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High temperature mechanical properties and surface fatigue behavior improving of steel alloy via laser shock peening

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ABSTRACT

Laser shock peening was carried out to reveal the effects on ASTM: 410L 00C_r12 microstructures and fatigue resistance in the temperature range 25–600 °C. The new conception of pinning effect was proposed to explain the improvements at the high temperature. Residual stress was measured by X-ray diffraction with $\sin^2\psi$ method, a high temperature extensometer was utilized to measure the strain and control the strain signal. The grain and precipitated phase evolutionary process were observed by scanning electron microscopy. These results show that a deep layer of compressive residual stress is developed by laser shock peening, and ultimately the isothermal stress-controlled fatigue behavior is enhanced significantly. The formation of high density dislocation structure and the pinning effect at the high temperature, which induces a stronger surface, lower residual stress relaxation and more stable dislocation arrangement. The results have profound guiding significance for fatigue strengthening mechanism of components at the elevated temperature.

1. Introduction

Many components work in high temperature conditions, and the thermo-mechanical stability of the microstructure is related to the fatigue behavior of the treated materials at elevated temperatures. Conventional fatigue strengthening mechanism generally produces a surface layer with high compressive residual stress and work-hardening [1,2], such as shot peening and deep rolling. Moreover, these traditional fatigue strengthening mechanisms are only effective at the room temperature [3]. Furthermore, it was found that work-hardening and residual stress may be reduced significantly after cyclic loading [4], especially at high temperatures. Half of the initial compressive stress may disappear in 10 min even at moderate engine temperature [3]. However, the improvement in the fatigue lifetime by mechanical surface treatments is known to depend mostly on the depth distribution, stability of the induced residual stresses and work hardening in the near-surface regions [5].

Laser shock peening (LSP) is an established mechanical surface treatment technology, which is generally utilized to improve the metallic surface [6,7]. Compared with conventional surface mechanical treatment methods [8,9], LSP could change near-surface microstructure and residual stress state, and eventually make material present a higher thermal stability. In addition, the treated component in LSP has a lower surface roughness, which reduces cracks initiation at the surface [10]. Therefore, material surface after LSP would be expected to be suitable under the high temperature fatigue conditions.

According to Aerospace Material Specification (AMS) 2546 “Laser peening standard (2004.8)” [11], the working temperatures of stainless steel should not exceed 399 °C after LSP, but there is no clear specification to the heat-resistant steel. Moreover, few researchers have investigated whether LSP would play the same effect at high temperatures, and how is about the relationship that fatigue behavior and stress stability of heat-resistant steel after LSP at high temperature.

In this paper, the isothermal fatigue tests were carried out to investigate the fatigue behavior of ASTM: 410L (Standard Test Method for Wear Layer Thickness of Resilient Floor Coverings by Optical Measurement) 00C_r12 steel after LSP in the temperature range 25–600 °C. The effect of the LSP was also investigated on improving the fatigue behavior of ASTM: 410L 00C_r12 at high temperature.

2. Experiments and analysis

The material utilized in this study is the ASTM: 410L 00C_r12 steel, which is one kind of heat-resistant steel with good thermo-

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Table 1
Chemical compositions of $00C_r12$ alloy.

Composition	C	Si	Mn	S	P	Cr	Ni
Percent (Wt.%)	$\leqslant$0.030	$\leqslant$1.00	$\leqslant$1.00	$\leqslant$0.030	$\leqslant$0.035	11.00–13.00	$\leqslant$0.60

stable susceptibility and organization stability and usually utilized at the elevated temperatures. The composition of ASTM: 410L $00C_r12$ alloy is given in Table 1, and the dimensions and schematic of standard stretches fatigue ASTM: 410L $00C_r12$ specimen as shown in Fig. 1. The LSP was performed using a nanosecond Nd:YAG laser with the pulse duration of 20 ns and laser power density of 3.29 GW/cm^2, and the spot-size diameter was approximately 6 mm. Surrounding specimen surfaces were also treated under the same conditions.

Residual stress was measured in different positions across the LSP regions by using standard X-ray diffraction (XRD) technique with the $\sin^2\psi$ method. Depth profiles were obtained by successive electrolytic removal of the material. The residual stress relaxation by sample cyclic loading was investigated using MTS880 closed-loop universal testing machine. The load was cycled between 0 and 350 MPa upper limit (equivalent to 85% of yield strength), at a stress ratio $R = 0.1$, starting from low to high. A high temperature extensometer (MTS model No. 632-13F-20, gauge length 25 mm) was utilized to measure the strain and control the strain signal. Isothermal fatigue experiments were performed under load control in tension–compression on a standard testing machine with a load ratio of $R = 0.5$, a frequency of 40 Hz and temperatures of 25–600 °C. The cylindrical samples were heated with a radiant heating. In order to minimize thermal gradients, 10 min earlier than the actual fatigue tests began to heat the smooth cylindrical specimens. Scanning electron microscopy (SEM) was employed to observe the grain and precipitated phase evolutionary process. All of these measurements are intended to give an indication of the local fatigue behavior after LSP.

3. Results and discussions

3.1. Residual stress

LSP induced compressive residual stress of about 380 MPa at the ASTM: 410L $00C_r12$ surface and 400 MPa in the subsurface maximum in a depth of approximately 0.1 mm, as shown in Fig. 2. The compressive residual stresses play an important role on retard subsequent crack propagation [12]. The variation of the diffraction peak width across the laser shocked sample suggests that the sample has yielded significant plastic deformation to a depth of around 1 mm. And even the residual stress has also been changed from compressive stress to tensile stress due to the plastic affected depth. The higher plastic affected depth lead to a higher resistance to crack propagation during fatigue cyclic loading. According to Nikitin and Altenberger [13,14], plastic affected depth would significantly affect the fatigue behavior of materials, especially in push–pull loading fatigue test utilized in this study.

The physical process of LSP is rather complex due to the multi-physical phenomena [15]. A better understanding of the mechanism of high temperature residual stress relaxation is beneficial for developing a physics-based relaxation model. LSP induced residual stress would release in high temperature process for further plastic deformation even under relatively low cyclic loading. The stress relaxation process could be expressed by the Zener-Wert-Avrami function as [16,17],

$$\frac{\sigma_t}{\sigma_0} = \exp[-(At)^m] \quad (1)$$

$$A = B\exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where σ_t is the surface residual stress in high temperature process, σ_0 is the surface residual stress after LSP, m is a numerical parameter dependent on the dominant relaxation mechanism, t is the ageing time, A is a function dependent on the material and temperature, B is a constant, Q is the activation enthalpy for the relaxation process. R is the Boltzmann constant, and T is the ageing temperature.

This model incorporates the residual stress relaxation of heat-resistant steel in the temperature enhancing process. The residual stress relaxation rate is proportional to the applied stress amplitude [18] and the number of stress cycles. As shown in Fig. 3, with the holding time increasing, the compressive flow strength decreases for a given plastic off-set. In addition, residual stress relaxation increases gradually with temperature increasing. After the sample was incubated for 15 h at the temperatures of 400 °C and 500 °C, the residual stresses would release by 50% and 62% respectively. This fully illustrates that the residual stresses are not stable at high temperature. Moreover, compressive stresses are also not stable under the elevated temperature and plastic deformation conditions. Thermal exposure to service temperatures would reduce residual stresses by more than 50%, the underlying mechanism is very similar to the well-known stress relaxation observed for creep under constant strain, and this pattern is coherent with the results reported in the literature [19].

3.2. Fatigue cycle life

Fig. 4 shows the fatigue life of samples before and after laser-shocked, which clearly indicates that the fatigue life of ASTM: 410L $00C_r12$ is significantly enhanced by LSP in the temperature range 25–600 °C. The fatigue life is enhanced about 128% in the low cycle regime of 10^5 cycles at 25 °C. Already at 400 °C, the fatigue life have been enhanced by 102%. Moreover, at the highest temperature of 600 °C, the fatigue life have also been enhanced by 53.8%, although reduced as compared to that at 400 °C. These results may be come from the creation of near-surface compressive residual stresses, and a near-surface work hardened layer which is stable during thermal exposure or fatigue cycling at temperatures up to or exceeding 600 °C. The effect of this work hardened layer is to reduce the plastic strain amplitude, which acts to lessen the driving force for fatigue damage. In addition, the yield strength and ultimate tensile strength are also increased after LSP. Between 25 and 600 °C the laser-shocked state is always exhibiting a lower plastic strain amplitudes than the un-treated state.

3.3. Fracture surface

Fig. 5 shows SEM micrographs of un-treated ASTM: 410L $00C_r12$ at 400 °C. The un-treated state exhibits a fully austenitic microstructure and some dislocation tangles with low density. Fig. 6 represents the near-surface microstructures after LSP at 400 °C. A layer of deformation induced martensite and micro-twins are presented in near-surface regions. However, there were neither any