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Effects of curved geometry on residual stress in laser peening

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ABSTRACT

Prevention of failure in materials has been extensively researched for centuries by people all over the world. Sustained or cyclic loading is a major cause of failure in many situations. There can be other contributing factors, such as manufacturing defects and the presence of unfavorable residual stresses. But residual stresses can also play a positive role and can enhance the life of the component, if applied properly. Laser peening (LP) is a surface enhancement technique that can impede crack initiation and propagation by inducing favorable compressive residual stresses in the peened components. Laser peening can generate deeper compressive stresses compared with other surface enhancement techniques, such as shot peening, and it has been used to improve the fatigue life of components in aerospace, automotive and medical applications. In this work, the effects of laser peening are studied by using two dimensional finite element simulation models created with ABAQUS©. Crack initiation often occurs along the curved regions or fillets of structural components because of the presence of high stress concentrations. These critical regions are modeled as a curved geometry to capture the curvature effects using simulation models. Concave and convex simulation models are created and compared with flat geometry to investigate the effects of curvature in a laser peening problem. A mechanism of residual stress generation in curved models is used to explain the residual stress results obtained from finite element models. The results predict that increasing the radius of curvature in a concave model decreases the compressive residual stress generated in the component while increasing the radius of curvature of a convex model increases the compressive residual stress induced in the material when compared with a flat component.

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1. Introduction

Many structural failures happen because of fatigue cracks in the surface regions. There exist methods named surface enhancement techniques, which induce favorable residual stresses on surface regions of peened components, thereby improving the fatigue life of the component. These methods are effective to relieve problems such as tensile stress buildup, which is the main reason of failure in many components. Surface enhancement techniques play an important role in improving the life of the peened components by creating compressive stress field on the surface, and thus, delay or eliminate the crack initiation and propagation inside the material [1]. In some cases, the growth of the initiated cracks can be completely arrested [2]. Shot peening is the most commonly used surface enhancement techniques. Other widely applied methods in the industry are low plasticity burnishing, water jet peening, laser peening, roller burnishing, ultrasonic peening, peen forming, cavity peening, etc. Laser peening generates deeper compressive stresses compared with other surface enhancement techniques like shot peening, making it appealing to the industry. Fig. 1 shows the mechanics behind residual stress generation in laser peening. When the material is peened under loading, the surface region in contact is plastically deformed. The surrounding bulk material, which is elastically deformed, tries to get back to its initial state generating compressive stresses in the surface region while tensile stresses are created in the subsurface to attain static equilibrium in the material.

Many experiments were performed to understand the mechanisms of the laser peening phenomenon [3–5]. Researchers in France did the ground work to come up with the laser beam profile and the eventual pressure profile [6,7]. The results compared Gaussian and sharp rise time pulse and found that sharp rise time pulses can generate higher pressures when compared with the Gaussian pulse shape. Ballard created an analytical model which can determine the surface residual stresses and plastically affected depth [8]. This model assumed uniaxial strain and was based on elastic-perfectly plastic solution. The shock wave propagation is a complex phenomenon and three dimensional in nature. Because of the limitations in prediction using analytical models, several researchers created simulation models based on finite element analysis to predict the residual stress behavior. Braisted and Brockman created a two dimensional axisymmetric finite element model to predict the effects of laser peening [9]. They considered a triangular ramp to model the pressure time history and adopted a two-step simulation procedure (explicit–implicit

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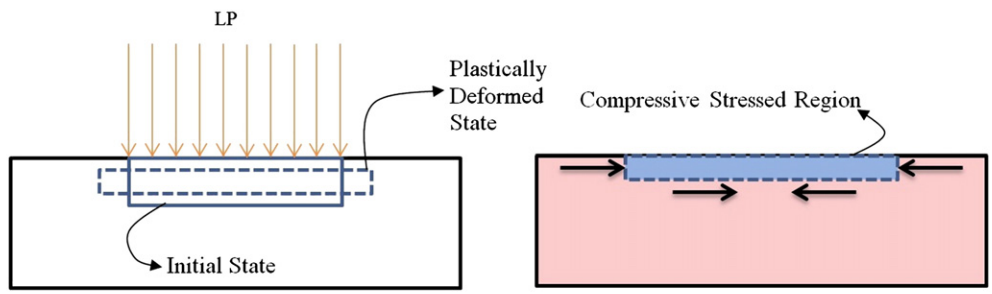

Fig. 1. Mechanics of residual stress generation in laser peening.

algorithm) to obtain results for the dynamic analysis. Peyre et al. followed this approach and used experimentally determined parameters such as pressure loading, dynamic yield strength and residual stress (from XRD method) to validate the model [10]. Ding and Ye extended the 2D model to 3D modeling techniques and used quarter symmetric models to simulate a single shot laser peening problem [11]. They also conducted two sided laser peening for thin specimens and observed the formation of tensile stresses in the mid-regions [12]. Hu et al. conducted 3D laser peening simulations and considered the effect of multiple shots [13]. They also constructed a symmetric cell using overlapped laser shots, which can be used for simulating large scale laser peening problems efficiently by duplicating the residual stresses predicted in a single cell to others [14,15]. Singh et al. also built 3D models and devised parametric optimization strategies to maximize the residual stress induced in the component [16,17]. Spradlin et al. created simulation models to predict the fatigue life in a laser peened component and validated with experiments [18].

But very few researchers have investigated the effects of laser peening on curved geometry. Predicting the residual stress induced in a curved geometry cannot be based on the trends obtained from a flat model since neglecting the curvature effect can lead to an incorrect assumption of residual stress profiles. Ding et al. conducted preliminary investigations on the effect of two-sided laser peening on a cylindrical model in aluminum alloy using simulation models [19]. They found out that tensile stresses are generated at the center of the cylinder and increasing the diameter of the specimen can reduce the magnitude of tensile stresses. DeWald and Hill made residual stress prediction of complex three dimensional geometries by applying eigenstrain theory for reducing the computational costs [20].

This research aims to investigate whether curvature plays a critical role in resulting residual stresses by creating finite element models representing curved geometry. Two dimensional axisymmetric models are created to represent flat, convex and concave geometries. Each simulation is equivalent to a single laser shot with a circular profile striking the center of the specimen in every case. Observing from the finite element results, a mechanism involving residual stress generation for convex and concave geometries is explained based on plastic strain theory. Understanding the effect of component curvature can be useful in predicting the residual stress on any curved geometry. A mathematical relationship connecting the residual stress and radius of curvature is developed based on the results. The difference in residual stress fields for different geometries can be attributed to the difference in deformation compatibility of the curved geometry in comparison with a flat geometry. It was found that increasing the radius of curvature for a concave geometry decreases the compressive residual stress whereas increasing the radius of curvature of a convex geometry increases the compressive residual stress in the material. A monotonically increasing linear relationship between compressive residual stress and degree of curvature was observed for a concave geometry while decreasing linear relationship was observed for convex geometry.

2. Laser peening mechanism

A pictorial representation of a typical laser peening method is shown in Fig. 2. The target material is typically coated with an ablative overlay and confined by a transparent overlay. When the laser pulse impacts the material, the absorbent material vaporizes and creates plasma. This plasma which is confined by the transparent overlay creates a pressure pulse which is propagated into the material as a shock wave. When the stress created by shock wave exceeds dynamic yield strength of the material, this results in plastic deformation of the surface microstructure, generating compressive stresses inside the material, significantly more near the surface.

The ablative overlay protects the material surface from temperature effects and makes laser peening a purely mechanical process. The transparent overlay confines the plasma from rapid expansion away from the material surface which helps to obtain a high intensity pressure pulse into the material. Black paint or tape is considered most of the time as the opaque overlay while flowing water along the peening surface is usually taken as the transparent overlay. Laser peening has important applications in aerospace industry such as aircraft wings, turbine blades, engine components, valves and transmission components. Apart from aerospace applications, specialized applications in auto (e.g. crankshafts, gears, and frames), medical (e.g. orthopedic implants, surgical tools), nuclear (e.g. waste storage canisters) and manufacturing industries make the science of laser peening to be an excellent area for researchers.

3. Motivation for considering curved geometry

The practical problem of the F-22 fighter aircraft wing attachment prone to fatigue failure is shown in Fig. 3 [21]. The red circles indicate

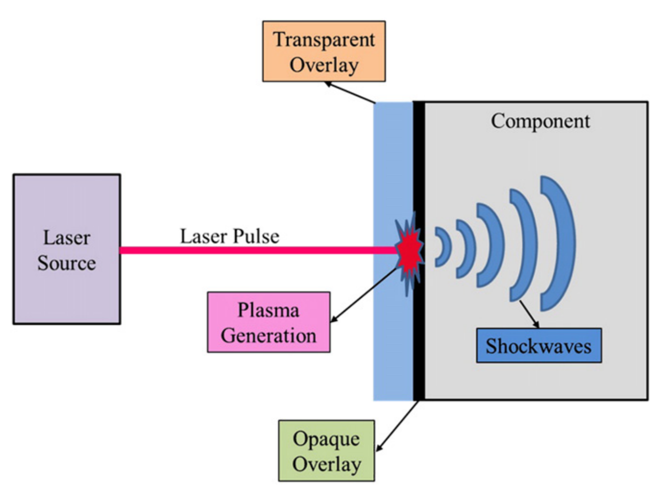

Fig. 2. Schematic of laser peening.

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