but the increase was not large.

(2) Laser shock reinforcement can effectively increase the corrosion fatigue life of 2Cr13 stainless steel three-point bend test sample, reduce the corrosion fatigue crack growth rate of the test sample, and further improve the anti-corrosion fatigue performance with the increase of LSP layer number. Compared with the unstrengthen samples, the corrosion fatigue life of lsp-1 and lsp-2 samples in 3.5% NaCl solution increased by 30.8% and 47%, respectively. The corrosion fatigue life of 10% NCL solution increased by 38.8% and 52.6%, respectively. The concentration of NaCl solution is inversely
proportional to the corrosion fatigue life of the sample. With the increase of NaCl solution concentration, the corrosion fatigue life of the sample decreased.

(3) The residual compressive stress and grain refinement generated by laser impact enhancement inhibited the growth of corrosion fatigue crack, which reduced the growth rate of corrosion fatigue crack. Meanwhile, LSP inhibited the corrosion effect of NaCl solution and improved the anti-corrosion fatigue performance of 2Cr13 stainless steel.

References
[1] Feng A X, Zhou P C, Nie G F, et al. Influence of heat treatment and laser shock processing on impact toughness of 2Cr13 martensite stainless steel[J]. Chinese Journal of Lasers, 2012, 39(8):0803002.
[2] Xu Q D, Lin X, Song M H, et al. Microstructure of heat-affected zone of laser forming repaired 2Cr13 stainless steel[J]. Acta Metallurgica Sinica, 2013, 49(5):605.
[3] Han D, Liu D X, Liu S T. Failure analysis of 2Cr13 stainless steel blade in a low pressure steam turbine[J]. Materials for Mechanical Engineering, 2007, 31(7):45-48.
[4] Li M Z, Zhao Y L. Study on improving fatigue strength technology of 2Cr13 martensitic stainless steel[J]. Hot Working Technology, 2010, 39(12):171-172.
[5] Xi Y T, Liu D X, Dong H. Improvement of erosion and erosion–corrosion resistance of AISI420 stainless steel by low temperature plasma nitriding[J]. Applied Surface Science, 2008, 254(18):5953-5958.
[6] Lai Z L, Wang C, Li Y H, et al. Effects of laser shock peening and ultrasonic shot peening on fatigue property of 1Cr11Ni2W2MoV stainless steel[J]. Laser & Optoelectronics Progress, 2013, 50(5):051403.
[7] Zhao W, Zhang T, Xin R, et al. Effects of Thermally Sprayed Aluminum Coating on the Corrosion Fatigue Behavior of X80 Steel in 3.5 wt.% NaCl[J]. Journal of Thermal Spray Technology, 2015, 24(6):974-983.
[8] Wang M M. Effects of aluminum spray coating on marine corrosion fatigue crack initiation of X80 steel[D]. China University of Petroleum (East China), 2013.
[9] Luo K Y, Zhou Y, Lu J Z, et al. Influence of laser shock peening on microstructure and property of cladding layer of 316L stainless steel[J]. Chinese Journal of Lasers, 2017, 44(4):0402005.
[10] Li X C. Investigation of laser shock processing on corrosion resistance of AZ31 magnesium alloy[D]. Jiangsu University, 2014.
[11] Sun Y J, Zhou J Z, Huang S, et al. Research on biological corrosion resistance of medical Ti6Al4V alloy subjected to laser peening[J]. Chinese Journal of Lasers, 2017, 44(7):0702003.
[12] Ren X D, Zhang T, Zhang Y K, et al. Improving fatigue properties of 00Cr12 alloy by laser shock processing[J]. Chinese Journal of Lasers, 2010, 37(8):2111-2115.
[13] Zhou J Z, Huang S, Zuo L D, et al. Effects of laser peening on residual stresses and fatigue crack growth properties of Ti–6Al–4V titanium alloy[J]. Optics & Lasers in Engineering, 2014, 52(1):189-194.
[14] Ge M Z, Xiang J Y. Effect of laser shock peening on microstructure and fatigue crack growth rate of AZ31B magnesium alloy[J]. Journal of Alloys & Compounds, 2016, 680:544-552.
[15] Begum Z, Poonguzhali A, Basu R, et al. Studies of the tensile and corrosion fatigue behaviour of austenitic stainless steels[J]. Corrosion Science, 2011, 53(4):1424-1432.
[16] Zhou J Z, Xu Z C, Huang S, et al. Effects of different stress ratios on fatigue crack growth in laser shot peened 6061-T6 aluminum alloy[J]. Chinese Journal of Lasers, 2011, 38(9):0903006.
[17] Wang C, Lai Z L, He W F, et al. Effect of multi-impact on high cycle fatigue properties of 1Cr11Ni2W2MoV stainless steel subject to laser shock processing[J]. Chinese Journal of Lasers, 2014, 41(1):0103001.
[18] Paris P C, Erdogan F. A critical analysis of crack propagation laws[J]. Journal of Basic Engineering, 1963, 85(4):528-533.
[19] Zhang J, Gu X, Zhu L, et al. Numerical simulation of fatigue life of 7050 aluminum alloy
processed by laser shock processing[J]. Chinese Journal of Lasers, 2010, 37(12):3192-3195.

[20] Li Y, He W F, Nie X F, et al. Fatigue crack growth behavior of TC17 titanium alloy with laser shock peening[J]. China Surface Engineering, 2017, 30(3):40-47.

[21] Bergant Z, Trdan U, Grum J. Effects of laser shock processing on high cycle fatigue crack growth rate and fracture toughness of aluminium alloy 6082-T651[J]. International Journal of Fatigue, 2016, 87:444-455.

[22] Nie X F, He W, Zang S, et al. Effect study and application to improve high cycle fatigue resistance of TC11 titanium alloy by laser shock peening with multiple impacts[J]. Surface & Coatings Technology, 2014, 253(9):68-75.

[23] Prabhakaran S, Kulkarni A, Vasanth G, et al. Laser shock peening without coating induced residual stress distribution, wettability characteristics and enhanced pitting corrosion resistance of austenitic stainless steel[J]. Applied Surface Science, 2017, 428:17-30.

[24] Ge M Z, Xiang J Y, Zhang Y K. Effect of Laser Shock Processing on Mechanical Properties of AZ31B Magnesium Alloy[J]. Journal of Materials Engineering, 2013(9):54-59.