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Research paper

Geometry distortion and residual stress of alternate double-sided laser peening of thin section component

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ABSTRACT

Laser peening of components with thin section is of great concern in industry to improve anti-fatigue properties. This study proposes alternate double-sided laser peening (ADLP) as an optional way for the surface treatment of thin section component to overcome the risk of internal spallation and facility cost in simultaneous double-sided laser peening (SDLP). Experiments are conducted on the special-designed samples with thin section to investigate the distortion behavior and residual stress under laser peening of both sides sequentially. Numerical model are developed to analyze the generation and recover of geometry distortion for ADLP process. The results shows that the geometry distortion after single-sided laser peening is observed to be sensitive to laser pulse energy to generate different profile directions. The feasibility of ADSP is proved for the treatment of thin section with distortion control because the second laser peening on the other side of thin section can eliminate the distortion. The generation of different distortion behaviors is found to be closely related to the plastic strain field generated by the transmission of shock-induced stress wave across the thickness section. The numerical simulation shows that a symmetric tensile plastic strain field in plane section is generated across the thickness section for each laser pulse energy after completing laser peening on both sides. Furthermore, both experiments and model prediction propose that compressive residual stress is induced on both sides of thin section by ADLP process, which ensures the ADLP process effective for the treatment of thin section.

1. Introduction

Laser peening (LP) irradiates metal surface by utilizing a short-pulsed laser with high power density to induce plasma pressure to generate compressive residual stresses through cold working. In the past several years, laser peening has been proposed as an effective way for several metals to improve the service life of fatigue, corrosion and wearing, especially suited for some locally critical regions with the precisely controlled laser beam (Pant et al., 2013).

Much work has been carried out on laser peening of bulk metal material previously to investigate residual stress field, microstructure evolution and property improvement (Bhamare et al., 2013; Huang et al., 2013). Components with thin section is also of great concern to utilize laser peening as an effective way to improve their service life. For example, laser peening of leading and trailing edges of blade airfoils has been used in industry to extend service life of engine compressor blade to avoid increasing thicknesses along the airfoil leading edge, which would add extra weight to compressor. Rankin and Hill presents the experimental determined compressive residual stresses across the section imposed by laser peening near the edge of a thin sheet of titanium alloy (Rankin and Hill, 2003). Laser peening can impart blade edge with a state of compressive residual stresses throughout the entire thickness section, which is greatly desirable to resist low and high cycle fatigue under foreign object damage (Shepard et al., 2001). Laser peening of thin components only from single side is difficult to ensure compressive residual stresses on both sides. Meanwhile, single-sided shock loading would produce much undesirable distortion, which affects aerodynamic performance of blades (Mannava et al., 1996). Therefore, simultaneous double-sided laser peening (SDLP) is commonly utilized previously for the treatment of components with thin cross-section like blade leading edge to prevent undesirable distortion. However, the process cost of SDLP would be greatly increased because it is necessary to generate twice the power as for only doing one side. Moreover, the split two opposite beams for SDLP is difficult to develop because it requires a precisely calibrated and positioned beam setup. And it is also difficult to ensure the simultaneous laser shocks from both sides due to the accessibility of laser beam for parts with a complex geometry. Furthermore, the critical problem of SDLP is the potential risk of internal spallation damage due to the reflected tensile waves from both sides arriving at the middle of cross section simultaneously to

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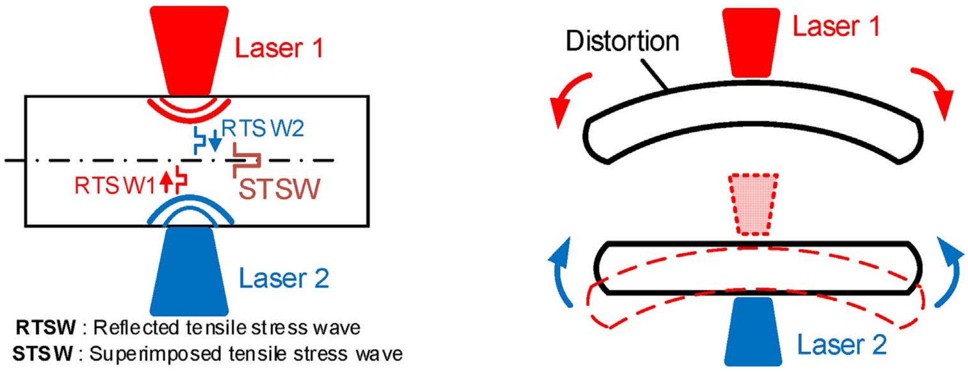

Fig. 1. Schematic of laser peening for thin section treatment: (a) simultaneous double-sided laser peening (SDLP); (b) alternate double-sided laser peening (ADLP).

double the amplitude of tensile stresses intensity (Ding and Ye, 2003; Ivetic, 2011). Therefore, it is still necessary to explore an effective way to avoid the spallation risk of SDLP and decrease the process cost of thin component treatment in spite of SDLP is an optional way for distortion control.

Different from laser peening of thin components with the requirement of distortion control, several studies have been conducted previously on the distortion of thin metal sheet after laser peening only from single side, which is mainly proposed as a forming process. Shen et al. and Zhen et al. adopted laser dynamic forming as a deep draw process with a semi-mold for thin foils forming (Shen et al., 2016b; Zheng et al., 2013). More similar to distortion of thin section components induced by single-side laser peening, Hackel et al. proposed this phenomenon to generate a complex three-dimensional shape with small curvatures (Hackel and Harris, 2002). Chen et al. investigated the shape of extremely thin metal foils under laser shock loading (Chen et al., 2004). Edwards et al. also observed a large distortion of thin sheet metal under the scanned laser shocks (Edward et al., 2007). Ocaña et al. (2007) investigated the bending of thin stainless steel strips with different shock positions and pulse energies. Hu et al. experimentally observed the conversion of bending direction of sheet metal by varying sheet thickness and laser power densities (Hu et al., 2010b). Shen et al. investigated bending deformation and modifications of surface properties after laser peen forming for copper, titanium strips (Shen et al., 2016a). Similar to laser peen forming, laser peening only from one side of thin components is beneficial to avoid the risk of internal spallation due to double tensile stress intensity. But contrary to laser peen forming, distortion generated by single-sided laser peening is unexpected and must be eliminated besides ensuring compressive residual stresses on both sides. Toparli et al. investigated the residual stresses of aluminum alloy plates with the thickness of 2 mm after single-sided laser peening and geometry distortion was observed (Toparli and Fitzpatrick, 2016). The possible solution for this problem, which has been ignored in the previous investigations is to apply the second laser peening on the other side to counteract the distortion and also generate the anticipated residual stress field on both sides. Although Correa et al. investigated the effect of scanning strategy on the residual stress and fatigue properties of 316L stainless steel by performing experiments of double-sided LP in an alternate way, the distortion is not existed due to its thick cross section of 6 mm (Correa et al., 2015). Therefore, the feasibility of ADLP for thin section requires further study concerning the formation of geometry distortion and residual stress in detail. Moreover, it is still unknown about the dynamic deforming behavior during alternate laser peening from both sides. This is very important to understand the response of thin components under laser peening.

In this study, ADLP irradiating only one side of thin components at a time, is proposed as an effective way to overcome the risk of internal spallation in SDLP. The development and elimination of distortion after alternate double-sided laser irradiations is analyzed both from experiments and numerical simulation. The deforming behavior is analyzed together with the plastic strain field and dynamic stress wave transmission. The possibility to induce compressive residual stress on both sides is also characterized to verify its possibility for the treatment of thin components.

2. Alternate-side laser peening of thin section

Laser peening is a process to drive high amplitude stress waves with several GPa into a metal surface through a short-pulsed laser irradiation, where the power density must be greater than 1 GW/cm^2 (Montross et al., 2002). It is usually carried out with an absorbent layer of tape and a confinement layer of water. The absorbent layer is used to isolate the specimen from pulsed laser ablation. Meanwhile, a thin part of it would be vaporized to induce plasma under laser irradiations through the transparent confinement layer. The confinement layer can restrict the plasma expanding to increase the pressure loading to ensure exceeding material yielding strength. SDLP as shown in Fig. 1(a) is commonly performed by irradiating both sides of a thin section with the split two opposite beams. During laser shock loading, each driven stress wave initiating from front surface would be reflected from the back surface to become tensile. When arriving at the middle of section simultaneously, two reflected tensile stress waves (denoted by RTSW 1 & 2 as shown in Fig. 1(a)) are superimposed to become a double-enhanced tensile stress wave (denoted by STSW as shown in Fig. 1(a)), which becomes the main reason to cause internal spallation damage. Different from SDLP process, ADLP proposed in this study, is performed as shown in Fig. 1(b) by irradiating both sides of thin section sequentially. At first, the thin component is treated by the scanned laser shocks only from one side, which may generate some geometry distortion due to weak resistance to bending driven by the shock loading. Then, the other side of thin section is operated to face the laser beam to apply the second scanning of laser shocks. After laser peening of both sides alternately, the distortion is expected to recover with compressive residual stresses on both sides.

3. Experimental methods

A Q-switched Nd:YAG pulse laser was operated with the pulse duration of 10 ns in FWHM (Full Width at Half Maximum) and wavelength of 532 nm for laser peening experiments. The laser pulse energy was adjustable by inserting a beam splitter with a specified transmittance. The split laser beam for laser peening transmitted through a beam expander firstly for divergence improvement and then a positive long-focus lens with the focal length of 750 mm to the target surface with the spot diameter of 2.0 mm. In experiments, five pulse energies of the split beam for experiments were measured to be 0.20 J, 0.31 J, 0.39 J, 0.60 J and 0.815 J. The flow water and black tape were used as the confinement and absorbent layers, respectively. Samples were clamped by the fixture and operated by an industrial robot to move relative to the fixed laser beam.

Fig. 2 provides the sample geometry with thin section for experiments. It is designed with a semi-constrained configuration, where two