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Investigation of the fatigue life of pre- and post-drilling hole in dog-bone specimen subjected to laser shot peening

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ABSTRACT

The influence of processing sequence of laser shot peening (LSP) on the fatigue properties of fastener hole was investigated with finite element method and experiments. The results show that different processing sequences lead to different residual stress distributions and different fatigue lives. The compressive residual stresses (CRS) are squeezed into two-sided surface layers of fastener hole by two sided laser shot peening, and the ellipse CRS fields are found on both sided surfaces of sample. However, when the pre-drilling hole in dog-bone specimen is subjected to LSP, the tensile stresses appear at its mid-thickness region, while the CRS distribute in the entire thickness region of the post-drilling hole after LSP. The fatigue crack initiation of specimens treated by LSP stems from the subsurface layer of hole edge. The fatigue striation spacing of specimen with post-drilling hole after LSP is narrower in comparison with that of case with pre-drilling hole before LSP. The fatigue life of post-drilling hole is longer than that of the pre-drilling hole.

1. Introduction

Laser shot peening (LSP) is a viable surface modification technology to increase metallic mechanical property, especially to improve its fatigue performance [1]. When the specimens are subjected to high pressure shock wave induced by laser, the beneficial compressive residual stresses (CRS) are inserted into the superficial layer [2,3]. Some previous research results show that the CRS play an important role in fatigue failure behaviors, which not only shift the fatigue crack initiation from the surface into the sub-surface layer, but also slow down the crack propagation [4,5]. Compared with the traditional strengthening technologies, such as shot peening, LSP has some advantages resulted from its accurate processing position and precise control intensity of shock wave. It is a flexible and powerful tool to treat any surface where the strengthening is required, especially for fatigue critical regions in structural components, such as small holes, narrow grooves, fillets and welds, where the geometric stress concentration always occurs. Moreover, it can squeeze the CRS into material to a depth of 1–2 mm, which is about four to eight times deeper than that achieved by conventional shot peening. The deeper residual stresses are beneficial to extend the fatigue life. Now, LSP has been applied successfully to strengthen aircraft gas turbine engine blades to improve its resistance to foreign object damage [6].

Mechanical fastening has been a common structural assembly in the construction of aerospace structures. For example, metal sheets are fastened by a number of rivets to construct the aircraft skin. The extremely high stress concentration factors are always generated at the edge of fastener holes. Experienced the fatigue loadings during aircraft service, the fastener hole easily cracks, which may lead to a catastrophic failure of the component in joint areas. In order to improve fatigue performance of fastener hole in critical structural components, such as outer wing panels, cold extruding method is used to induce the compressive residual stress into the wall of pre-existing fastener hole [7]. Recently, there have lots of attempts to implement the LSP treatment on the fastener hole. For instance, Yang et al. [8] have investigated the single LSP on fatigue behavior of Al 2024-T3 plate with fastener holes. Ren et al. [9] have researched the effect of single LSP on the fatigue behavior and residual stresses of 7050 specimens hole. Zhang Y.K. et al. [10] have investigated that the hole treated by single LSP has an obvious endurance to fatigue crack initiation and growth. Zhang H. et al. [11] have studied a method for optimizing laser parameters in LSP to gain better side surface quality of the hole. These works are very useful for gaining insight into the fatigue behaviors of the laser-treated components with hole, but they didn't refer to the influence of processing sequence on its fatigue life. Only G. Ivetic et al. [12] have taken into account the effect of the sequence of operation on the hole fatigue life. However, his conclusions have been drawn from the LSP treatment without protective coating. Influences of processing sequence of LSP on the hole of sample with protective layer are still not fully understood. More importantly, the protective covering is widely used in confined LSP treatment to shield from heat damage induced by laser. Therefore, the component with hole treated by LSP is a topic that can be researched to get more insights into LSP to improve eventually this technique.

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The objective of present work was to investigate the fatigue behaviors of the pre- and post-drilling hole in dog-bone specimen subjected to two-sided LSP. The software ABAQUS was used to simulate the CRS field, and further to predict the crack initiation location in specimens experienced different approaches. In order to exam the simulated results, the contrast fatigue tests were carried out respectively with specimens processed by different approaches, and the fracture surfaces were all observed by scanning electron microscopy (SEM) to display the differences in fatigue crack initiation and fatigue striation spacing.

2. Simulation of residual stress

When a short-duration laser pulse with high energy passes through a transparent confining overlay and irradiates on the surface of the absorbing layer, which is deposited on the target surface. The absorbing layer is instantaneously vaporized, ionized and transformed further into plasma with high pressure in a very short time, so a sudden shock load acts on the material surface, and induces stress wave propagating into material. When the peak pressure of stress wave goes beyond the dynamic yield strength of material, the CRS are introduced at the surface layer. Combined with other machined methods, LSP can be applied potentially to the thin-wall aerospace components with fastener hole.

There exist two approaches to accomplish hole processing. One is to drill hole first, and then to implement LSP treatment on the region around the pre-drilling hole, which is called pre-drilling before LSP (PDBL). For example, the open hole in aircraft skin must be first drilled before its assembly, and then LSP is applied to the pre-existing hole in critical aerospace structures. The other is to carry out first the LSP treatment in the desired area, and then to drill hole in the treated region, which is called post-drilling after LSP (PDAL). Due to the complexity of interaction between the material and stress wave induced by laser, the finite element method (FEM) is validated to be a useful approach to simulate the CRS field [13,14]. In current study, the software ABAQUS, a combination of explicit and implicit analysis algorithms package, is employed to simulate the CRS distribution in the samples experienced the PDBL and the PDAL, respectively. The simulation process usually includes two steps, dynamic analysis step and static analysis step. The ABAQUS/Explicit is employed in dynamic analysis step to analyze the interaction between the stress wave and material. When the kinetic energy tends to zero and the internal energy tends to constant simultaneously, it indicates that the interaction of the stress waves in the material is quite weak and the plastic deformation is driven to be stable. When the dynamic stress state of the target material becomes approximately stable [15], the ABAQUS/Implicit is applied to the static analysis step to release the elastic energy stored in dynamic calculated results. After the implicit analysis is performed, a stable residual stress field is obtained. The processes of the simulations with different processing sequence are illustrated in Fig. 1.

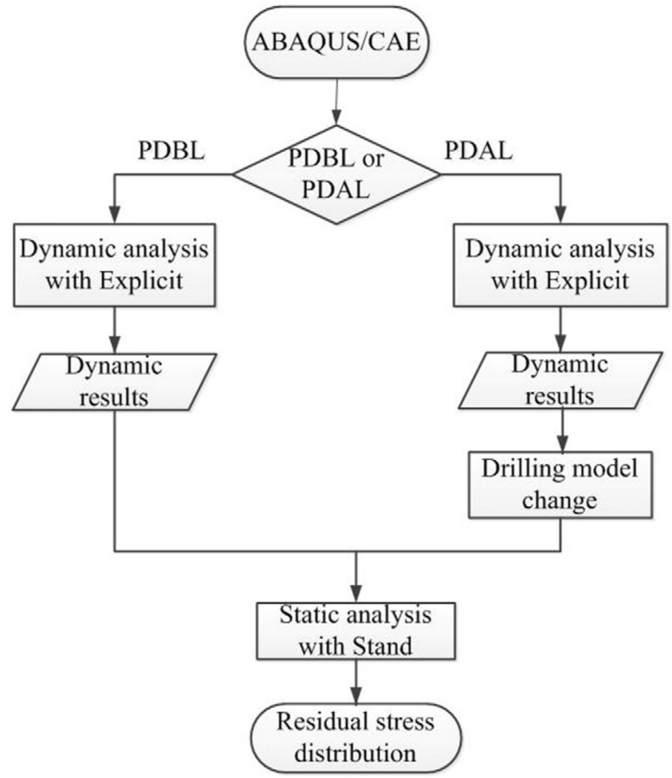

Fig. 1. The processes to simulate the CRS field.

2.1. Finite element model

In simulation, laser parameters are selected as following: the output of laser energy is 3 J. The local spot is 2 mm in diameter, and the pulse duration of full width at half maximum (FWHM) is 8 ns. A laser pulse with about 3.85 $GW\cdot cm^{-2}$ is used to induce the shock wave to impact target surface. Owing to the complexity of the generation of high pressure plasma and shock wave, its physical process needs to be simplified. According to the confined mode theory established by Fabbro to describe the shock wave evolution [16], the peak pressure P loaded on material surface can be calculated as follow

$$P(GPa) = 0.01\sqrt{\frac{\alpha}{2\alpha+3}} \times \sqrt{Z(g\cdot cm^{-2}\cdot s^{-1})} \times \sqrt{I_0(GW\cdot cm^{-2})} \qquad (1)$$

where Z is the reduced acoustic impedance $[2/Z = 1/Z_1 + 1/Z_2]$ of the confining Z_1 and target Z_2 materials, and α is the efficiency of the plasma-material interaction (typically $\alpha \approx 0.25$) [17]. In the case, water is used as the confining layer, and its acoustic impedance Z_1 is $1.65\times10^5\ g\cdot cm^{-2}\cdot s^{-1}$. The acoustic impedance of the specimen is $Z_2 = \rho D = \sqrt{\rho E} = \sqrt{2780\times68.9\times10^8} = 13.86\times10^5 g\cdot cm^{-2}\cdot s^{-1}$. The laser power density is about 3.85 $GW\cdot cm^2$.

According to the above mentioned model, the persisting time of laser shock wave is 2–3 times as long as the duration of the laser pulse [18]. Here, the loading time of the shock wave is assumed to 3 times, and the loading history is depicted in Fig. 2.

In order to gain a uniform and higher magnitude CRS field, the overlapping LSP is applied [19] to the target surface, which can overcome the shortcomings induced by a single LSP, for instance, the average amplitude of the CRS is relative small after one laser peening and its value of CRS at the center of laser spot is lower than that at the location far away from the center [20,21]. A desire treated area is depicted in Fig. 3, which lies in the central zone in specimen surface. It is orderly

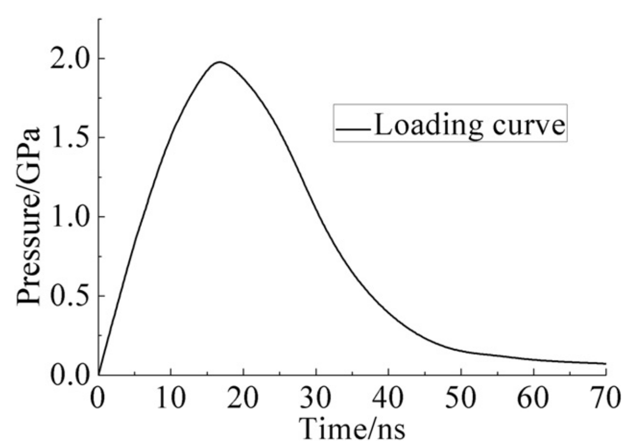

Fig. 2. The laser shock loading history.