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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

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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 ºC 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 ν=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

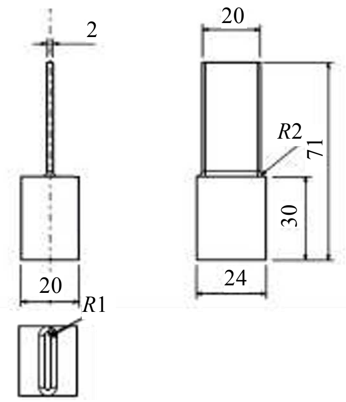

Fig.1 Diagrammatic sketch of K24 simulated blade

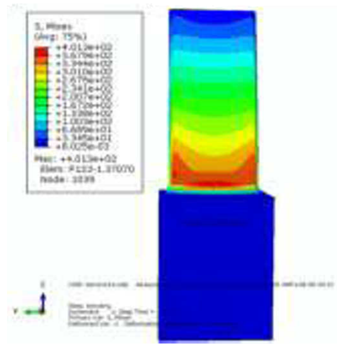

Fig.2 First-order model and stress distribution of simulated blade

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