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ARTICLE

Shot-Peened Surface Residual Stress Relaxation and Fatigue Resistance of 17-4PH Steel at Elevated Temperature

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Abstract: Shot peening treatment was adopted to strengthen the steel surface, and the influence of the temperature field on the residual stress and fatigue resistance of the 17-4PH stainless steel was investigated. Firstly, the microstructure analysis by scanning electron microscope (SEM) and the nondestructive testing by X-ray technology were carried out to evaluate the residual stress of 17-4PH steel after shot peening treatments at room temperature. Fatigue property tests were conducted on the rotary bending fatigue tester and the related properties were presented through S-N curve. Then, by adopting the optimum shot peening treatment, the fatigue resistance and residual stress relaxation on the shot-peened surface were studied at 150, 300 and 450 °C. The results demonstrate that the low intensity shot peening parameters are the optimized ones for 17-4PH stainless steel at room temperature. Meanwhile, the shot peening treatment can significantly improve the fatigue life of 17-4PH steel at the environment temperature T<300 °C. However, the fatigue properties of 17-4PH steel decrease significantly at T>450 °C. When the shot-peened 17-4PH steel is applied at high temperature, the serious residual stress relaxation and the reduced surface integrity become the predominant effects for the reduced fatigue resistance. The results provide experimental basis for the application of shot peening treatment in special industrial fields, such as steam turbine industry.

Key words: shot peening; residual stress; high temperature; fatigue resistance

Shot peening is a well-known surface treatment method to improve the fatigue resistance of metals[1-3]. In recent years, the fatigue behavior of shot-peened industrial turbine components has attracted more and more interests, especially in the field of blade and the impeller attachments commonly with severe stress concentration. Theoretically, shot peening is particularly effective in promoting the fatigue life of 718 alloys and FV448 gas turbine materials with low loads[3,4]. The crack shape effects on short crack growth and the compressive residual stress field were also predicted using a 3D finite element (FE) model[5]. By in-situ fatigue equipment and synchrotron radiation residual stress measurement, James et al[6] found that the influences of shot peening on fatigue cycling depend on the complex profiles of the 12CrNiMo martensitic steel blades.

More importantly, the high temperature fatigue performance of shot-peened components in the hot sections of turbines is becoming one of the research focuses. The influences of different shot peening treatments on the high temperature fatigue properties were different for GH4169 and FGH96 powder alloys[7,8]. For shot-peened Ti811 and TC4 titanium alloys subjected to fretting fatigue, different relaxation behavior of residual stress at elevated temperatures was also found[9,10]. For shot-peened nickel-based superalloy, oxidizing environment causes recrystallization in the near surface, but does not affect

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the residual stress-relaxation behavior[11].

However, most of the researches were focused on the superalloys and titanium alloys. The investigation on stainless steel materials lacks, although the steel materials have been extensively applied in the turbine system[12]. In this research, the shot-peened surface residual stress relaxation and fatigue resistance of 17-4PH martensitic stainless steel were studied. Firstly, the process parameters of shot peening were optimized at room temperature. Then, the high temperature fatigue performance and residual stress release of shot-peened 17-4PH steel were investigated at different temperatures.

1 Experiment

The test was conducted on the basis of the ambient temperature condition of turbine blades. The 17-4PH stainless steel was selected as the test material. The effects of different temperatures (room temperature, 150, 300 and 450 °C) on fatigue resistance of 17-4PH steel were studied. The chemical composition of 17-4PH steel is shown in Table 1. The heat treatment of the material was processed by solution heat treatment and aging treatment. According to the specification of heat treatment, the mechanical properties of 17-4PH steel are shown in Table 2. For comparison, the as-received sample was not processed through shot peening.

Shot peening tests were carried out on the shot peening machine with a model PR TRAT 4G7 4SM. Specimens were shot-peened by ASH110 cast steel with 100% coverage degree. The projectile distance was 500 mm and spray angle was 45°. Three kinds of shot peening intensities were used, namely 0.076, 0.146 and 0.196 mmA.

Fatigue property tests for S-N curve measurement under different shot peening processes at room temperature were carried out on a PQ-6 rotary bending fatigue tester. The geometry dimensions of the fatigue specimens are shown in Fig. 1. The speed of the test machine was 2200 r/min, and the maximum fatigue cycle was 5×10^6 cycles. High temperature tensile fatigue test conditions were controlled by PLG-100C microcomputer. The stress ratio R was 0.1. The test temperatures of 150, 300 and 450 °C were adopted to simulate the working conditions of turbines. The specimens were heated at different temperatures for 50 h before fatigue tests.

The cross-sectional hardness of shot-peened specimens was measured by HV-1000 type microhardness tester. The Knoop indenter was selected and the load time was 20 s with the load

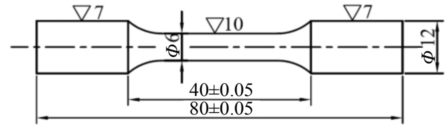

Fig.1 Geometry dimensions of the fatigue specimen

of 0.245 N.

The D/MAX 2200 PC microcomputer equipped with X-ray stress analyzer was used in the residual stress test. The scanning method was fixed Ψ_0 method with Ψ_0 of 0°, 10°, 20° and 30°. Cu Kα target radiation with 40 kV tube voltage and 30 mA tube current was used as test conditions. Radiation area was 1 mm×2 mm and 2θ scan range was 111.76°~120.16°. The stress constant was −744 MP/°. The residual compressive stress distribution along the depth direction of shot peening strengthened layer was obtained. Electrolytic layer by layer polishing was adopted to thin layers. The electrolyte temperature was 60 °C and the thinning rate was controlled at 5 mm/min.

To study the effect of different shot peening intensity parameters, the microstructures of specimens were observed by an OLYMPUS optical metallographic microscope. In order to assess the fatigue damage, the surface morphology and fatigue fracture morphology of shot-peened specimens were observed by FEI Quanta650 scanning electron microscope (SEM).

2 Results and Discussion

2.1 Optimization of shot peening at room temperature

In order to determine the stress level of the median fatigue life, the S-N curve of 17-4PH stainless steel without shot peening is measured. Fig.2 shows the S-N curve of 17-4PH specimen which is investigated by rotary bending fatigue test. When the fatigue stress is 850 MPa, the fatigue life is only 32 500 cycles. The result is close to that of low cycle fatigue test, whose fatigue life is less than 10 000 cycles. With the decrease of fatigue stress level, the fatigue life increases gradually. As shown in Fig. 2, the fatigue limit of 17-4PH stainless steel is

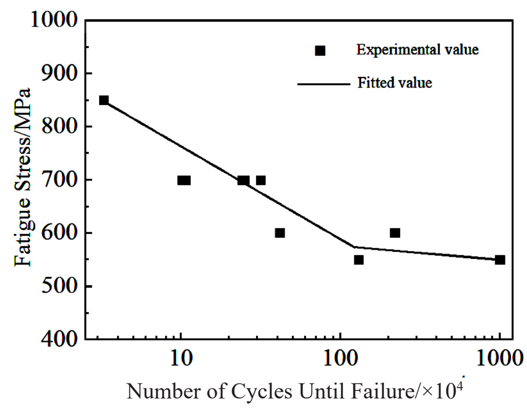

Fig.2 Fatigue S-N curve of 17-4PH specimen without shot peening

Table 1 Chemical composition of 17-4PH steel (wt%)

C	Cr	Ni	Cu	Si	Mn	Nb	P	S	Fe
0.048	16.755	3.645	2.665	0.303	0.224	0.265	0.033	0.030	Bal.

Table 2 Mechanical properties of 17-4PH steel after heat treatment

Hardness/ HRC	Yield strength/ MPa	Tensile strength/ MPa	Elongation/ %	Section shrinkage/%
29	970	1012	17.4	66.3

550 MPa. When the fatigue stress is 700 MPa, the average fatigue life of 17-4PH steel is 20 000 cycles and the dispersion is small. Therefore, the 700 MPa stress level is chosen as the stress level to optimize shot peening conditions.

Fig.3 shows the experimental results of the influence of different shot peening intensities on the fatigue life of 17-4PH stainless steel. It appears that the shot peening can greatly increase the fatigue life of 17-4PH material. The fatigue life decreases with increasing the shot peening intensity. It can be seen that the fatigue resistance of 17-4PH significantly improves by shot peening with ASH110 steel and low intensity of 0.076 mmA. The similar experimental phenomena have been found for aluminum alloys and other materials, i.e., low shot peening intensity is conducive to the improvement of fatigue life[13].

The fatigue fracture morphologies of 17-4PH specimens with and without shot peening at different intensities are shown in Fig. 4. The arrows in the figures indicate the locations of the crack origins. As shown in Fig. 4a, the fatigue crack initiation position is on the surface of the specimen, which is one of the main characteristics of fatigue damage of metal without shot peening under rotating bending fatigue load. The source area presents a cleavage pattern and shows signs of grinding.

Fig.4b~4d show the fracture characteristics of fatigue specimen of 17-4PH steel treated with different shot peening intensities. It is evident that the crack initiation position of the fatigue specimen is located at about 100 μm below the surface of the specimen. This is one of the main characteristics of fatigue damage of metal materials under shot bending fatigue load. The reason is that the residual compressive stress on the

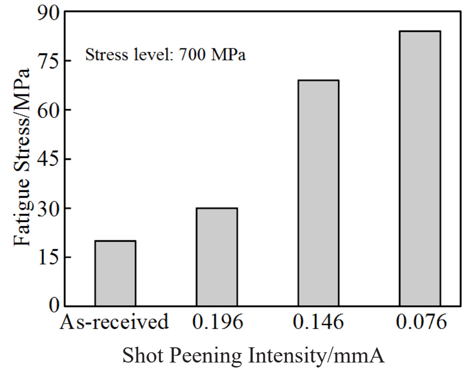

Fig.3 Fatigue life of specimens after treatment with different shot peening intensities

surface introduced by shot peening counteracts the fatigue load and moves the maximum effective fatigue stress to the inside of the steel[14]. The fatigue source region is basically in the same plane as the main fracture due to the crack initiation in the steel. The crack presents a radial pattern at the center of the source area and a cleavage characteristic on the microcosmic level. The instantaneous fracture zone presents dimple characteristics, which is a typical characteristic of ductile metallic materials[15]. Fig.4c and 4d show the similar results of the other shot-peened specimens.

Fig.5 shows the effects of shot peening on the surface morphology of different specimens. It is found that shot peening pits increase under the higher shot peening intensity. After shot peening with low intensity of 0.076 mmA, there are

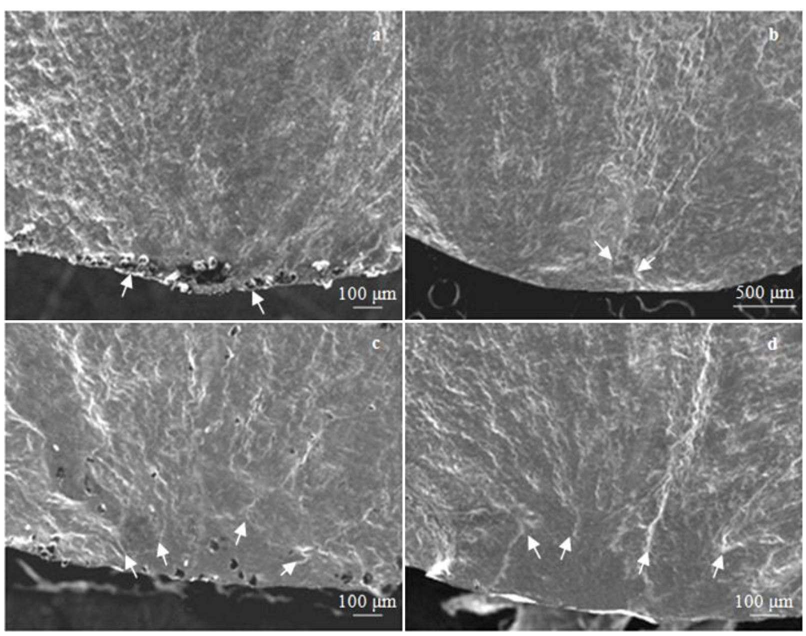

Fig.4 Morphologies of fatigue specimens after treatment with different shot peening intensities: (a) as-received, (b) 0.076 mmA, (c) 0.146 mmA, and (d) 0.196 mmA (arrow indicates the initiation site of fatigue crack)

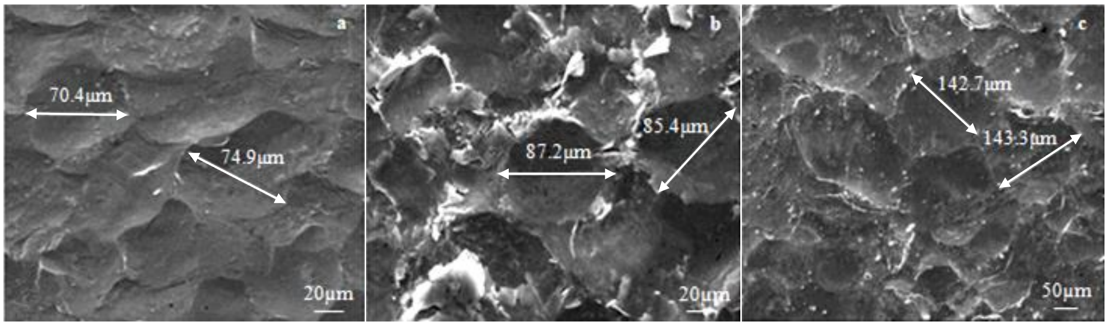

Fig.5 Surface morphologies of specimens after surface treatment with different intensities: (a) 0.076 mmA, (b) 0.146 mmA, and (c) 0.196 mmA

slight crater marks on the surface of the specimen, and no obvious damage mark is found on the surface. From Fig.5b, after shot peening with medium intensity of 0.146 mmA, the crater marks on the specimen surface are very clear. The surface plastic deformation is obvious and there is a seriously local-cracked phenomenon. As shown in Fig.5c, the plastic deformation becomes obvious, and there is also a local-chapped phenomenon and a delamination failure phenomenon, indicating that low intensity shot peening on the surface of 17-4PH stainless steel causes slight surface damage.

Fig.6 reveals the effect of shot peening intensity on the surface roughness of 17-4PH stainless steel. It can be seen that the high-speed projectiles on the specimen surface cause plastic deformation. The specimen surface after shot peening has a large number of craters and surface delamination, thus, the surface roughness of the material increases. Promoted shot peening intensity increases the surface roughness. This process is accompanied by intensive impact on the specimen surface at high shot peening intensity and high projectile velocity[16].

Fig.7 shows the influence of shot peening intensity on the $HK_{0.05}$ microhardness of 17-4PH stainless steel profile. It can be found that the initial microhardness increases slightly with

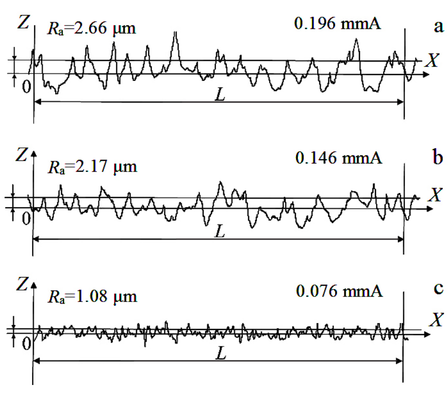

Fig.6 Surface roughness of specimens after treatment with different intensities: (a) 0.196 mmA, (b) 0.146 mmA, and (c) 0.076 mmA

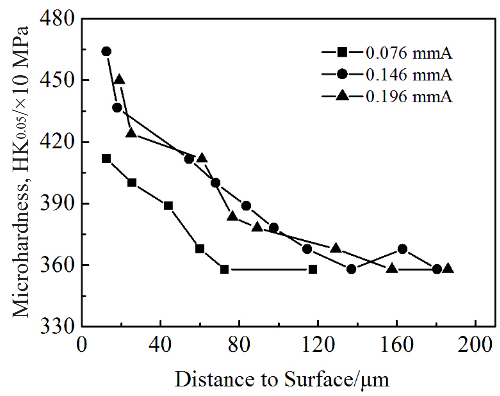

Fig.7 Microhardness distribution of specimens after treatment with different intensities

the increase of shot peening intensity. However, when the shot peening intensity reaches a moderate level, the surface hardness no longer increases with the increase of shot peening intensity, but stabilizes around 4600 MPa. This is determined by the mechanism of shot peening. The impact of the projectile makes the crystal surface of the specimen refined and compact, and the dislocation density increases greatly. At the same time, the cold hardening effect of the specimen surface increases, and the yield intensity of the surface layer increases significantly[17].

However, when the shot peening intensity increases to a certain level, the effect on the surface microstructure and the plastic deformation caused by the shot peening become stable. As a result, the impact of increasing the shot peening intensity on the hardness of specimen surface is not significant[18]. For the depth of shot peening influence layer, the hardness influence layer is about 70 μm with lower shot peening intensity, 140 μm with medium shot peening intensity and 160 μm with higher shot peening intensity, as shown in Fig. 7. The higher the shot peening intensity, the greater the depth of work hardening affected layer. This is because with the increase of shot peening intensity, the effect of projectile on the steel surface is more intense, and the depth of surface wave of the projectile impact specimen is greater.

Fig.8 is the results of residual stress distribution for 17-4PH shot-peened profile. It can be seen that the residual stress of gradient distribution is introduced to the surface of 17-4PH steel by shot peening. The maximum residual compressive stress σ_{mrs} does not lie in the surface layer of specimen, but improves with the increase of shot peening intensity from the layer below the surface of 15~75 μm. With the increase of shot peening intensity, the surface residual stress σ_{srs} and maximum residual stress σ_{mrs} increase.

2.2 Fatigue strengthening effect of shot-peened samples at different temperatures

The high temperature fatigue test samples were treated by the optimized shot peening process with the low intensity of 0.076 mmA and compared with the original specimen without shot peening. Fig.9 shows the average fatigue life test results of as-received and shot-peened samples at 150 °C. Before the fatigue tests, the fatigue specimens were heated at 150 °C for 50 h. The influence of temperature on the shot-peened surface is fully considered. It is evident that shot peening significantly improves the fatigue life of 17-4PH stainless steel under the stress condition of 880 MPa. Therefore, the low-intensity shot peening parameters effectively improve the fatigue resistance of 17-4PH stainless steel at 150 °C.

Fig.10 exhibits the fatigue life test results of 17-4PH stainless steel substrate and shot-peened samples at 300 °C. It can be found that shot peening significantly improves the fatigue life of 17-4PH stainless steel under the stress condition of 850 MPa. However, the experimental data of the fatigue life of the samples strengthened by shot peening at 300 °C are more dispersive. This is closely related to the shot peening parameters. In order to ensure the stability of shot peening strengthening effect, the shot peening technique parameters are strictly controlled in production.

Fig.11 shows the fatigue life test results of 17-4PH stainless steel substrate and shot-peened samples at 450 °C. Before the fatigue tests, the fatigue specimens were heated at 450 °C for 50 h. The shot peening significantly reduces the fatigue life of 17-4PH stainless steel at 450 °C with stress condition of 840 MPa. The shot peening not only fails to improve the fatigue resistance of 17-4PH stainless steel, but also weakens its fatigue resistance. The reason is that the surface residual compressive stress induced by shot peening is obviously relaxed at 450 °C, and the favorable factors for improving fatigue properties weaken. At the same time, as shown in Fig.6, shot peening results in the increase of surface roughness and even surface damage, which are detrimental to fatigue performance. The ef-

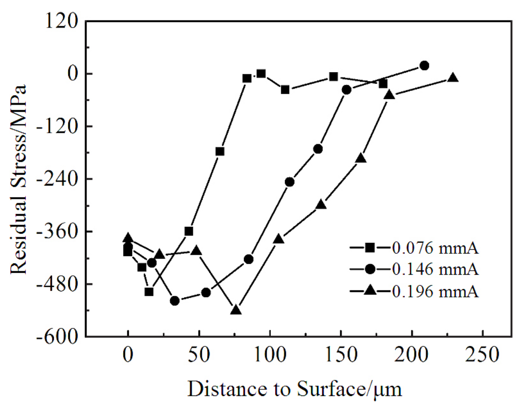

Fig.8 Residual stress of specimens after treatment with different intensities

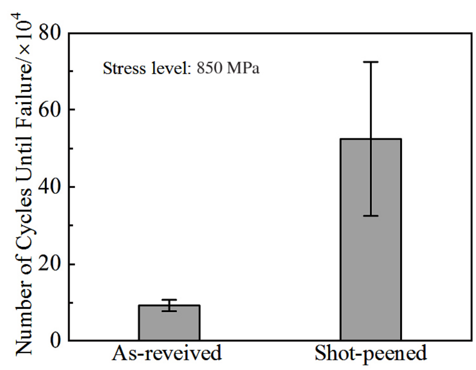

Fig.10 Fatigue test results of 17-4PH steel with and without shot peening at 300 °C

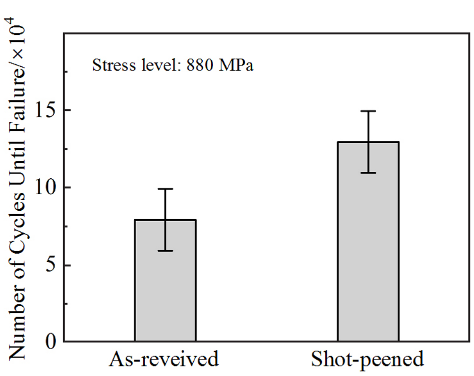

Fig.9 Fatigue test results of 17-4PH steel with and without shot peening at 150 °C

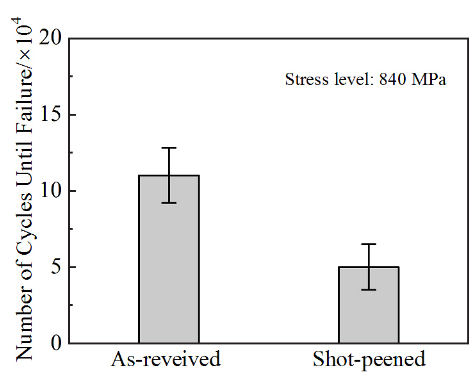

Fig.11 Fatigue test results of 17-4PH steel with and without shot peening at 450 °C

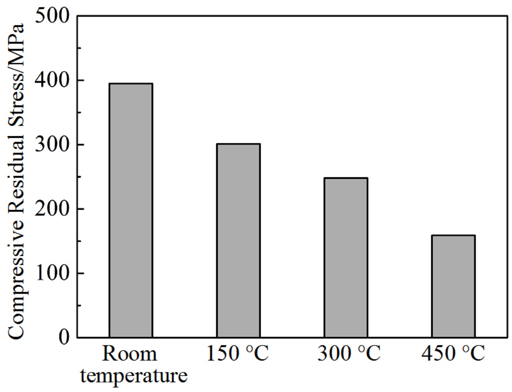

Fig.12 Relaxation results of compressive residual stress of shot-peened 17-4PH steel at different temperatures

fect of weakening factor is stronger than that of strengthening factor. Therefore, at 450 °C, the fatigue resistance of samples treated by shot peening is worse than that of the as-received 17-4PH stainless steel substrate.

Fig.12 reveals the relaxation effect of residual stress on the shot-peened surface of 17-4PH at different temperatures for 50 h. It can be found that the higher the temperature, the more serious the residual stress relaxation. When the temperature rises to 450 °C, the surface residual stress of specimen 17-4PH relaxes by about 60%. This is the main reason why the fatigue resistance of the shot-peened sample is worse than that of the as-received sample at high temperature (450 °C). The results in this study provide scientific technical support for the practical application of 17-4PH on turbine blades. Similar experimental studies were carried out on titanium alloy, 304 stainless steel and other materials[19-21].

It is found that the relaxation of high temperature residual stress leads to a significant reduction of shot peening strengthening effect. The surface damage caused by shot peening leads to a rapid decrease of high temperature fatigue properties at higher temperatures, as shown in Fig.6 and 11. Therefore, the weakening of fatigue resistance is not only due to the release of residual stress, but also related to the surface integrity damage caused by shot peening. The analysis above implies that for the shot-peened 17-4PH steel at elevated temperature, the dominated mechanism is the serious relaxation of the residual stress and the reduction of surface integrity. The study points the way to the better usage of shot peening for the 17-4PH material in turbine products.

3 Conclusions

1) Low intensity shot peening is the optimized strengthening process condition for 17-4PH stainless steel at room temperature.

2) After shot peening treatment, the fatigue life of 17-4PH stainless steel is effectively enhanced at temperature<300 °C. However, the shot peening treatment leads to the evident decrease of fatigue resistance at temperature>450 °C.

3) The decreased fatigue resistance at the elevated temperature is ascribed to the serious residual stress relaxation and the reduced surface integrity after shot peening.

References

1 Kovaci H, Bozkurt Y B, Yetim A F *et al*. *Surface and Coatings Technology*[J], 2019, 360: 78
2 Liu Mingxia, Zhang Haicun, Liu Daoxin *et al*. *Rare Metal Materials and Engineering* [J], 2012, 41(S1): 236 (in Chinese)
3 He B Y, Soady K A, Mellor B G *et al*. *International Journal of Fatigue*[J], 2016, 82: 280
4 Eriksson R, Moverare J, Chen Z. *International Journal of Fatigue*[J], 2019, 124: 34
5 You C, He B Y, Achintha M *et al*. *International Journal of Fatigue*[J], 2017, 104: 120
6 James M N, Newby M, Hattingh D G *et al*. *Procedia Engineering*[J], 2010, 2(1): 441
7 Wang Xin, Hu Rengao, Hu Bo *et al*. *China Surface Engineering* [J], 2015, 28(6): 7 (in Chinese)
8 Wang Xin, Chen Xing, Wang Xiaofeng *et al*. *Rare Metal Materials and Engineering*[J], 2019, 48(1): 269 (in Chinese)
9 Zhang Xiaohua, Liu Daoxin, Gao Guangrui *et al*. *Rare Metal Materials and Engineering*[J], 2005, 34(12): 1985 (in Chinese)
10 Lee H, Mall S. *Materials Science and Engineering A*[J], 2004, 366: 412
11 Foss B J, Gray S, Hardy M C *et al*. *Acta Materialia*[J], 2013, 61: 2548
12 Liu Mingxia, Chang Gengrong, Fu Fuxing *et al*. *Materials for Mechanical Engineering*[J], 2018, 42(1): 89 (in Chinese)
13 Li P, Liu D X, Guan Y Y *et al*. *Materials for Mechanical Engineering*[J], 2015, 39(1): 86
14 Mahmoudi A H, Ghasemi A, Farrahi G H *et al*. *Materials & Design*[J], 2016, 90: 478
15 Li C Q, Fu G Y, Yang W *et al*. *Engineering Fracture Mechanics* [J], 2017, 178: 39
16 Bagherifard S, Ghelichi R, Guagliano M. *Applied Surface Science*[J], 2012, 258(18): 6831
17 Klemenz M, Schulze V, Rohr I *et al*. *Journal of Materials Processing Technology*[J], 2009, 209(8): 4093
18 Wang Z, Jiang C H, Gan X Y *et al*. *Applied Surface Science*[J], 2010, 257(4): 1154
19 Thomas M, Lindley T, Rugg D *et al*. *Acta Materialia*[J], 2012, 60 (13-14): 5040
20 Hayashi M, Enomoto K. *International Journal of Fatigue*[J], 2006, 28(11): 1626
21 Segurado E, Belzunce F J, Pariente I F. *Surface and Coating Technology*[J], 2018, 340: 25

温度场下17-4PH钢喷丸表面残余应力松弛及疲劳强度

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摘　要：采用喷丸处理对17-4PH不锈钢进行表面强化，研究了温度场对其残余应力和疲劳性能的影响。结果表明，结合扫描电镜等微观结构分析，采用X射线无损检测技术对室温下17-4PH不锈钢在不同喷丸参数处理后的表面残余应力进行了评价，利用旋转弯曲疲劳试验机测试了喷丸后样品的S-N疲劳曲线。然后，采用优化的喷丸处理方法，研究了17-4PH材料在150、300和450 ℃不同温度场下的高温疲劳性能和表面残余应力松弛特性。实验结果表明，17-4PH不锈钢的最佳室温喷丸工艺应选用低强度喷丸参数。同时，针对此最佳喷丸强化工艺的高温疲劳试验表明，当环境温度T<300 ℃时，喷丸能显著提高17-4PH不锈钢的疲劳寿命，当温度T>450 ℃时，17-4PH的疲劳性能反而显著降低。进一步分析表明，对于喷丸后17-4PH的高温服役，其疲劳性能降低机理是由于残余应力的严重松弛和表面完整性的降低。

关键词：喷丸；残余应力；高温；抗疲劳强度

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