Effect of Laser Shock Processing Residual Stress on Pellet Traveling Grate Surface Crack

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Abstract
The effect of the laser shock processing on Pellet Traveling Grate surface fatigue crack growth performance were investigated from the theory of the fracture mechanics. A stress formula was set up to indicate the function of the residual stress on fatigue life. The effect of the compressive stresses was deemed responsible for increasing the resistance to fatigue crack growth of the Pellet Traveling Grate. It was observed that the dynamic stress intensity factor of the crack and the stress ratio were declined due to laser shock processing, which would make the spread doorsill of the fatigue crack increasing. The results indicate a significant reduction in fatigue crack growth rates using laser shock processning specimens. It is shown that the near-surface microstructures, which in Pellet Traveling Grate consist of a layer of work hardened nanoscale grains, play a critical role in the enhancement of fatigue life by mechanical surface treatment.
Keywords Laser shock, Residual stress, Pellet Traveling Grate, Crack expand

1 Introduction

In recent years, the pellet has obtained favor and been taken seriously as the high quality raw material, and has the tendency of replacing the agglomerate gradually. The chain fire grate machine is a core equipment in the production of pelletizing mineral aggregate, and as a non-sign design large-scale equipment, which core part movement chain system operates in an alternation temperature environment from normal temperature to 1050°C for a long time. The main bottleneck question is that the alternation high temperature environment forms the complex heat expansion and the alternation thermal load, which causes the heat-resisting service life to be shorter and the pelletizing chain fire grate machine requires extremely high performances of heat shock fatigue, strength at high temperatures and wear-resisting ability of spare part material[1]. Therefore, enhancing the fatigue resistance ability of the crucial element and guaranteeing the reliability of the movement are the difficult problems of the entire equipment technology.

Laser shock processing is to use the high power density (GW/cm^2 magnitude), short pulse (ns magnitude) to impact the energy conversion body in the metal surface. After laser energy absorption, the temperature is elevated rapidly, forming the shock-wave with a high peak-to-peak value, which means that the energy of light is transformed into the shock-wave mechanical energy. The shock-wave pressure which reaches as highly as counts GPa causes that the microscopic plastic deformation happens in the material surface layer, and forms the residual compressive stress layer, LSP improves the mechanical property of the metallic material effectively, which would enhance the fatigue life and the anti-stress corrosion performance of the material in a large scale specially. Compared with the conventional method, this kind of high rate of strain strengthening technology has a unique superiority [2-3].

Regarding to the stress destruction in the surface of essential spare part axis in chain fire grate machine, this article uses the technology of laser shock processing to enhance the fatigue life and the wear resistance of the axis, and the results indicate that using advanced surface treatment technology of the shock-wave mechanics effect induced by the strong laser can effectively improve the surface layer stress condition of the axis material, and specially can enhance the fatigue life performance of the material obviously.

2 Residual Stress Analysis

In the laser shock processing, the coating raises the laser energy coupling efficiency, and the coating is able to enhance the absorption of the laser energy, which causes the absorption coating gasification to form the plasma to explode, producing the high-pressured shock-wave separately disseminates to the metal target and the restraint level. The high-pressured shock-wave plays the strengthening and the distortion roles to the metal target, and the superficial residual compressive stress is enhanced greatly.

Researching the fatigue short fracture growth problem in laser shock processing residual compressive stress field has also solved the problems of the crack rate of expansion caused by residual stress and life prediction[4-6]. the model of metal surface's influence layer depth and superficial residual compressive stress after laser shock processing proposed by Ballard[7] is based on in this article, and the shock wave parameters of peak pressure is optimized in condition of ideal surface stress. A residual stress model which is used to calculate the longitudinal and plane shock-wave system's ideal elastic-plasticity response for metallic material is proposed, and some basic suppositions are made as fellow:

(1) Distortion induced by the laser shock processing is single axle and plane; (2) Distribution of pressure pulse induced by laser is even in space; (3) The material obeys Von the Mises yield criterion, and the elastic deformation and the strain strengthening effect of the material are neglected.

The residual stress's production has two stages, as shown in Fig.1. (a) During the time of laser pulse, a pure uniaxial stress is generated along the shock-wave propagation direction because of rapid spraying by plasma, while a tensile stress is generated in the plane parallel to the material surface ; (b) After laser pulse vanishing, the plastic strain happens to the laser impact zone's volume, and two axle compressive stress field is produced in the plane parallel to the impact surface due to that the plastic strain is limited by the metallic material around.

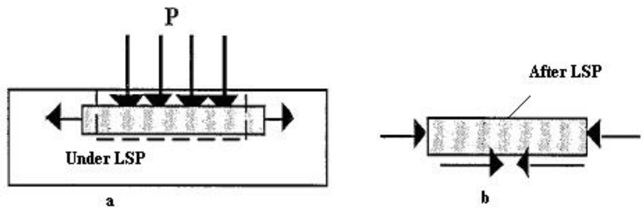

Fig.1 Schematic of the residual stress induced by the LSP

According to the hooke's law, the metal surface plasticity strain ε_p can be written as[8],

$$\varepsilon_p = \frac{-2HEL}{3\lambda + 2\mu}\left(\frac{P}{HEL} - 1\right) \tag{1}$$

Where HEL is the Hugoniot limit of elasticity, P is the laser shock-wave pressure, and λ and μ are the Lame's parameters. To determine the residual stress field in the materials impact area, regarding any impact condition assigned, the plastic influence depth was calculated as,

$$L_p = \frac{C_{el}C_{pl}\tau}{C_{el} - C_{pl}}\left(\frac{P - HEL}{2HEL}\right) \tag{2}$$

C_{el} and C_{pl} represent the elasticity speed and the plastic speed separately, and τ is the duration of laser pulse. And ρ represents the target material's density, while C_{el} and C_{pl} can be defined as,

$$C_{el} = \sqrt{\frac{\lambda + 2\mu}{\rho}}, C_{pl} = \sqrt{\frac{\lambda + 2\mu/3}{\rho}} \tag{3}$$

Therefore, according to the influence level depth, the compressive residual stress produced in the elastic-plasticity semi-infinite body can be shown as,

$$\sigma_{surf} = \sigma_0 - \left[\mu\varepsilon_p\frac{1+\nu}{1-\nu} + \sigma_0\right]\left[1 - \frac{4\sqrt{2}}{\pi}(1+\nu)\frac{L_p}{r_0\sqrt{2}}\right] \tag{4}$$

Where ρ_0 represents the laser facular's radius, and σ_0 represents the initial superficial residual stress which may be zero in the ordinary circumstances. The formula (4) indicates that the metal surface residual stress's peak-to-peak value increases with the laser peak pressure in the laser impact process, while the peak pressure is related to the incident laser power density.

3 Laser Shock Experiment

The laser treatment was carried out at the Jiangsu university strong laser laboratorys high power and Nd:Glass laser implement, with its laser pulse wave is 1.06μm,and syntory laser stick is made by $\phi 6mm \times 80mm$ yttrium aluminum garnet. One stair Nd:Glass laser magnify beforehand and four steps main amplifier by two ways, and big caliber quarter wave piece and high strength big caliber polarize film was adopt, Q switch, the output laser film wave at half maximum is about 20ns, the pulse repletion rate is 0.5Hz and the pulse energy was 28J to 36J corresponding to laser energy densities at the metals surface of 56J/cm^2 and 72 J/cm^2. The experiment material is 12CrMoV, whose thickness is 5mm. Before the experiment, the test sample surface was polished with the ethyl alcohol. The axis material was made into the standard test specimen.

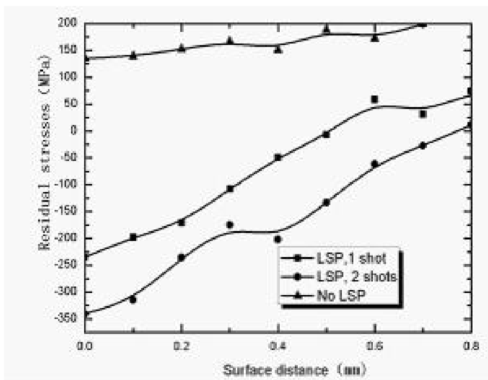

Fig.2 Residual stress of the staff in different conditions

The depths of the impact zone indicate that after laser shock processing, its superficial residual stress is transformed from tensile stress to compressive stress, as shown in Fig.2. The surface residual stress is qualitatively changed from the 135.7MPa tensile stress to - 230.6MPa compressive stresses, which scope is reached as highly as 3 times. And the hardness is obviously enhanced, which has an important value to enhance fatigue life of the work piece.

4 Results and Discussions

4.1 Material Performance Influence

After laser shock processing, the residual stress of the 12CrMoV is qualitatively changed from the 135.7MPa tensile stress to 230.6MPa compressive stress, correspondingly surface hardness is enhanced from HV252 to HV530. Fig.3 shows the result of metallography observed, and the big arrow shows the crack that the naked eye sees, which assumes the bending shape and branches out many small cracks; the small arrow shows the small crack which branches out from two sides of the big crack. By magnifying part of the crack that naked eye sees in Fig.3, it can be seen that the small cracks along with both sides of the crack are along crystal cracks.

Obviously these along crystal small cracks indicate that the crack that can be seen by naked eye is also to expand along the crystal. It is only because the latter is a little wider, and its characteristic of along crystal crack is not clearer than the small cracks.Fig.4 shows the microstructure of the axis test specimen by chemical reagent corrosion. It is the axis high-temperature steel normal tissue. And Fig.4 demonstrates that crack is to expand along the crystal.

Fig.3 Metallographic grinding in the surface morphology of the cracks

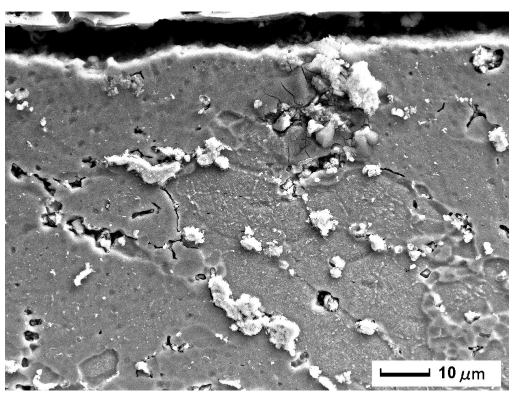

Fig.4 Microstructure of the small axis

4.2 Influence to Crack Growth

After laser shock processing, residual compressive stress remains in the surface, and the residual stress will weaken in the process of test specimen surface withstanding cyclic loading, and the residual stress on the test sample section is a distribution rather than a definite value. In order to analyze that simply, the effect of the residual stress was estimated with mean stress's viewpoint, and the influence of mean stress to fatigue limit is often described with the Goodman relations [9], which is shown in Fig.5.

In Fig.5, σ_m is the mean stress, and σ_b is the corresponding tensile strength, while σ_p^0 is fatigue limit when$\sigma_m = 0$. As average pressure exists, the fatigue limit may be represented as.

$$\sigma_p^m = \sigma_p^0 - (\sigma_p^0/\sigma_b)/\sigma_m = \sigma_p^0 - m\sigma_m \tag{5}$$

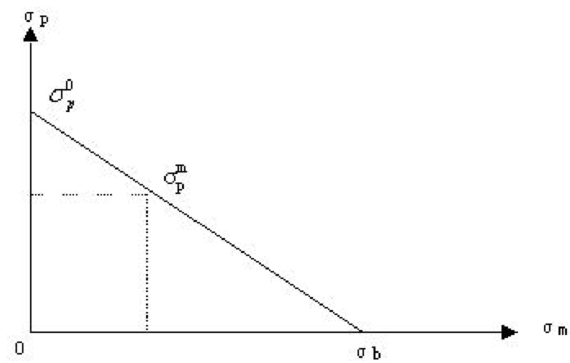

Fig.5 Goodman sketch map of the relationship between stress and metal fatigue limit

In the formula(4.1),$m = \sigma_p^0/\sigma_b$ denotes the slope of the line between σ_p^0 and σ_b in Fig.5, which is called the mean stress sensitive coefficient. When the residual stress σ_r exists and also it is thought to be equivalent with mean stress, the formula (5) can be rewritten as.

$$\sigma_p^{r+m} = \sigma_p^0 - m(\sigma_m + \sigma_r) \tag{6}$$

Compare formula (5) with formula (6), it is known that the change of materials fatigue limit induced by the residual stress is.

$$\Delta\sigma_p^r = \sigma_p^{r+m} - \sigma_p^m = -m\sigma_r \tag{7}$$

It could be seen that the materials fatigue limit would decrease if the residual tensile stress remains in test specimens surface, while the materials fatigue limit would increase when the residual compressive stress remains in test specimens surface, and m may also be called as the residual stress function coefficient. Therefore, the residual stresss influence may be estimated quantificationally if the materials residual stress function coefficien m and the test samples residual stress value are known.

The problem of crack growth in residual compressive stress field, besides the influence of residual stress to fatigue limit, and also influence of the residual stress to the crack growth threshold should be considered. According to the revision relations proposed by EI Haddad [10] and so on, the fatigue limit of the short crack in the metal surface can be calculate as

$$\Delta\sigma = \frac{\Delta K_{th}}{y[\pi(R + a_0)]^{0.5}} \tag{8}$$

Where $\Delta\sigma$ is the fatigue limited stress, and ΔK_{th} is the cracks threshold stress intensity factor, and y is the scoop channel's shape factor, and a_0 is the materials critical crack length.

$$\Delta K_{th} = \Delta\sigma y[\pi(R + a_0)]^{0.5} \tag{9}$$

After laser shock processing, the existence of the residual compressive stress in the metallic material surface greatly enhances the fatigue limit in the formula (9), and its result will cause the threshold value to obtain the enhancement, and in this condition the crack is not easily generated; the cracks that have extended will stop extending in the high residual compressive stress region and become the non-extension cracks, and a more universal influence is that the fatigue crack growth rate is reduced obviously in the residual compressive stress field. This is because that the residual compressive stress reduces the mean stress in alternating load, and reduces the alternating tensile stress that the test sample surface actual withstands. Meanwhile, laser shock processing enhances the plastic deformation resistance of the sample surface hardened layer, which enhances the fatigue strength of the material. When ratio of materials fatigue strength (σ_R) and value of test sample surface withstanding stress (σ_ω)$\sigma_R/\sigma_\omega > 1$, he probability of the formation of fatigue crack is greatly reduced [11]. The influence of the residual stress to the fatigue crack growth rate can be described with Forman formula,

$$\frac{da}{dN} = C(\Delta K)^m / [(1 - R)K - \Delta K)] \tag{10}$$

In the formula (10), ΔK is the cracks threshold stress intensity factor, and R is the stress ratio, while C and m are constants. When residual compressive stress exists after laser shock processing, it can be known that the stress ratio R is smaller than the stress ratio R_W when residual compressive stress doesnt exist. Obviously the residual compressive stress not only could reduce the expansion speed of the fatigue cracking, but also enhance the fatigue cracking expansion resisting force of the test sample.

5 Conclusions

The compressive residual stress is formed in the impact metal surface during laser shock processing,. The residual compressive stress is equivalent to negative average residual stress, and it can enhance the anti-fatigue strength of the workpiece.

The compressive residual stress increases the locking force of the crack and reduces the expansion speed of the fatigue cracking obviously, and also can close the metal plate crack effectively.After a large number of experiments, the empirical datum is summarized and theories are consummated unceasingly, and the high rate of strain strengthening theory and the laser shock processing database are established.

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