Efficient Prediction of Bending Deformation with Eigenstrain for

Laser Peen Forming

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Abstract

Laser peen forming, is a purely mechanical forming method achieved through the use of laser energy to form large-scale metal plate with small curvatures. The eigenstrain modeling method is used to cut the computational cost to obtain predictions in an efficiently way. The eigenstrain in one representative cell of overlapping laser shocks is obtained by an explicit model to simulate short shock induced plastic deformation. Then, the bending deformation of metal plate is analyzed with an elastic model using the simulated eigenstrain as initial strain. The eigenstrain is incorporated into the elastic model by thermal expansion with a predefined unit temperature field and different anisotropic thermal expansion coefficients. The model can give a consistent prediction for the deformed shape on aluminum alloy 2024-T351.

Keywords: Laser Peen Forming, Eigenstrain, Bending, Aluminum alloy, Finite Element Analysis

Introduction

Laser peen forming (LPF), a derivative of laser shock processing technology, is a locally effective forming process to form complex curvatures without dies. It is now emerging as a viable means for the shaping of metallic components. As a purely mechanical forming method, LPF has advantages of non-contact, tool-free and high efficiency and precision. Its non-thermal process also makes it possible to form without material degradation or even improve them by inducing compressive stress over the target surface, which is desirable because it is important in industry for shaped metal parts to resist cracks from corrosion and fatigue [Ocaña et al., (2007)].

The forming process of LPF has attracted many concerns of researchers. Hackle and Harris demonstrated that it could contour the thick part over its large area and showed that an enhanced convex curvature was achieved [Hackel and Harris, (2002)]. Hu et al investigated the mechanism of laser peen forming that can induce two bending directions under different plate thickness and laser conditions [Hu et al., (2010)]. However, a large number of trial-and-error experiments are typically required on components such as integral wing panel forming before practical applications can be achieved. Beyond direct explicit modeling of material dynamic response, the eigenstrain-based modeling method, which has been intensively investigated in the prediction of welding induced residual stress and distortion, has recently received attention for use in predicting residual stress for LP processes. Korsunsky adopted this method first to predict residual elastic strain with a simplified analytical model, where the eigenstrain distribution is determined by solving an inverse problem with the residual elastic strain using X-ray diffraction [Korsunsky, (2006)]. Achintha & Nowell have just adopted this method to predict laser-peening-induced residual stress to demonstrate feasibility [Achintha and Nowell, (2011)]. Further attention must be paid on the eigenstrain modeling of LPF with overlapping patterns to predict the deformed shape efficiently for a largescale component.

The aim of this work is to propose a model approach using eigenstrain methodology to predict the deformed shape of a square aluminum plate by LPF. The repeating pattern of plastic strain field is identified and averaged in two axis directions. Then the approximate uniform eigenstrain field is applied to a thermo-elastic model to predict the deformed shape to compare with experiments.

LPF Experiments

The typical application of LPF is carried out under a confined regime configuration. The specimen is undergo a high strain rate deformation and be dynamically yielded due to the rapid laser induced shock pressure. A large number of laser shocks are applied successively to the specimen surface according to the specified path. It will generate incremental deformations in the specimen, which can be accumulated to obtain bending with convex or concave shape depending on process parameters.

Experiments were conducted with a Q-switched Nd:YAG pulsed laser source in the fundamental transverse electro-magnetic mode. The laser was operated at the repetition frequency of 10 Hz and the pulse duration of about 10 ns in FWHM (Full Width at Half Maximum). A wavelength of 532 nm was selected for experiments. The laser output pulse energy measured by a power meter was about 0.93J/pulse. The expanded laser beam passed through a positive long-focus lens to the target surface with the desired beam diameter of 2.0 mm. One kind of black tape, thick enough to maintain its integrity after irradiation of laser pulses, was used as the sacrificial overlay. Water was used as the transparent overlay to confine the generated plasma.

4 mm thick plate sample of aluminum alloy 2024-T351 is prepared with the size of 67 mm ×67 mm. The sample was clamped by the fixture as shown in Fig. 1a. They were manipulated by an industrial robot to move with the predefined scanning path of the fixed laser beam. The overlap of laser spots was set to be 50%, and the shocked-covered region was 40×40 mm in the center area. Fig. 1b shows top view of the sample with scanning laser shocks on the surface. It can be found that the shocked region has some shallow indentations. And the contour surface of sample was quantified by surface profile measurements with a Keyence KS-1100 optical surface profilometer as shown in Fig.1c. It can be found that the pate is deformed with convex curvatures in two directions after square distributed laser shocks.



Fig.1 The plate sample formed by laser peen forming with fixture: (a) the device to clamp sample ; (b) top view of the shocked surface; (c) measured surface contour

Eigenstrain-based Modeling Approach

The term eigenstrain, noted by ε^* , was introduced by Toshio Mura (1987) to indicate any strain arising in material due to inelastic processes such as plastic deformation, crystallographic transformation, or thermal expansion mismatch between components of an assembly [Mura, (1987)]. Eigenstrain accounts for all permanent strains that arise in material exhibiting inelastic behavior. The process-induced residual stress and deflections can be predicted through including the eigenstrain as the initial elastic strain distribution [Hu and Grandhi, (2012)].

The generation of deflections due to laser shocks can be regarded as a pure mechanical process. The eigenstrain in laser peen forming is only represented by the plastic strain. Once the representative eigenstrain distribution has been determined under process conditions, the bending deflection and residual stress can be solved with a finite element (FE) model with full scale of component. The corresponding bending moments M_x^* and M_y^* mainly depend on the in-plane eigenstrain components of ε_x^* in the longitude direction and ε_y^* in the transverse direction, respectively [Murakawa et al., (2009)]:

$$M_x^* = E \int \varepsilon_x^* (z - h/2) dx dz \tag{1}$$

$$M_{y}^{*} = E \int \varepsilon_{y}^{*} (z - h/2) dy dz$$
⁽²⁾

where h is the plate thickness.

The eigenstrain value is mainly related to the process parameters, material properties, and the specimen thickness in the LPF process, but it is geometry insensitive. Moreover, the eigenstrain generated by each shock is confined to a local region. It allows us to adopt a very small representative cell model to obtain the eigenstrain field, and then apply them to a large-scale model for efficient predictions under the same process conditions and material. For the prediction of deformed shape induced by large-scale array of overlapping shocks, the plastic strains in one repeating pattern of overlapped laser shocks as shown in Fig.2 is very useful to significantly reduce the computation cost. Considering an example of 50% overlap with each laser shock separated with 0.5R in Fig.2a, the representative cell size can be selected to be square with the dimension of 2Raccording to the distribution of laser shocks. The dimension with spot size 2R is proposed as the simplest repeating pattern for most conditions because it is consistent with the covered area of each shock. The plastic strain field in one representative cell can be reproduced and applied to the practical part model as eigenstrain, one after another, to predict the residual stress and deformation fields based on the characteristic of the repeating pattern. The eigenstrain in one representative cell can be determined efficiently through an explicit infinite-square plate model by simulating multiple sequential laser shocks as shown in Fig.2b. Then the determined eigenstrain field can be applied to the elastic model one by one as shown in Fig.2c for the prediction of deformation fields.



Fig.2 The repeating pattern of a large scale overlapping laser shocks with the percentage overlap of 50%: (a) full-size plate with arrays of overlapping laser shocks; (b) infinite-square pate model to determine the eigenstrain in one representative model; (c) full-size plate model to predict the deformed shape and residual stresses.

Therefore, the eigenstrain-based modeling of LPF process includes two FE models. One is the explicit FE model of a infinite-square plate to determine the eigenstrain in one representative cell. As shown in Fig. 3, this dynamic model is composed of finite part and infinite part. The size of

finite part is determined by the critical distance analysis to be $14R \times 14R$, and shock-covered region is $10R \times 10R$ on the top surface.



Fig.3 Infinite-square plate model to determine eigenstrain in one representative cell

The time history of shock pressure loading p(t) is calculated by one-dimensional analytical model, proposed by Berthe et al [Berthe et al., (1997)], and the spatial distribution of the pressure considers the difference on the transverse and longitudinal direction with the Eq. 3

$$p(r,t) = p(t)e^{-\frac{(x^2/\beta_1 + y^2/\beta_2)}{R^2}}$$
(3)

Some uncertain parameters existing in the Berthe's model and spatial equation were calibrated first to give a consistent prediction of indentation profiles of single shock. In the infinite-square plate model, the target material is subjected to a shock pressure of few GPa with a short interaction time. The material model for simulation must consider the material behavior dependence of high strain rate to simulate the high-velocity process. The simplified Johnson-Cook model without thermal effect is adopted as the constitutive equation in the explicit model to consider the high-strain-rate effect on the flow behavior of metals:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*) \tag{4}$$

where $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless strain rate, and A, B, C and n are considered to be material constants [Johnson, (1985)]. Table 1 provides the material properties of aluminum alloy 2024-T351 required for dynamic simulation.

Table 1 Material properties of aluminum alloy 2024-T351			
Properties		2024-T351	Units
Density, ρ		2770	kg m ⁻³
Poisson's ratio, v		0.33	
Elastic modulus, E		73.1	GPa
JC model	A	265	MPa
	В	426	MPa
	n	0.34	
	С	0.015	

After the eigenstrain is determined, the eigenstrain field in the representative cell are averaged in x and y directions, respectively. Then they are imported into the elastic model in the center region with laser shocks for the computation of deformation field. The thermal analysis is an optional method to incorporate the determined eigenstrain field into the model. In the thermal analysis, if the model is defined with the material property of anisotropic thermal expansion coefficients α , the corresponding strain can be calculated as $\varepsilon = \alpha \Delta T$ under the temperature field ΔT . Therefore, the eigenstrain field can be imported by assigning the anisotropic thermal expansion ratios equal to the

value of eigenstrain with six components at each position (Eq.5) and applying a unit temperature variation (Eq.6) to the full model in the Abaqus/implicit module:

$$\alpha(x, y, z) = \varepsilon^*(x, y, z)$$

$$T(x, y, z) = 1$$
(5)
(6)

Results and discussion

Figure 4 provides the model output of dynamic model and static elastic modes for eigenstrain and deformed shape, respectively. The contours of simulated equivalent plastic strain field on the top surface are shown in Fig. 4a. It can be observed that the plastic strain distribution is periodic with repeating patterns for the model. Due to the 2-axis distribution of shock pressure, the plastic strain in *x*-direction is a little more than that in *y*-direction. With the eigenstrain in one representative cell determined by the infinite plate model, the in plane plastic strain ε_x^* and ε_y^* along the depth is averaged within the representative cell. After importing to the full size model of plate sample, the deformed shape as shown in 4b is provided with the predicted contour of deformation with the z-displacement. It can be found that a convex shape can be obtained with square shock in the center area.



Fig.4 Model output of dynamic model and static elastic modes: (a) eigenstrain in the dynamic model; (b) z-displacement of deformed shaped in the static elastic model

To validate the eigenstrain strain modeling method, the bending profiles obtained by experiments are compared with the predicted values in Fig.5. Fig.5a shows the z-displacement of the centerline along x direction on the top surface for the experiment and simulation. The experimental results shows that the downward bending is about 534 μ m, while the model predicted value is about 433 μ m, producing a consistent agreement but a little underestimated. Fig.5b shows the z-displacement of the centerline along y direction. The experimental results shows that the downward bending is about 380 μ m, while the model predicted value is about 388 μ m, while the model predicted value is about 380 μ m, also producing a good agreement with the bending profile.



Fig.5 Infinite-square plate model to determine eigenstrain in one representative cell

Conclusions

The eigenstrain modeling method is developed to predict the deformation shape of square plate after laser peen forming. The predictions are validated by the experimental results of overlapping LPF bending of 2024-T351aluminum alloy plate. The eigenstrain modeling method is verified to be an effective approach to simulate the LPF process to predict the bending deformation. The prediction for the large-scale LPF forming process can be completed by identifying the eigenstrain in one representative cell and applying it one after another in the shocked region as an approximation of the actual eigenstrain field. Compared with the direct explicit modeling methods, a shorter computation time is taken for the eigenstrain modeling method to complete the simulation for the LSP application on the large-scale components.

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