Compressive Residual Stress Optimization in Laser Peening of a Curved Geometry

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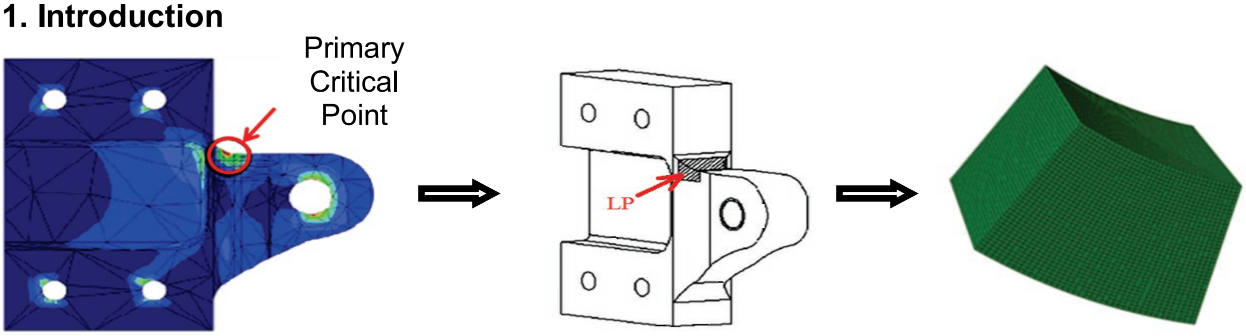
Abstract

Laser Peening (LP) is a surface enhancement technique that can delay crack nucleation by inducing compressive residual stresses. High stress concentration along the curved portion of a structural component is a common cause for crack initiation, which can lead to fatigue failure. Most fatigue cracks nucleate near the surface and propagate into the component. A simulation model can be used to investigate the effects of LP on crack growth behavior in an efficient manner. In this work, a 3D finite element model is created using ABAQUS© to simulate the non-linear dynamic response of a sequential two-shot LP impact on a component's surface. This work uses these simulation results as an objective function to maximize the compressive residual stresses induced along a component's edge. Peak pressure pulse amplitude, mid-span duration and curvature are the design variables considered. A tensile stress constraint at critical locations completes the problem formulation. The computational cost of LP simulation is high due to incremental time analyses, so surrogate simulation models are used to reduce the number of finite element analyses required during optimization. These surrogate models, referred to as function approximations, are based on gradient information gathered from the LP simulation and are employed to reach an optimum design more quickly. This work focuses on the design optimization of the considered LP parameters for fatigue life extension of curved geometries.

Keywords: Laser Peening, Residual Stress, Finite Element Analysis, Optimization, Curved Geometry, Function Approximations.

1. Introduction



(a) (b) (c)

Figure 1. Critical Geometry Representation of an Aircraft Lug : (a) Coarsely meshed model used for peak stress identification, (b) Schematic of target region to be subjected to LP, (c) Finely meshed curved region for use in LP residual stress analysis

Critical regions of an aircraft lug are prone to fatigue cracks. Finite element analyses conducted on this lug found that the primary critical point where structural failure occurs is an area around the component's edges. These regions are subjected to surface enhancement techniques used in industry which can induce favorable compressive stress and thereby delay crack nucleation of which the most common method is shot peening. Other commonly used methods include low plasticity burnishing, water jet peening, and Laser Peening (LP) and each method has its own advantages and disadvantages. Considering that our problem involves complex geometry, modeling compatibility and minimal surface damage, LP would be the best choice. LP can be applied to improve the fatigue strength at these critical locations. Modeling the curved portion of geometry rather than an entire lug helps to utilize these results in other components with similar geometries, thus saving computational time. Figure 1 represents this concept.

2. Laser Peening Process

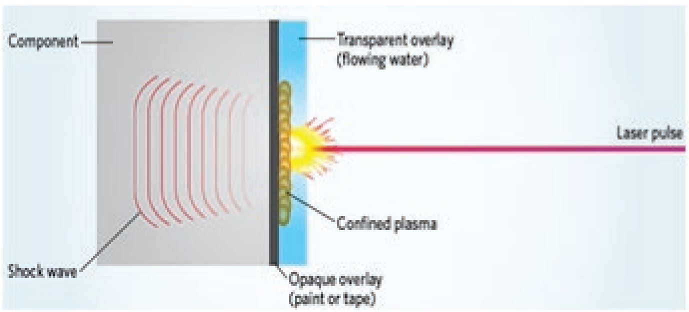


Figure 2. Schematic of Laser Peening Process

When a high intensity laser pulse strikes the peening material that has been prepared with an absorbent coating and a transparent overlay, the absorbent material vaporizes and expands due to the high energy input resulting in plasma. The confined plasma creates a pressure pulse, which propagates into the material as a shock wave. When the stress created by the shockwave exceeds dynamic yield strength, plastic deformation occurs and changes the surface microstructure, imparting compressive residual stresses in the surface regions [1]. Figure 2 is a pictorial representation of the LP method. For the Ti-6Al-4V alloy considered, an ND:YAG laser is used with black paint as the absorbent coating and water as the transparent overlay.

3. LP Simulation and Design Parameters Considered

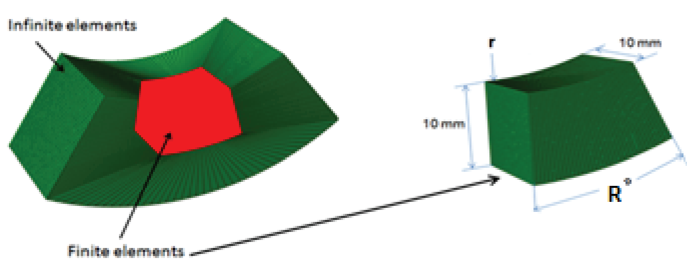
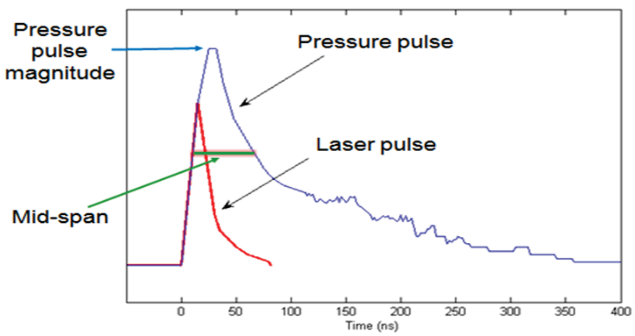


Figure 3. Finite and Infinite Elements

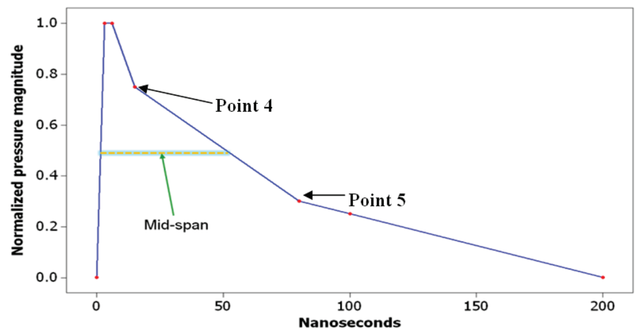
The FE model shown in Figure 3 encompasses both finite and infinite elements. The finite element region is used to model the plastically affected zone. A curved, 80x80x80 element meshed region is used to represent the finite region and is comprised of C3D8R elements. These eight-node finite elements can undergo non-linearity to represent large deformation due to high pressure impact. Infinite elements are assumed to be elastic elements and are used as non-reflecting boundaries comprising of eight-node linear CIN3D8 elements. The material properties used for this simulation are that of Ti-6Al-4V, which is extensively used in aerospace industry. The strain rate for LP is in the order of 1million/second. The Johnson Cook Model has been an efficient material model to deal with high strain rate processes and is used here [2].

The critical region is modeled as a curved geometry, and a load is applied on the curved surface. A 22.5^0 degree of curvature model is shown in Figure 3 with its geometric dimensions. The radius is chosen so as to maintain the length of the edge at 10 mm. The range of degree of curvature(R) in the design is considered between 0^0 and 45^0.

There are many types of pressure pulse shapes that can be generated using a laser system for LSP. The most well known are Gaussian and sharp rise shapes. It was discovered by experiments that the sharp rise shape produces better results than the Gaussian shape. Therefore, this shape is used in industry to generate a better residual stress profile. Figure 4(a) shows the laser beam as well as the generated pressure profile [3]. Plastic deformation occurs only if the pressure pulse is greater than 1 HEL (Hugoniot Elastic Limit), which is a function of dynamic yield strength. If the pressure is very high, then spallation will occur. Hence the bounds for the pressure pulse duration (3 GPa – 7 GPa) have been chosen accordingly.



(a)



(b)

Figure 4.(a) Laser beam and Pressure Profile, (b) Pressure Profile Input to Simulation

In experiments, the laser beam mid-span duration varies from 10–30 nanoseconds(ns) as shown in the Figure 4(a). The pressure pulse mid-span duration is approximately 2 to 2.5 times that of the laser beam mid-span duration. Therefore 20 ns and 60 ns are taken as upper and lower limits for the mid-span duration. The temporal pressure profile input to the simulation box can be approximated by seven representative points as shown in Figure 4(b). Point 5 controls the mid-span duration, and a two-point formula can be used to find the Point 5, keeping Point 4 constant and limits for Point 5 was obtained. The bounds for point 5 considered was 30 ns to 90 ns.

3.1. Simulation Procedure

The conventional explicit-implicit procedure adopted for laser shock peening involves two steps [4]. The first step involves a dynamic analysis performed in ABAQUS/Explicit until plastic saturation within the model takes place. The explicit portion of the analysis then ends, and the procedure moves to the second step, which achieves force equilibrium using ABAQUS/Standard and outputs the final residual stress field. It was found that by increasing the time of the explicit simulation and removing the implicit phase, residual stress profiles can be obtained without a loss of accuracy. The total explicit time considered varies depending on material properties and LP parameters. An explicit total time of 40 microseconds was validated for different loading conditions and has been employed for the current research. A flow diagram of the extended explicit procedure is shown in Figure 5.

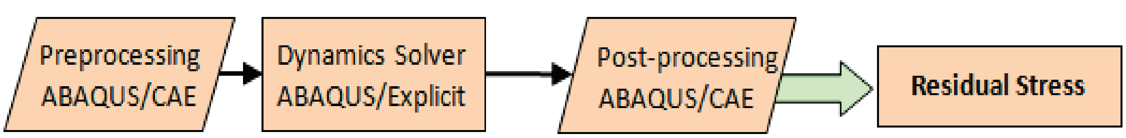


Figure 5. Extended Explicit Procedure

4. Optimization Approach

The choice of cost function was based on the major output of the simulation, which is the residual stress profile. Compressive residual stress along the center node of the edge where the laser shot is impacted is considered as objective function. Choosing design variables that minimize the objective function might be the best suitable combination to prevent fatigue failure.

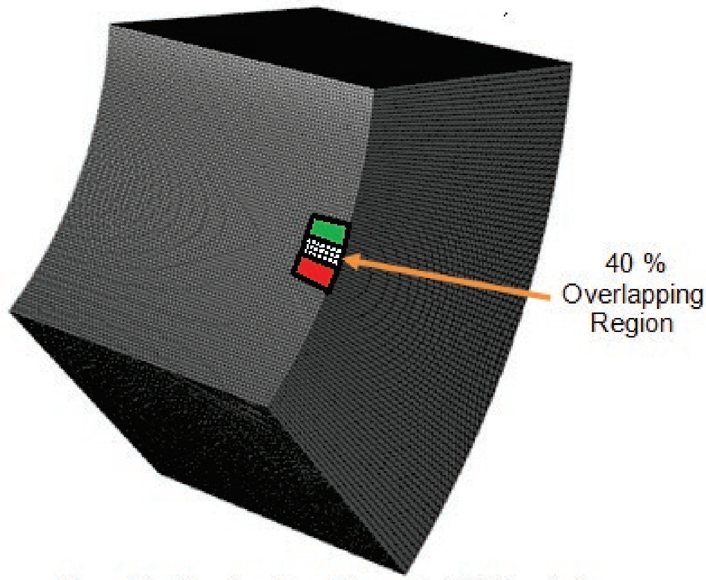


Figure 6. Overlapping of two shot LP simulation

LP imparts compressive residual stresses near the surface regions. But at the same time, tensile stresses will be created inside the material to maintain equilibrium. If the tensile stresses are high, it can lead to fatigue cracks in the sub-surface regions. Hence a constraint is required to maintain an allowable tensile stress inside the material. This constraint helps to maintain safety while maximizing the objective function.

Throughout this work, an LP pattern of two square shots (2.5mm x 2.5mm), overlapping by 40 % was used as shown in Figure 6. The three design variables (peak pressure pulse amplitude, pulse duration and degree of curvature) were selected based on geometric and loading conditions. The steps taken to reach an optimum solution have been represented by Figure 7.

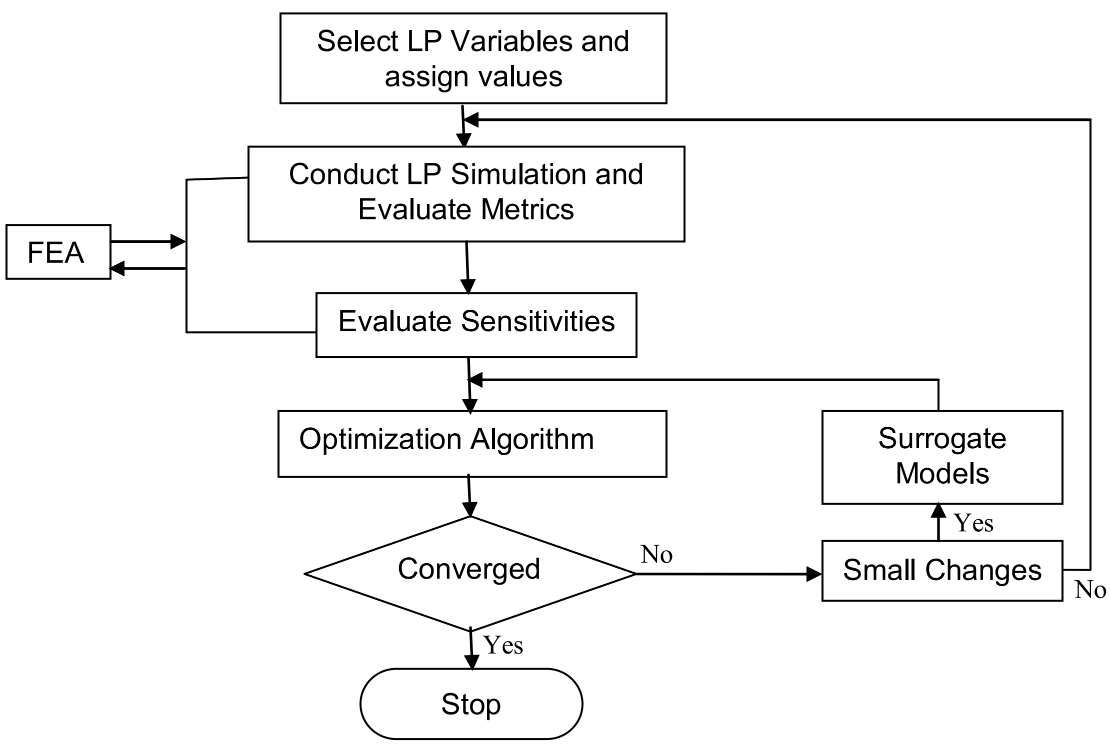
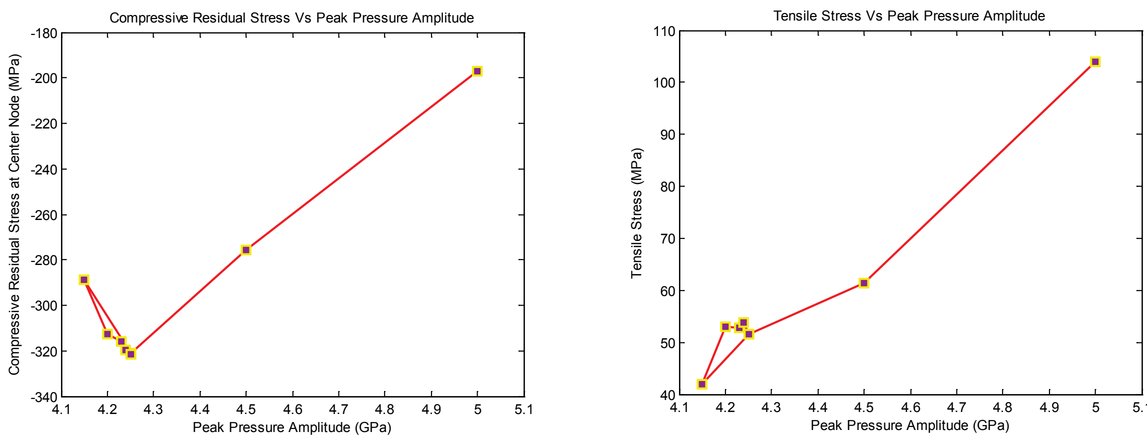


Figure 7. Flow Diagram of LP Optimization Procedure

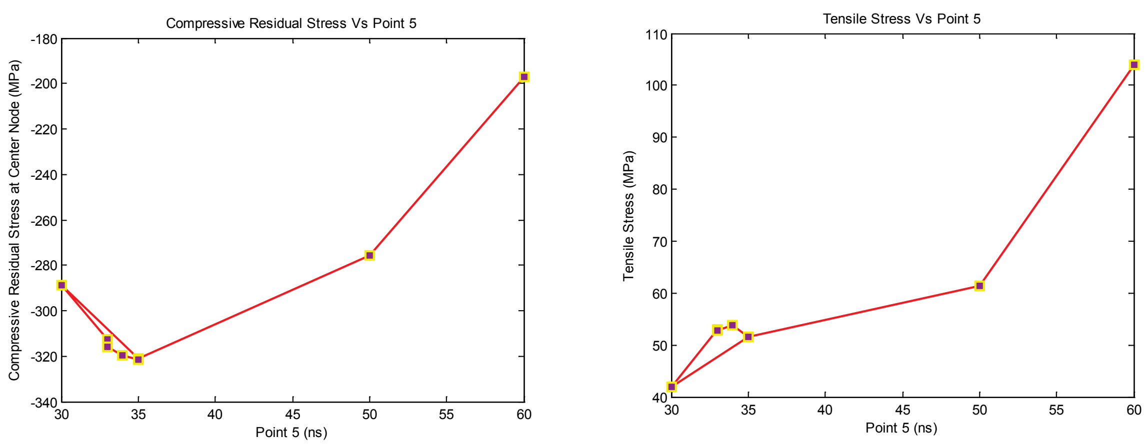
5. Results and Discussion

The initial design point is taken as the center point of the design space; Peak Pressure (P) = 5 GPa, Point 5 (T) = 60ns, Degree of Curvature (R) =22.5^0. An ABAQUS/EXPLICIT FEA model is run at the initial design point to obtain the function value and gradients. A conservative approximation is constructed based on the current design point; Based on the conservative approximation, a new design point is obtained. Two-Point Adaptive Nonlinear Approximations (TANA1) can be created for both the objective function and the constraint using these two points, and then the simulation is run iteratively until the convergence criterion is satisfied [5]. As the gradients change their directions, smaller step sizes are taken to reach an optimum solution. The optimum solution was achieved in 8 iterations. Although the degree of curvature is an important design parameter, it was peak pressure amplitude and mid-span duration that dominated the optimization process. The variation of these two parameters has been shown in the Figures 8 and 9.



(a) (b)

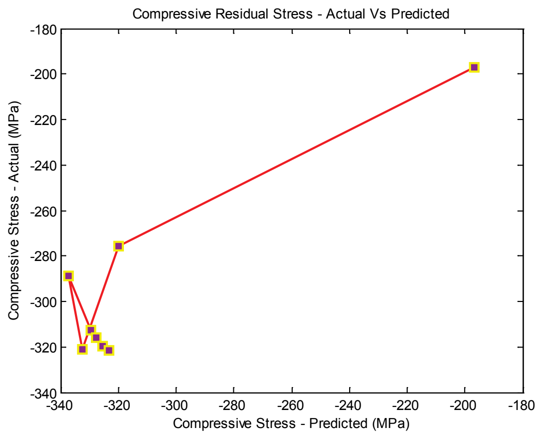
Figure 8. Effect of Peak Pressure Amplitude to: (a) Compressive Residual Stress
(b) Tensile Stress



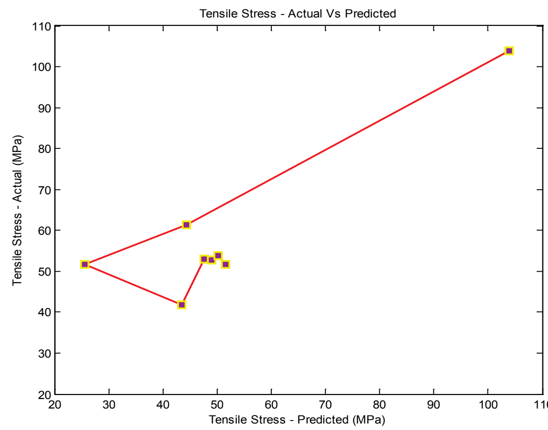
(a) (b)

Figure 9. Effect of Mid-Span Duration(Point 5) to: (a) Compressive Residual Stress
(b) Tensile Stress

The function approximation was found to be an efficient tool in reaching an optimum solution quickly. Figure 10 shows the accuracy of this method for predicting good results.



(a)



(b)

Figure 10. Actual Vs Predicted Function Values for: (a) Compressive Residual Stress
(b) Tensile Stress

6. Conclusions

1. A local optimum point for laser peening simulation for the particular geometry and loading conditions was found. The optimum was found to be P = 4.25GPa, T = 35ns and R = 20^0 which gives a compressive residual stress = 321.6 MPa.
2. Constraint violation happened only at the initial design. New design configurations satisfied the tensile stress constraint while maximizing the compressive stress value at the center of the edge.
3. Although degree of curvature has definite effects on laser peening simulations, the current problem was dominated by pressure pulse duration and peak pressure amplitude to determine an optimum design configuration. A good understanding of the problem will help to select a good starting point, which will result in convergence of the solution at a faster rate.
4. Non-linear variations for the two dominating variables inside the design space result in an optimum inside the bounds, rather than along the boundary.
5. Function approximations were found to be not very accurate in determining the system behavior in the initial iterations. Function approximations help to reach an optimum at a faster rate, and it can be seen that convergence is reached quickly if enough iterations are allowed to run.

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