Rare Metal Materials and Engineering
Volume 46, Issue 12, December 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(12): 3682-3687.

ARTICLE

Experiment Study on Improving Fatigue Strength of K24 Nickel Based Alloy by Laser Shock Processing without Coating

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Abstract: Laser shock processing without coating (LSPwC) was used to improve the fatigue resistance of K24 nickel based alloy. Firstly, high cycle vibration fatigue experiment was adopted to verify the LSPwC strengthening effect. Compared to the untreated samples, the results of the vibration fatigue experiments show that the fatigue strength of K24 alloy is enhanced and improved from 282 MPa to 328 MPa after LSPwC. Secondly, the effects of multiple impacts on mechanical properties and fatigue fracture morphologies were investigated, which were observed and measured by scan electron microscope (SEM), X-ray diffractometer and microhardness tester. The results indicate that the residual stress presents compressive state on the superficial layer with about 150 μm depth and the maximum value reaches –595 MPa. The microhardness ($HV_{0.5}$) is about 5260 MPa with about 100 μm depth from the top surface after three impacts. The fracture observation indicates that the flatness area is larger in the fatigue crack initiation (FCI) after LSPwC; meanwhile, the growth rate of fatigue crack is decreased. Lastly, the strengthening mechanism of LSPwC on the fatigue resistance was discussed based on the experimental results.

Key words: laser shock processing without coating; K24 nickel based alloy; high-cycle fatigue; fatigue fracture; residual stress; strengthening mechanism

High cycle fatigue (HCF) is currently the primary cause of component failures in turbine aircraft engines, which seriously affects the engines performance and flight safety. In most cases, the fatigue failures of materials are sensitive to their surface states[1]. Thus, optimization of the surface microstructure and mechanical properties can effectively improve the reliability and service lifetime. Various surface modification techniques, such as shot peening (SP), ultrasonic shot peening (USSP), have been developed on the engines blades[2,3]. Laser shock processing (LSP) is an innovative surface treatment technique, which generates the plasma shock wave with high pressure and short duration and then induces compressive residual stress and grain refinement on the surface of target material. It has been proved to improve the fatigue performance, corrosion resistance, and erosion resistance[4,5]. Li et al indicated that LSP can effectively improve the fatigue strength of K417 nickel based alloy and discussed the strengthening mechanism[6]. Zhou et al investigated the distribution of residual stress fields of IN718 superalloy by LSP based on three-dimensional nonlinear finite element analysis[7].

In the present paper, K24 nickel alloy used as aero engine turbine blade was chosen to investigate the effect on fatigue property. During the investigation process, we found that K24 alloy has a larger surface toughness and some holes inside the material. It can affect the shock wave propagation, and results in the decrease of fatigue strength of K24 after LSP treatment. So we put forward a new surface treatment technology called laser shock processing without coating (LSPwC). Compared with LSP, LSPwC has an advantage on the material with larger surface roughness because ablation occurs on the material surface immediately by

Received date: December 25, 2016
Foundation item: National Basic Research Program of China (2015CB057400); National Natural Science Foundation of China (51405506, 51505496)
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reason of laser irradiating material surface directly and then continuous smooth surface is formed. On the other hand, the material with internal holes has less sensitivity on shock wave because the LSPwC affected layer is thinner. LSPwC has been shown to be effective in improving the fatigue properties of a number of metals and alloys, such as titanium alloy, stainless steel, aluminum alloy. However, there are few reports about nickel based superalloy[8-12].

In the present paper, the effects of LSPwC in K24 nickel based alloy were investigated in detail. K24 alloy simulation blades were processed by LSPwC. Vibration fatigue test was conducted to validate the effect on the fatigue resistance. The influence mechanism was analyzed by the fatigue fracture observation, residual stress and microhardness.

1 Experiment

The material is the K24 nickel based alloy, which is widely used in many applications including rotor blades and countervanes of aero engine below 950 ℃ because of its high temperature fatigue strength, good ductility and excellent manufacturability. The chemical composition of K24 nickel based alloy (wt%) is shown in Table 1[13]. The elasticity modulus E=213 GPa, poisson ratio v=0.30 and the tensile strength σ_b=930 MPa. The K24 alloy simulated blades are schematically shown in Fig.1. According to the first-order stress distribution of blade as shown in Fig.2, the largest equivalent stress located in the transfer place between leaf and R groove of blade, so the shock area was validated at the up 5 mm of blade root.

LSPwC is a surface modification technology which is from LSP. It has many features such as low energy (mJ), small spot size (μm) and no protective coating covered on the target material surface. In the processing of LSPwC, the pulsed laser induced shock wave peak pressure[14] and the Hugoniot fatigue limit of material[15] could be estimated by:

$$P_{\max} = 0.01\sqrt{[\xi/(2\xi+3)]ZI} \quad (1)$$

$$\sigma_{\mathrm{HEL}} = (\frac{K}{2G}+\frac{2}{3})Y_0 \quad (2)$$

where Y_0 is the Tresca yield stress, K is the bulk modulus, G is the shear modulus, I is the laser power density, ξ is the ionization constant and Z is the equivalent impedance.

According to Eq. (1) and (2), the plastic deformation will be induced when the shock wave pressure is larger than 1.8 GW/cm^2. LSPwC experiments were performed using a Q-switched Nd:YAG laser operating at 2 Hz repetition rate with a wavelength of 532 nm, the full width at half maximum (FWHM) of the pulses was about 8 ns. The LSPwC parameters are shown in Table 2.

Fig.3 shows a schematic illustration and layout of LSPwC used in the present work. The process of unequal stress impact was conducted in the LSPwC experiment since it can avoid the accumulation of plastic deformation at the edge of blade with the thickness of only 2 mm[16]. Samples were submerged in a water bath, and the strengthen region was divided into four areas. The local area 1 is the higher power density region with 4.97 GW/cm^2 and other areas are lower power density region with 2.21 GW/cm^2, the shock path are shown in Fig.3c, and the samples were shocked at the same layer with 3 times.

The surface and cross section residual stress were measured by the X-350A X-ray diffractometer with the sin2ψ-method. Diffracted Cr-Kα characteristic X-ray from a

Table 1 Composition of K24 Nickel based super alloy (wt%)[13]

Cr	Co	Mo	Ti	Al	W	C
8.5~10.5	12.0~15.0	2.7~3.4	4.2~4.7	5.0~5.7	1.0~1.8	0.14~0.20

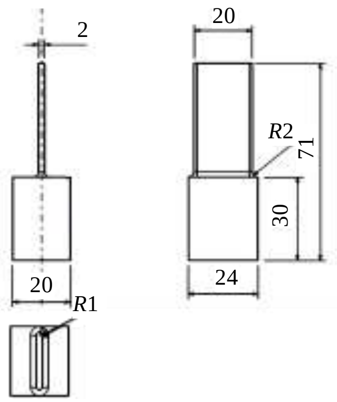

Fig.1 Diagrammatic sketch of K24 simulated blade

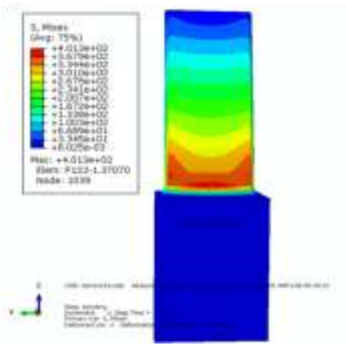

Fig.2 First-order model and stress distribution of simulated blade

Table 2 Laser shock processing without coating parameters

Parameter	Value
Laser wavelength/nm	532
Pulse energy/mJ	50
Pulse duration/ns	8
Spot diameter/mm	0.4/0.6
Repetition-rate/Hz	3
Lapping rate/%	60

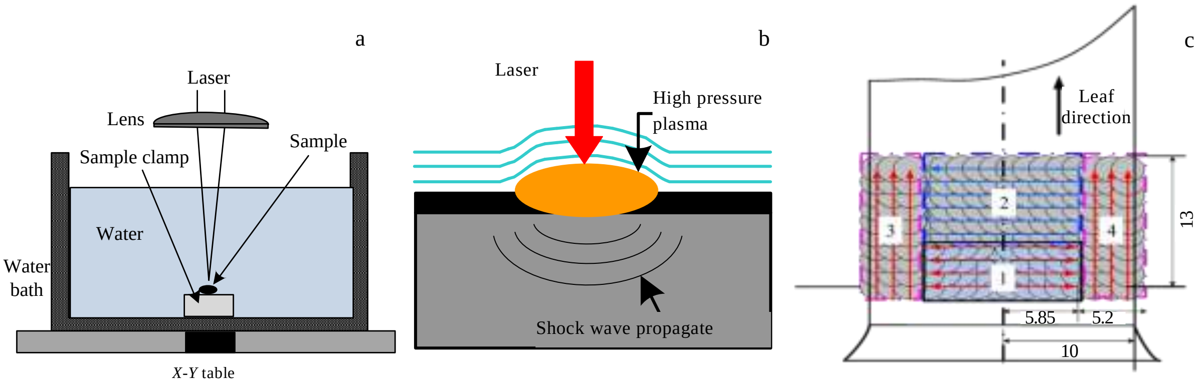

Fig.3 Schematic diagram and layout of LSPwC: (a) principle diagram of LSPwC, (b) laser-induced shock wave, and (c) shocked area and layouts of LSPwC

Ni {213}-Bragg peak of the Ni phase was detected with 2θ of 121°~135°, with a step width of 0.1°, and 0.5 s for each step. Depth profiles of the specimens were obtained by successive chemical etching removal of material (etchant solution: 24% saturated HNO_3 solution + 14% HF solution + 62% H_2O solution, etching rate: 0.2~0.5 μm/s). Residual stress was obtained by taking the average values of three different spots of the same depth.

The Vickers's micro-hardness on the surface and cross-sections of LSPwC specimens was measured by MVS-1000JMT2 micro-hardness tester. The indentation load of 5 N was applied for micro-hardness measurements, and the loading time was 10 s. Micro-hardness results were obtained by taking the average values of three different spots of the same depth.

2 Results and Discussion

2.1 Fatigue performance

Vibration simulation blades were manufactured under the processing technique of factual turbine blade. One half of specimens were LSPwC processed with three impacts. The fatigue limit of the specimens was tested by the up-and-down method. Fatigue tests were conducted at the maximum stress, room temperature and resonant frequency in the air, to test the fatigue limits without and with LSPwC at 10^7 cycles. When the excitation frequency drops cumulatively to 1% below the cycle index number 10^7, the test will stop and the specimen block can be defined as "break"; otherwise the specimen block can be defined as "exceeded". Vibration fatigue test was carried out on D-300-3 electric vibration system.

According to the up-and-down method of material fatigue, the fatigue test results without and with LSPwC are shown in Fig.4. It can be calculated that the fatigue limit without LSPwC is 282 MPa and with that of LSPwC processed specimens is 328 MPa, improved by about 16.3%. It demonstrates that LSPwC can improve the fatigue performance of K24 nickel based alloy effectively.

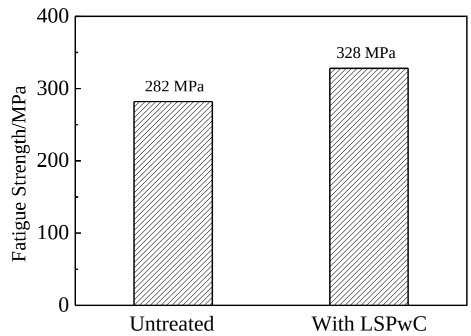

Fig.4 Vibration fatigue strength of K24 alloy under different processing status

2.2 Residual stress and microhardness

The residual compressive stress and microhardness distributions as a function of depth are presented in Fig.5. It can be noted that the significant residual compressive stresses and high microhardness mainly exist in near-surface regions. After three impacts, high-amplitude residual compressive stresses and microhardness are induced, and the maximal values locate in the top surface of metal. The largest compressive residual stress with –595 MPa locates at the surface, and the affected depth of residual stress is about 150 μm. The largest microhardness is about 5260 MPa which locates at the surface and the affected depth is about 100 μm. In depth, the value of residual compressive stress and microhardness decreases gradually. The shock wave pressure decays with the increasing depth in shock wave propagation in material. In other words, the root cause of the residual stress and microhardness distributions is the decreasing pressure of shock wave when shock wave propagates into deep with attenuation.

2.3 Fatigue fracture morphologies

Generally speaking, the morphology of fatigue fracture is the direct result of material progressive wreck[14], and partly it can reflect the change of macroscopic properties. So it is valuable to carry out quantitative investigation of the macroscopic and microscopic fatigue fracture morphologies, and then analyze the fatigue properties of metallic material induced by multiple LSPwC impacts. In the present paper, the fatigue enhancement mechanism of LSPwC on the fatigue crack initiation (FCI) and fatigue crack growth (FCG) resistance are also revealed.

2.3.1 Fracture morphologies without LSPwC

In the process of vibration fatigue test, FCI was formed as the accumulation of material wreck because of the interaction of slip bands and grain boundary. The sample with the vibration stress level of σ_a=304 MPa and fatigue life of N_f=0.739×10^7 cycles was chosen and the typical fatigue fracture morphologies without LSPwC are shown in Fig.6. The fractograph with small quasi-cleavage facets, jagged gliding-cleavage facets and quasi-plume fracture facets in the growth region is shown in Fig.6a. Quasi-cleavage facets are produced by the interaction of slip planes in the state of fatigue crack growth. The FCI of the untreated sample occurs from the center of samples and locates in the top surface. Clear river patterns and abundant cleavage steps were observed on the fracture of blades before LSPwC, as shown in Fig.6b (red box in Fig.6a).

2.3.2 Fracture morphologies with three LSPwC impacts

After LSPwC, the fatigue sample with vibration stress level of σ_a=320 MPa and fatigue life of N_f=1.0×10^7 cycles was chosen. It can be seen that crack source also initiates at the area with the largest stress and there are some small smooth surfaces on the fatigue fracture morphology near the FCI, and the patterns on the fracture are flat with a larger propagation zone compared with untreated samples, as shown in Fig.7a. It is indicated that LSPwC can improve the life of FCI by delaying the form of FCI.

After LSPwC treatment, the local stress is more complicated compared with that of untreated samples, and the secondary cracks can be clearly found on the sample subjected to 3 LSPwC impacts (as shown in Fig.7b), which reduce the growth rate through changing the growth path near the secondary cracks. And it shows that the fatigue striations spacing is smaller on the fracture morphology. It is well known that the fatigue striations spacing is the approximation of FCG rate da/dN[17]. Therefore, the da/dN of untreated sample at the stage of FCG is correspondingly faster, while the rate of the samples subjected to multiple LSPwC impacts decreases significantly. The larger flatness area near FCI and the smaller fatigue striations represent the lower da/dN of samples subjected to 3 LSPwC impacts and the fatigue life of FCG is improved. Above all, LSPwC can improve the fatigue life through delaying the formation of fatigue initiation and decreasing the crack growth rate.

2.3.3 Effect mechanism of fatigue performance

LSPwC has difference between with LSP, but all of their objectives are to form a favorable strengthening deformation layer and to produce high amplitude residual compressive stresses. The fatigue strength improving

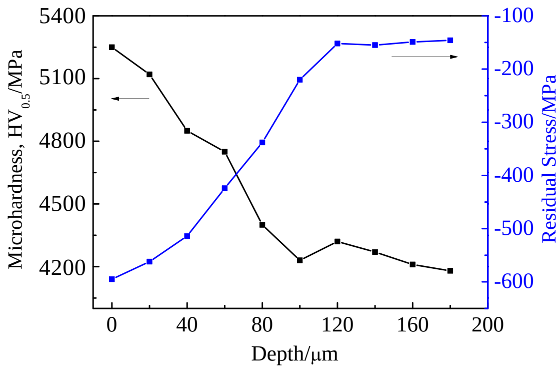

Fig.5 Residual stress profiles and microhardness of the surface layer after 3 impacts

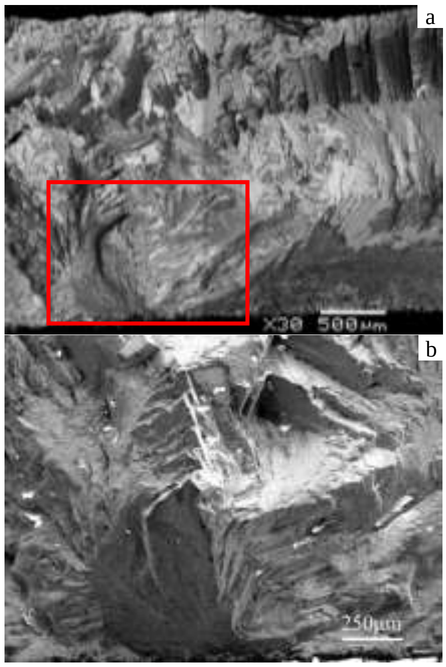

Fig.6 Typical fractographies of specimens without LSPwC (σ_a=304 MPa, N_f=0.739×10^7)

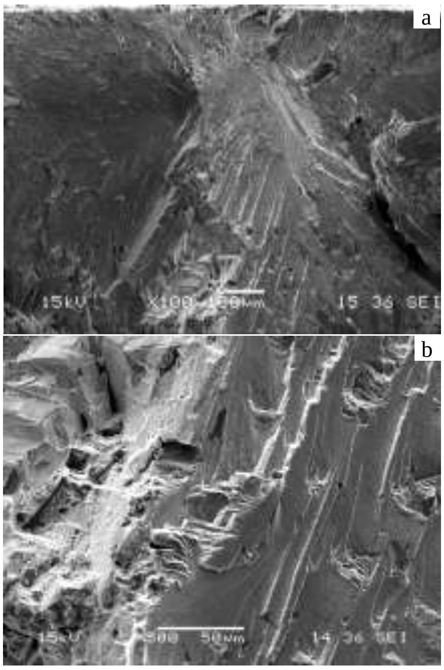

Fig.7 Typical fractographies of specimens with three LSPwC impacts: (a) crack source and (b) FCG region (σ_a=320 MPa, N_f=1.0×10^7)

effectively of K24 alloy after LSPwC is mainly attributed to the comprehensive action of the residual compressive stresses and surface hardening, which is in line with the strengthening mechanism of LSP[5,17].

According to the Goodman theory, the following equations are achieved[18]:

$$\sigma_{\mathrm{p}}^{\mathrm{m}} = \sigma_{\mathrm{p}}^{0} - (\sigma_{\mathrm{p}}^{0} / \sigma_{\mathrm{b}})\sigma_{\mathrm{m}} = \sigma_{\mathrm{p}}^{0} - m\sigma_{\mathrm{m}} \tag{3}$$

$$\sigma_{\mathrm{p}}^{\mathrm{r+m}} = \sigma_{\mathrm{p}}^{0} - m(\sigma_{\mathrm{r}} + \sigma_{\mathrm{m}}) \tag{4}$$

$$\Delta\sigma_{\mathrm{p}}^{\mathrm{r}} = \sigma_{\mathrm{p}}^{\mathrm{r+m}} - \sigma_{\mathrm{p}}^{\mathrm{m}} = -m\sigma_{\mathrm{r}} \tag{5}$$

According to Eq.(5), the formation of compressive residual stresses in the surface strengthening layer causes the initiation of the fatigue cracks at the vulnerable area under the affected layer. Thus, compressive residual stress dramatically prolongs the crack initiation life, and hence increases the fatigue life of treated samples. In addition, compressive residual stress can discharge the tensile stress in the process of fatigue, and reduce the stress intensity factors, enhance the fatigue crack closure effect, and increase the critical stress of crack propagation, decrease the crack propagation rate (da/dN). Thereby, the expansion of fatigue crack can be retarded and the fatigue performance of metal materials is improved. Therefore, the compressive residual stress induced by LSPwC is very efficient in enhancing the fatigue capability of K24 nickel based alloy.

3 Conclusions

1) With 3 LSPwC impacts, residual compressive stress is –595 MPa and the affected depth is 150 μm. The surface micro-hardness of the sample is 5260 MPa and the corresponding affected depth is 100 μm.

2) Multiple LSPwC impacts can effectively retard the initiation of fatigue crack, reduce the growth rate of fatigue crack, and improve the fatigue resistance.

3) Owing to the action of high amplitude residual compressive stress and surface hardening, the fatigue limit of vibration specimen is improved from 282 MPa to 328 MPa, about increased by 16.3%.

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无保护层激光冲击强化提高 K24 镍基合金疲劳强度试验研究

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摘　要：通过采用无保护层激光冲击强化提高K24镍基合金的抗疲劳特性。首先，采用高周振动疲劳试验验证了无保护层激光冲击强化效果，疲劳试验结果表明，强化后K24镍基合金疲劳强度相比于未强化试件的282 MPa提高到328 MPa。其次，通过采用扫描电镜（SEM）观察、残余应力和显微硬度测试研究了多次冲击对K24镍基合金机械性能以及断口形貌的影响。残余应力测试结果表明，无保护层激光冲击强化后表面形成了压应力，表面最大达到–595 MPa，且影响深度为150 μm。同样3次冲击后表面显微硬度（$HV_{0.5}$）增加到5260 MPa，深度约为100 μm。断口形貌特征表明强化后裂纹源区更加平坦，同时裂纹扩展速率降低。最后，基于疲劳试验和力学性能测试结果进一步讨论了激光冲击强化提高疲劳强度的影响机制。

关键词：无保护层激光冲击强化；K24 镍基合金；高周疲劳；疲劳断口；残余应力；强化机制

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