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Study on stress relaxation characteristics of FGH95 powder superalloy treated by laser shock peening

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Abstract

Aiming at the phenomenon that the residual stress induced by Laser Shock Peening (LSP) will relax and redistribute under various loads, temperature, cyclic load, and the dual treatment of temperature and cyclic load on the residual stress relaxation of FGH95 powder superalloy after LSP treatment were studied, and the analysis model of relevant residual stress relaxation was constructed. The purpose is to understand the strengthening effect and stability of the alloy under temperature and cyclic load after LSP treatment. With the increase of treatment temperature, the relaxation of residual stress became more and more obvious. Most of the residual stress relaxation occurred in the first 30 min of temperature treatment, then slowed down and stabilized after 1 h. The residual stress was initially relaxed in the first 50 cycles, remained roughly unchanged between 50 and 5000 cycles. The intensify of the cyclic load increasing, adding material yield level, further plastic deformation and residual stress relaxation rate increases. With the increase of load intensify and load ratio, residual stress relaxation was also increased. The residual stress relaxation rate after 600 °C and cyclic load treatment was 56.2%, both greater than that after 600 °C or cyclic treatment of 25 °C, but less than the sum of the two conditions. The results of this paper provide a reference for the LSP of the FGH95 powder superalloy turbine disk and other aero engine parts.

1. Introduction

FGH95 is a powder superalloy developed in China. It is a high alloyed γ′ phase precipitation-strengthened nickel-base alloy. Its microstructure is mainly composed of γ matrix, γ′ phase and carbides. The composition and microstructure of the alloy are similar to that of Rene95 alloy made by GE Company in the United States [1]. The γ′ volume fraction of the alloy is about 50% ∼ 55%, and the alloy has a good strength at 650 °C. The alloy can be used to manufacture high-temperature rotor parts such as turbine disks, compressor disks, and turbine retaining rings for new engines with high thrust ratios [2].

The parts of engine high temperature rotor experiences complex thermal and mechanical cyclic loads during engine operation. The stress concentration area of the part will initiate microcracks before other areas, and then the cracks will propagate until fatigue failure [3]. Surface treatment results in plastic deformation of the surface and high residual compressive stress near the surface. The residual compressive stress counteracts part of the tensile load, thus inhibiting fatigue crack initiation and propagation. However, Residual stress will relax and redistribute under various loads, such as temperature, cyclic load, vibration load, etc. It is very important to study the stability of residual compressive stress induced by surface treatment under these loads. Compared with Shot Peening (SP), Laser Shock Peening (LSP) generates deeper compressive stresses through relatively low cold processing, and these compressive stresses maintain good stability even after high temperature treatment [4].
This characteristic makes LSP more suitable than SP for nickel-based alloys used in engine turbine disk operating at high temperatures. There have been relevant reports on the stability of residual compressive stress of nickel-based alloy introduced by LSP [4–15]. Chin et al [4] compared and analyzed the thermal relaxation phenomenon of residual stress of Inconel 718 nickel-based alloy after LSP and SP treatment, and the results also showed that the residual stress relaxation rate of SP-treated sample was faster under the condition of thermal exposure. Altenberger et al [5] also found that the residual stress was no longer stable at high temperature, but the LSP induced microstructure of Ti-6Al-4V titanium alloy was still relatively stable at 673 K (400 °C), and the slip band and dislocation entangling generated by the surface hardened layer were also relatively stable, thus effectively prolonging the crack initiation life. Buchanan et al [13] studied the thermal relaxation of residual stress in IN100 nickel-base alloy after LSP and SP treatment respectively. After exposure at 650 °C for 10 h, the surface residual stress and the peak residual stress of the SP-treated samples were reduced by −500MPa and −800MPa, respectively. By LSP processing sample surface residual stress and the peak value of the subsurface residual stress reduction degree were small, 350MPa and 200MPa, respectively. Li Yuqin et al [14] studied the influence of thermal load on the stability of GH4133 nickel-based superalloy LSP treated by comparative experiment. Although the residual stress of the sample after LSP was reduced to some extent after heat treatment of 500 °C/1h, the fatigue life of the sample was still 1.34 times longer than that of the sample without treatment, indicating that the GH4133 nickel-base superalloy treated by LSP has excellent stability of high-temperature fatigue performance at 500 °C. Ramakrishnan [15] studied the thermal stability of residual stress induced by LSP of Ti-6242 titanium alloy within the temperature range of (315 °C /482 °C /538 °C) and its influence on the increase of fatigue strength. The results showed that even at 538 °C, the enhancement effect of LSP could be achieved. Under 225 MPa loading, the lifetime of LSP sample and LSP + 482 °C sample was increased by 6 times and 1.34 times, respectively, compared with the untreated sample.

In the open literature about thermal residual stress relaxation and high temperature mechanical fatigue research main goal is to high temperature deformation of titanium alloy and wrought nickel-base superalloy, almost no residual stress relaxation of powder nickel-base superalloy. In this paper, the effects of temperature and cyclic load on residual stress relaxation of FGH95 powder superalloy treated by LSP were studied.

2. Objectives and scope

The main objective was to evaluate the strengthening stability of LSP of FGH95 powder superalloy used for turbine disk manufacturing. Due to the narrow structure of the mortise area of the turbine disk, LSP could only be carried out at oblique incidence, that is, the angle between the laser beam and the normal line on the surface of the site to be impacted was greater than 0°. The range of oblique impact angle of each area was determined by using MotoSim EG CRV offline programming software with a 2 mm beam [16]. The results show that when the angle of 60° was selected as the oblique impact angle, there was no interference in the region to be strengthened of the mortise structure.

3. Materials and methods

3.1. Experimental materials
The experimental materials used in this study were FGH95 powder superalloys with the specific chemical compositions shown in table 1.

3.2. Experimental treatment
3.2.1. LSP equipment
The LSP equipment used in this paper was PROCUDO®200, a third-generation single-longitudinal mode laser peen system produced by LSP Technologies in the United States, which employs a diode-pumped pulsed YLF
laser. Parameters of LSP: laser energy 8J, circular spot 2 mm, pulse width 20 ns, spot lap rate 30%, frequency 5HZ, impact number 1, incidence angle 60°, restraint layer water, absorption layer 3M Vinyl Tape black Tape. The processing path was an 'S'-shaped path, that is, from top to bottom, while impacting from left to right.

3.2.2. Temperature relaxation
The block samples with size of 19 mm × 19 mm × 5 mm were obtained by wire cutting. The burrs and scratches on the surface of the samples should be removed successively through the metallographic sandpaper of 180# to 3000# then polished with diamond polish and wool felt polishing cloth. Finally, the samples were cleaned by an ultrasonic cleaning machine equipped with anhydrous ethanol solution, and the surface of the samples were blown dry by a hair dryer. The block samples to be treated by LSP were shown in figure 1. The area to be impacted of the samples were 10 mm × 10 mm in the middle of the surface.

The 1300 °C high-temperature energy-saving box-type electric furnace produced by Tianjin Zhonghuan Electric Furnace Co., Ltd. was used for heat treatment. The treatment temperatures were 200 °C, 400 °C and 600 °C respectively, and the treatment times were 10 min, 30 min, 1 h, 2 h, 5 h and 10 h respectively, followed by rapid air cooling.

3.2.3. Cyclic relaxation
The dog-bone-shaped specimen with a length of 110 mm and a thickness of 2 mm were obtained by wire cutting. The middle area of the specimens was 30 mm × 7.5 mm, which were treated by LSP. The specimens were then ground, polished, cleaned and blow-dried according to the method described in section 3.2.2. The dog-bone-shaped specimens to be treated by LSP were shown in figure 2.

When the strength of applied cyclic load is lower than the yield strength of material, the relaxation of residual stress is not obvious [17]. The yield strength and tensile strength of FGH95 powder superalloy used in this paper are 760.4 MPa and 1164.4 MPa respectively. Cyclic loads were applied using the MTS Landmark 370.10 fatigue test system. Force-controlled tensile tests with of 800 MPa and 1000 MPa, load ratio R of 0.1 and 0.5, and frequency of 10 Hz. The cycles were 5, 50, 500 and 5000, respectively. The interrupt cycle tests and residual stress measurements were carried out at the selected number of cycles, and then the tests were resumed under the same exact conditions as before the interrupt.

3.3. Residual stress measurement
The residual stresses on the surface of the sample were measured by x-ray stress analyzer (XL-640 X, AstaTech, China) using sin²ψ method. The radiation target was MnKα, the step distance of 2θ was 0.04°, the diffraction crystal plane was (311), the stress constant was −181 MPa deg⁻¹, and the bragg’s angle was 152°. counting time was 10s, the voltage and current of the x-ray tube were 22 KV and 6 mA respectively, and the inner diameter of the collimation tube was Φ2 mm.
4. Result and discussion

4.1. Effect of temperature on stress relaxation

The relaxation results of residual stress on the sample surface are shown in Figure 3. As can be seen from Figure 3, the residual compressive stress obtained on the surface of FGH95 powder superalloy sample after LSP was about $-540$ MPa. In the temperature range of 200 °C to 600 °C, the residual stress would relax to varying degrees, but not completely. After 10 h of treatment at 200 °C, 400 °C and 600 °C respectively, the residual compressive stress would be reduced from $-540$ MPa to $-464$ MPa, $-414$ MPa and $-297$ MPa, with a decrease of 14.1%, 23.4% and 45.0%, respectively. With the increase of treatment temperature, the relaxation of residual stress became more and more obvious, relaxation rate increased. It shows that the temperature has a significant effect on the thermal relaxation of residual stress. It is also noted that the time of temperature treatment had a strong effect on residual stress relaxation, and the surface stress relaxed significantly even over a relatively short period of time. After 10 min of treatment at 200 °C, 400 °C and 600 °C, the residual compressive stress decreased to $-501$ MPa, $-477$ MPa and $-397$ MPa, 7.2%, 11.7% and 26.5%, respectively. This showed that the residual stress relaxes within 10 h, and the rates of relaxation in the first 10 min reached 51.3%, 50.1% and 58.9%; the rates in the first 30 min were 70%, 69.9% and 80.4%; at 200 °C, 400 °C and 600 °C respectively. Meanwhile, the rates in the first hour were 75.1%, 72.6% and 84.2%, respectively. Most of the residual compressive stress released in temperature treatment in the first 30 min, then slowed relaxation, after 1 h, residual stress tended to be stable.

Figure 2. The dog-bone-shaped specimen to be treated by LSP.

Figure 3. Residual stress relaxation under different treatment times at 200 °C, 400 °C and 600 °C.
According to the literature [6–10], the temperature relaxation of residual stress is mainly caused by two main reasons: material softening after heating and uneven distribution of residual compressive stress. Material of the inherent to yield stress and decreased with the increase of temperature; At the same time, the existence of residual compressive stress will promote plastic flow, promote dislocation slip and climb, reduce dislocation density, and then lead to the relaxation of residual stress. The higher the applied temperature is, the lower the yield stress of the material will be, and more dislocation rearrangement and annihilation will occur, which will aggravate the ratio of thermal relaxation. By the known, the higher the temperature, the greater the stress relaxation. After relaxation for a period of time, the release rate of residual stress slows down, which is mainly due to the increase of precipitation strengthening $\gamma'$ phase will increase the creep strength of the material, thus inhibiting dislocation movement.

The residual stress relaxation process of FGH95 powder superalloy after LSP was analyzed dynamically, and the relaxation rate and related influencing factors were determined by the residual stress temperature relaxation data. As shown in previous literature [6–10], the effect of temperature on residual stress relaxation can be expressed by Zener-Wert-Avrami function:

\[
\frac{\sigma_{rs}}{\sigma_{0}} = \exp\left[-(D_{ta})^{l}\right]
\]

Where, $\sigma_{rs}$ is the residual stress at a certain temperature $T_{a}$ at a certain time $t_{a}$; $\sigma_{0}$ is the initial residual stress at room temperature (298 kelvin temperature); $l$ is a numerical parameter dependent on the main relaxation mechanism; $D$ is a function dependent on materials and temperature:

\[
D = E \exp \left[-\frac{\Delta H}{KT_{a}} \right]
\]

Where $E$ is the material constant, $K$ is the Boltzmann constant, and $\Delta H$ is the activation enthalpy of $t_{a} - T_{a}$ the relaxation process in the experimental norm. From the equivalent form (1), namely:

\[
\ln \left[ \ln \left( \frac{\sigma_{0}}{\sigma_{rs}} \right) \right] = l \ln D + l \ln t_{a}
\]

At a selected temperature, a straight line with slope $l$ and intercept $\ln D$ is obtained from the scatter plot of $\ln \left[ \ln \left( \frac{\sigma_{0}}{\sigma_{rs}} \right) \right]$ and $\ln t_{a}$ through linear fitting, as shown in figure 4. In addition, after selecting ratio $\frac{\sigma_{0}}{\sigma_{rs}}$, the relationship between temperature and time can be deduced through formulas (2) and (3), namely:

\[
\frac{\ln \left[ \ln \left( \frac{\sigma_{0}}{\sigma_{rs}} \right) \right]}{l} - \ln E + \frac{\Delta H}{KT_{a}} = \ln t_{a}
\]
Figure 4 shows that the value of slope $l$ at 200 $^\circ$C (∼0.153) was slightly lower than that at 400 $^\circ$C (∼0.173) and 600 $^\circ$C (∼0.154), indicating that the relaxation dynamics was the slowest at 200 $^\circ$C and the residual stress could be maintained at 600 $^\circ$C. The values of $\ln \left( \frac{\sigma_a^0}{\sigma_{a,0}} \right)$ were selected as $-0.5$, $-1.0$, $-1.5$, $-2.0$ and $-2.5$, corresponding to 45.5%, 30.8%, 20.0%, 12.7% and 7.9% of the initial values of residual stress relaxation respectively. Scatter plots of $\ln t_a$ and $\frac{1}{KT_a}$ were drawn, as shown in figure 5, and linear fitting was performed on each set of data points selected for $\ln \left( \frac{\sigma_a^0}{\sigma_{a,0}} \right)$. Could be concluded from the graph corresponds $\ln \left( \frac{\sigma_a^0}{\sigma_{a,0}} \right)$ to the value of activation enthalpy $\Delta H$ were 0.815 eV and 0.806 eV and 0.798 eV and 0.789 eV and 0.781 eV. This phenomenon also explains the rate of residual stress relaxation is low, the activation enthalpy correspondingly smaller, residual stress in steady state is easier to excitation and relaxation; With the activation enthalpy increasing, the stability of residual stress increases gradually. The higher activation enthalpy of residual stress relaxation is due to the dislocation movement hindered by precipitation strengthening $\gamma'$ phase.

4.2. Effect of cyclic load on residual stress relaxation

4.2.1. Effect of number of cycle

The sample group with load intensity of 800 MPa and load ratio of 0.1 was selected. The residual stress after different cycles were compared, as shown in figure 6. The data on the figure shows that the initial residual stress of the sample treated by LSP was $-578.4$ MPa; after 5 cycles, the residual stress was $-468.3$ MPa, and the stress relaxation was 19.0%; after 50 cycles, the residual stress was $-430.8$ MPa, and the stress was relaxed by 25.5%; after 500 cycles, the residual stress was $-408.6$ MPa, the stress relaxation was 29.3%; finally in 5000 cycles, the residual stress was $-421.5$ MPa, the stress relaxation of 27.1%.

Based on the stress after 5000 cycles of relaxation, the stress relaxation in the first five cycles was 70.1%, the stress of the first 50 cycles was relaxed by 94.1%, the stress relaxation was 108.2% in the first 500 cycles. This phenomenon shows that the relaxation of residual stress is mainly in the initial cycles. At the same time, the cyclic load will improve the yield strength, the deformation will decrease in the further cycles, and the residual stress will gradually become stable [18].

4.2.2. Effect of load intensity

Two different sample groups with load intensity of 800 MPa and 1000 MPa were selected respectively, and the load ratio was 0.1. The residual stress after different load intensities were compared, as shown in figure 7. According to the figure, in the case of 1000 MPa load intensity, the residual stress after 5 cycles was $-458.1$ MPa, and the stress was relaxed by 20.8%; after 50 cycles, the residual stress was $-407.3$ MPa, and the stress relaxation was 29.6%; after 500 cycles, the residual stress was $-412.1$ MPa and the stress was...
relaxed by 28.8%; finally, at 5000 cycles, the residual stress was $-374.3$ MPa, and the stress was relaxed by 35.3%. This also indicates that the residual stress relaxes initially in the first 50 cycles and varies little between 50 and 5000 cycles.

Taking the stress value after 50 cycles of relaxation as reference, the residual stress relaxation under 800 MPa load intensity was $-147.6$ MPa; the residual stress relaxation at 1000 MPa was $-171.1$ MPa, which increased by 15.9%. The results show that the increase of cyclic load intensity will increase the relaxation of residual stress. This is mainly due to the increase of the load intensity, which will lead to the increase of the yield degree of the material, and further aggravate the degree of tensile plastic deformation, so that the residual stress of the material is further reconstructed and distributed, resulting in the phenomenon of residual stress relaxation.

4.2.3. Effect of load ratio

Two different sample groups with load ratio of 0.1 and 0.5 were selected respectively, and the load intensity was 1000 MPa. The residual stress after different load ratios were compared, as shown in figure 8. According to the figure, under the condition of load ratio of 0.5, after 5 cycles, the residual stress was $-347.7$ MPa, the stress relaxation was 39.9%; after 50 cycles, the residual stress was $-304.7$ MPa and the stress was relaxed by 47.3%; after a 500-cycle, residual stress was $-283.5$ MPa, the stress relaxation was 50.9%; finally in 5000 cycles, the residual stress was $-278.4$ MPa, the stress relaxation of 51.9%. The residual stress also relaxed in the first 50 cycles, with a relaxation of 91.2%, and decreased slightly in the subsequent 50 to 5000 cycles.
Stress relaxation after 50 cycles for reference, the residual stress relaxation under loading ratio of 0.1 was 171.1 MPa, the residual stress relaxation under loading ratio of 0.5 cycle was 273.7 MPa, the stress relaxation increased by 59.9%. This indicates that the increase of the load ratio will also aggravate the relaxation of the residual stress. This is mainly the increase of load ratio, actually will decrease the range of load fluctuation, thus increasing the load average, also will aggravate the degree of tensile plastic deformation, increase the residual stress relaxation.

4.3. Effect of temperature and cyclic load on residual stress relaxation

Two different sample groups at room temperature of 25 °C and 600 °C were selected respectively, with a load intensity of 1000 MPa and a load ratio of 0.1. The residual stresses after different temperatures and cyclic loads were compared, as shown in figure 9. According to the figure, under the condition of 600 °C, after 5 cycles, the residual stress was −269.9 MPa, the stress relaxation was 53.4%; after 50 cycles, the residual stress was −253.6 MPa and the stress was relaxed by 56.2%; after a 500-cycle, residual stress was −212.8 MPa, the stress relaxation was 63.2%; finally in 5000 cycles, the residual stress was −188.8 MPa, the stress relaxation of 67.4%. The residual stress of the sample treated by temperature of 600 °C and cyclic load also relaxed in the initial cycle, but the relaxation amount of the first 5 cycles accounted for 79.2% of the total value. Greater than the temperature of 25 °C and cyclic load after processing the first 5 cycles of relaxation, of 58.9%. At the same time, the stress change degree of 600 °C treatment increased in the subsequent 50 to 5000 cycles.

The residual stress relaxation rate after 1h treatment at 600 °C in figure 3 and after 50 cycles in the two treatments in figure 9 were calculated, as shown in figure 10. The figure shows that the residual stress relaxation
rate after 600 °C and cyclic load treatment was 56.2%, both greater than that after 600 °C or cyclic treatment of 25 °C, but less than the sum of the two conditions.

5. Conclusions

In this paper, the effects of temperature and cyclic load on residual stress relaxation of FGH95 powder superalloy treated by LSP were studied. The following conclusions were obtained:

(1) With the increase of treatment temperature, the relaxation of residual stress became more and more obvious, and the rate of relaxation increased. Most of the residual stress relaxation occurred in the first 30 min of temperature treatment, then slowed down and stabilized after 1 h. The temperature relaxation of residual stress is mainly caused by the softening of the material after heating and the uneven distribution of residual compressive stress. Material after warming, precipitation-strengthened γ′ phase increases, thus improve the creep strength and inhibition of dislocation motion, residual stress release at a slower pace. The thermal relaxation process of residual stress was analyzed by Zener-Wert-Avrami function, and the numerical parameters $l$ and activation enthalpy of relaxation mechanism after linear fitting of the function were analyzed.

(2) The residual stress was initially relaxed in the first 50 cycles, the yield strength was slightly increased in the tensile cycle, the deformation was reduced in the subsequent cycles, and the residual stress remained roughly unchanged between 50 and 5000 cycles. The intensity of the cyclic load increasing, adding material yield level, further plastic deformation and residual stress relaxation rate increases. With the increase of load ratio, the average value of load is increased, and the degree of plastic deformation and residual stress relaxation are also increased.

(3) The residual stress of the sample treated by temperature of 600 °C and cyclic load also relaxed in the initial cycle, but the relaxation amount of the first 5 cycles accounted for 79.2% of the total value. Greater than the temperature of 25 °C and cyclic load after processing the first 5 cycles of relaxation, of 58.9%. At the same time, the stress change degree of 600 °C treatment increased in the subsequent 50 to 5000 cycles. The increase of precipitation-strengthened γ′ phase after 600 °C treatment could improve the creep strength of the material, suppressed the dislocation movement, reduced the yield degree of the material, and then relieved the tensile plastic deformation, reduced the residual stress relaxation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Author contributions

Conceptualization, H.Z. and X.Q.; methodology, X.Q. and Y.Zhang.; formal analysis, J.C., Y.Zhao and W.W.; investigation, X.Q., X.G., Y.Zhao, X.W. and W.W.; data curation, Y.Zhao, X.W. and W.W.; writing, W.W.; supervision, Y.Zhang. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

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