Predictive Self-closed Modeling of Laser Shock Peening and Parametric Study

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Abstract
Laser shock peening process is characterized by high amplitude shock wave propagation in the targets and deep compressive residual stresses. In this presentation, a predictive self-closed model of LSP is presented, which consists of a plasma model to predict the pressure distribution resulting from laser-material interaction and a dynamic model to predict the resultant residual stresses. Parametric study results based on this predictive model are presented along with experimental results for several metals with black paint, vinyl tape, and aluminum tape coatings. For an aluminum tape coating, a thin glue layer that is used to connect the foil onto the substrate surface has usually been neglected in all previous FEM simulations. To gain a better understanding of the effect of the glue layer on the resultant residual stresses, a glue layer is added into the FEM between the coating material and substrate. The model prediction of residual stresses with a glue layer is compared with the experimental data and simulation results without a glue layer, which clearly shows that the simulation results with a glue layer yield better agreement with the measurement data.

Keywords Laser shock peening, self-closed model, residual stress, interface modeling

Introduction

Laser shock peening (LSP) process is characterized by generation of high pressure plasma, propagation of high amplitude shock wave, and introducing deep compressive residual stresses in the targets [1, 2]. In the LSP process, an opaque coating layer is usually applied on the surface of substrate material to protect the thermal damage which may occur in the process.

Several analytical models [1, 3, and 4] have been developed to consider the laser-matter interaction and laser-produced plasma in laser shock processing in a confined configuration (glass or water). However, the free variables in these models make the prediction of plasma pressure very difficult when the measurement data are not available. Recently a self-closed thermal model [2] was proposed to consider the LSP under water confinement, which has considered most of the important physical phenomena of LSP. More importantly, there are no free variables in this model and therefore it can be used for virtually any material in the LSP process. The finite element simulation of LSP and LSP-induced residual stresses has also been extensively reported in the literature [5-7]. However, the inputs of these finite element models, the confined plasma pressure, mostly come from the simple analytical model [1], which has two free variables. The coating layer was not considered in all these FEM analyses except in Ref. [7]. Due to the shock impedance mismatch at the interface between coating and substrate, it is necessary to model the coating layer in the FEM analysis. For an aluminum tape coating, a thin glue layer that is used to connect the foil onto the substrate surface has usually been neglected in all previous FEM simulations.

Laser-induced residual stresses and the change of target surface integrity by LSP under different laser parameters and coating materials remain a difficult task without taking into account of the real laser-induced plasma pressure with strict physics-based theories. The first objective of this work is to investigate the target surface integrity change and laser-induced residual stresses on various metal samples by LSP through predictive modeling and experimental studies. To gain a better understanding of the effect of the glue layer on the resultant residual stresses, a glue layer is added into the FEM between the coating material and substrate in this work. The model prediction of residual stresses with the glue layer is compared with the experimental data and simulation results without the glue layer, which clearly shows that the simulation results with the glue layer yield a better agreement with the measurement data.

LSP Experiment and Residual Stress Measurement

A laser beam is generated by a nanosecond Nd-YAG laser (Continuum Surelite), and then passes through a half-wave plate, a polarizer, three high reflecting mirrors and a focus lens, and finally focuses on the surface of a work-piece. The work-piece is placed into a water-filled tank to produce a water-confinement regime. The movement of the work-piece in X and Y direction is driven by two computer-controlled linear motion stages. The LSP conditions, as listed in Table 1, were designed to investigate the target surface integrity change and induced residual stresses under single shot and overlapping LSP for different materials. For LSP on aluminum 7075 workpiece, the glue layer on the aluminum tape is assumed to be around 12.5 µm, which only occupies one mesh cell of the numerical model in the direction of pressure wave propagation.

The residual stresses induced in the substrate material after the LSP process were measured with the X-Ray diffraction (XRD) technique. To fully characterize the effects of LSP, subsurface residual stresses were measured by utilizing a chemical etching technique to the depth of more than 1 mm below the original surface.

Table 1. LSP conditions used in this work

Substrate Material	4140 Steel		Ti64	Aluminum 7075
Coating Material	Black Paint	Vinyl Tape	Black Paint	Aluminum Tape
LSP Mode	Single Shot	Overlapping	Overlapping	Single Shot
Coating Thickness (µm)	50	100	100	50
Pulse Duration (ns)	6	20	6	6
Beam Diameter (mm)	0.3	5.0	1.2	1.5
Power Density (GW/cm^2)	3 ~ 7	7	4, 7	4
Laser Wavelength (nm)	532	1064	1064	1064

Theoretical Model

I. Confined Plasma Model

According to the criteria developed in Ref. [8], 1-D plasma expansion assumption is valid when the laser beam diameter is equal or larger than 300 µm. Since the laser beam diameter used in this work is between 0.3 to 5.0 mm, it is sufficient to use a 1-D model in this work to describe the confined plasma behavior under water. Therefore the confined plasma model developed earlier by Wu and Shin [2] was used in this work to calculate the LSP generated plasma pressure in a water confinement regime.

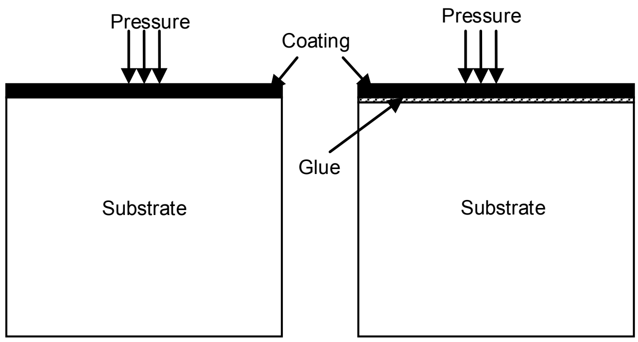
II. 3-D Finite Element Model

A 3-D finite element model (FEM), as shown in Fig. 1 (a), has been developed to calculate the shock wave propagation and the resultant residual stresses on the substrate material. For aluminum tape coating, a glue layer has been added between the coating and substrate, as shown in Fig. 1 (b), to consider the effect of glue layer on the resultant final residual stresses. The pressure load shown in Fig. 1, which is from the confined plasma pressure model, is modeled as a distributed load in ABAQUS. At the interface between materials, TIE constraint was used to couple the dynamic response of coating and substrate. The bottom surface of the workpiece is considered to be fixed.

Due to the high strain rate of LSP process (> 10^7 s^{-1}), it is necessary to consider the strain rate effect to accurately model the dynamic behavior of target material. In this work, the dynamic behavior of substrate material was described by Johnson-Cook model [9]:

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})\right], \ \dot{\varepsilon}_0 = 1\ s^{-1} \tag{1}$$

where $\dot{\varepsilon}$ represents strain rate and ε is strain, A, B, C, and n are material constants.
The temperature softening effect in Johnson-Cook model is not considered due to the use of coating material as a thermal protection layer. The Johnson-Cook model constants for all the three substrate materials used in this work are listed in Table 2.



(a) Setup without glue layer (b) Setup with glue layer
Fig. 1 System setup for FEM calculation in typical LSP process

Table 2. Johnson-Cook model constants for substrate and coating materials

	A (MPa)	B (MPa)	C	n
4140 Steel [9]	792	510	0.014	0.26
Ti64 [10]	840	550	0.064	0.812
Aluminum 7075 [9]	430	350	0.012	0.4
Aluminum [7]	120	300	0.1	0.35

For the coating material, black paint and vinyl tape was assumed to be elastic-perfectly plastic material in the FEM analysis. The mechanical and physical properties of black paint and vinyl can be obtained from Ref. [11-13]. For the aluminum tape coating, the aluminum part was treated with Johnson-Cook model (material constants listed in Table 2) and the glue part was taken as elastic-perfectly plastic material. The mechanical properties of glue are taken from typical metal adhesive from Ref. [14].

Results and Discussion

I. Single Shot LSP

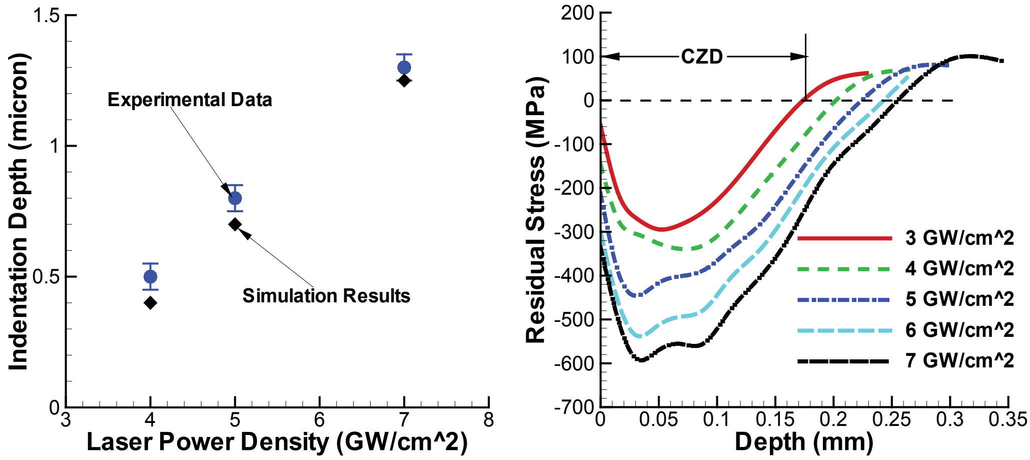
(A) Single Shot LSP on 4140 Steel

In this case, the substrate material was 4140 steel and the coating material was black paint. As mentioned in Table 1, the laser power density varied from 3 to 7 GW/cm^2 to investigate the effect of laser power density on the indentation profile and residual stresses. The indentation profile after LSP was measured by using an optical profilometer (Phase Shift Technologies, MicroXAM-100). The LSP-induced residual stress can also be predicted using the model developed in this work.

Figure 2 (a) shows the comparison of indentation depth from simulation results and experimental data. A reasonable agreement can be observed between the predicted and measured indentation depths under several laser power densities. The in-depth residual stress distribution for 4140 steel under different laser power densities is shown in Fig. 2 (b). As the power density increases from 3 to 7 GW/cm^2, the peak compressive residual stress also increases from about 250 MPa to 600 MPa. The compressive zone depth (CZD) shown in Fig. 2 (b) is defined as the depth of the region, which has compressive residual stresses after LSP. It can be seen from Fig. 2 (b) that the CZD increases from 0.17 mm to 0.25 mm with laser power densities changing from 3 GW/cm^2 to 7 GW/cm^2. Therefore higher laser power density can increase not only the peak residual stress but compressive zone depth.

(B) Single Shot LSP on Aluminum 7075

The laser beam profile was assumed to be top-hat in the previous FEM calculation based on the measurement of beam profile [15]. In fact, it is essentially a Gaussian beam from the laser cavity. Therefore, the Gaussian beam profile was employed in this part to calculate the residual stresses induced in the LSP process with the glue layer considered.



(a) Indentation depth (b) In-depth residual stress distribution

Fig. 2 Prediction of (a) indentation depth and (b) in-depth residual stresses under different laser power densities (substrate: 4140 steel, coating: black paint, Laser pulse duration 6 ns, beam diameter 300 μm, coating thickness 50 μm)

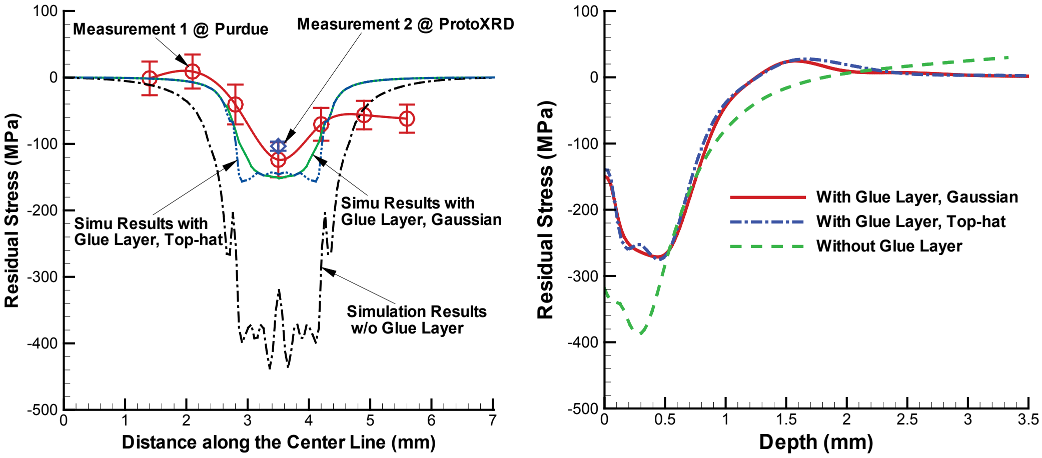
Figure 3 shows the comparison of simulation results and measurement data for single shot LSP on aluminum 7075 with aluminum tape coating. The measurement 1 shown in Fig. 3 (a) was conducted at Purdue University, while the measurement 2 was done by Proto Manufacturing Inc. It can be seen from Fig. 3 (a) that the simulation results with the glue layer and Gaussian beam profile yield better agreement with the measurement data, which probably due to the addition of the glue layer and a better representation of the real laser beam. The in-depth residual stresses after LSP are also compared between the case with the glue layer and the case without the glue layer in Fig. 3 (b). In the case with the glue layer, the peak residual stress in the substrate decreases from around 390 MPa to around 275 MPa. The compressive zone depth also reduces from around 1.8 mm to around 1.3 mm after adding the glue layer. The above example clearly shows that the simulation results with the glue layer have better agreement with the measurement data. By representing the laser beam as Gaussian, the simulation results are closer to the measurement data.

II. Overlapping LSP

(A) Overlapping LSP on 4140 Steel

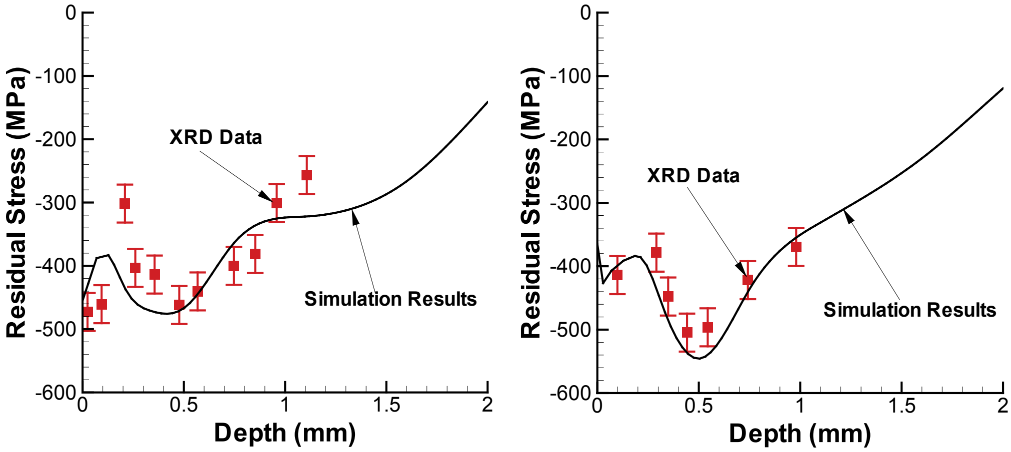
To investigate the laser-induced residual stress in multi-track overlapping LSP, several 4140 steel samples were shock peened by Laser Shock Peening Technology (LSPT) with larger beam diameter (5.0 mm). The coating material used at LSPT was standard black polyvinyl tape with the thickness of 100 μm. All the other LSP parameters are listed in Table 1. The laser beam spatial profile was assumed to be flat-top. The residual stresses of two LSPT samples with overlapping ratio of 40% and 50% were measured to the depth of more than 1 mm below the original surface by utilizing a chemical etching technique.

The residual stresses after each etching were measured and shown in Fig. 4. Simulation results of the laser-induced residual stresses are also plotted in Fig. 4. In the first case with overlapping ratio of 40%, there are several locations at which the simulation results differ a little more from the measured data than the rest of the results. The second case with overlapping ratio of 50% shows a better agreement between the model prediction and measurement data. Overall, the simulation results agree fairly well with the measured XRD data in both cases, which serves as a validation of our complete predictive LSP model. The CZDs in both overlapping LSP cases are more than 2 mm, which is much higher than those in the single shot LSP case mainly due to the longer laser pulse (20 ns v.s. 6 ns) according to Ref. [15]. The peak residual stress is also larger with higher overlapping ratio as indicated in Fig. 4.



(a) Surface residual stress (b) In-depth residual stress

Fig. 3 Comparison of (a) surface and (b) in-depth residual stresses after single shot LSP (Substrate: aluminum 7075, laser beam diameter 1.5 mm, power density 4 GW/cm^2, aluminum coating 37.5 μm, glue layer 12.5 μm)



(a) Overlapping ratio 40% (b) Overlapping ratio 50%

Fig. 4 Comparison of measured XRD results and simulation results for multi-track LSPT 4140 steel samples with different overlapping ratio (laser power density 7 GW/cm^2, beam diameter 5 mm, pulse duration 20 ns, wavelength 1064 nm, vinyl tape coating)

(B) Overlapping LSP on Ti64

Further residual stress prediction was carried out on a Ti64 sample. The workpieces were treated with two different laser power densities: 4 and 7 GW/cm^2. Other laser parameters are listed in Table 1. Figure 5 shows the simulation results and experimental data for residual stress distribution in the depth direction for Ti64 workpieces. It can be seen from Fig. 5 that higher laser power density can increase not only the peak residual stress but compressive zone depth as in the single shot LSP case. Overall, reasonable good agreements were obtained between the model predictions and measured XRD data for both cases.

Concluding Remarks

A predictive self-closed LSP model including a confined plasma model and a 3-D finite element model has been developed and used to simulate the single shot and overlapping LSP processes. For single shot LSP, the model prediction of indentation depths provided a good agreement with experimental data. For overlapping LSP, the peak residual stress is also larger with a higher overlapping ratio. It was found that higher laser power density can increase not only the peak residual stress but compressive zone depth in both single shot and overlapping LSP. Longer laser pulse results in larger compressive zone depths. For aluminum tape coating, the glue layer plays an important role in the LSP-induced residual stress in the substrate material. The simulation results with the glue layer and Gaussian beam profile yielded a better agreement with the measurement data. This work demonstrated the accuracy and usefulness of the self-closed predictive LSP model.

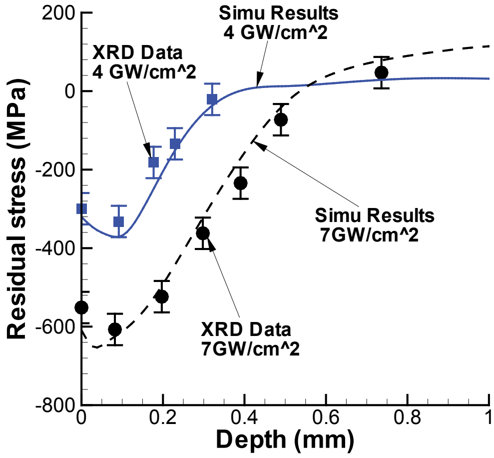


Fig. 5 Residual stress distribution for laser shock peening on Ti64 under different laser power densities (beam diameter: 1.2 mm, pulse duration 6 ns, wavelength 1064 nm, coating: 100 μm black paint, overlapping ratio: 50%)

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