Modified Symmetry Cell Approach for Simulation of Surface Enhancement Over Large Scale Structures

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Abstract

Physical surface enhancement techniques such as Shot Peening (SP), Laser Peening (LP), and Low Plasticity Burnishing (LPB) offer excellent fatigue mitigation options for the design engineer due to the compressive surface stresses they imbue. These techniques must typically be used on large surfaces to garner any type of advantage. To understand how these large-scale residual stress fields affect the fatigue life of a structure, the LP residual stress field must be in place on the simulated structure so that its effects on loading can be observed. A highly refined mesh is required to obtain a reasonably accurate residual stress field. This mesh refinement combined with any type of plasticity equates to a long simulation time. For processes that rely on a large number of simulations, i.e., each shot of an SP or LP pattern, this translates to a time-prohibitive simulation. By carefully constructing the simulated peening area outside the boundaries of the region of interest, an accurate symmetry cell is created in an AISI 1045 steel. The symmetry cell constructed within this work is then compared with previous symmetry cell methods and experimental data to demonstrate improvement in accuracy.

Keywords Symmetry Cell, Laser Peening, AISI 1045 Steel, FEA.

Introduction

Laser Peening (LP) is a surface enhancement technique that uses high-intensity, short duration lasers to induce compressive surface stresses in metallic components [1,2,3] which are desired to reduce the service loads seen by the part, and thus extend the service cycles to failure [1]. The LP process generally begins with the application of an ablative layer to the surface of the work piece to be laser peened. For this work the ablative layer is black paint, which is opaque to the laser. With the paint in place, a thin layer of laminar flow water is directed over the paint, after which the laser is fired directly at the surface [1]. Once the paint has absorbed enough energy from the laser, it rapidly transforms into plasma. The water curtain contains this rapid plasma expansion and forces the energy wave into the metallic material, contains this rapid expansion. In the wake of this energy wave, plastic deformations take place within the material, the magnitudes of which are decided by the peak pressure seen at the surface, its duration, and the material properties of the work piece (Figure 1a) [2,3].

The subsurface plastic waves caused by LP eventually dissipate as material damps out the shockwave energy. The stresses transition from plastic to elastic once they reach values below the Hugoniot Elastic Limit (HEL) at the current strain rate [4,5]. Once the stress waves dissipate, the material equilibrates, resulting in compressive stresses on the surface of the material and the corresponding tensile stresses sub-surface (Figure 1b) [1]. This process can be repeated several hundred to several thousand times, depending upon the shot pattern and scope of the component [6].

When simulating the application of large-scale LP, highly complex, elastic-plastic, densely meshed Finite Element (FE) models are required for an accurate representation of the induced stress fields. However, simulation times for a single shot can be on the order of a day. Thus, a brute force method of simulating large, multi-shot patterns is often time-prohibitive, and alternate methods must be explored. Hu and Yao have explored one such method, a symmetry cell approach [6].

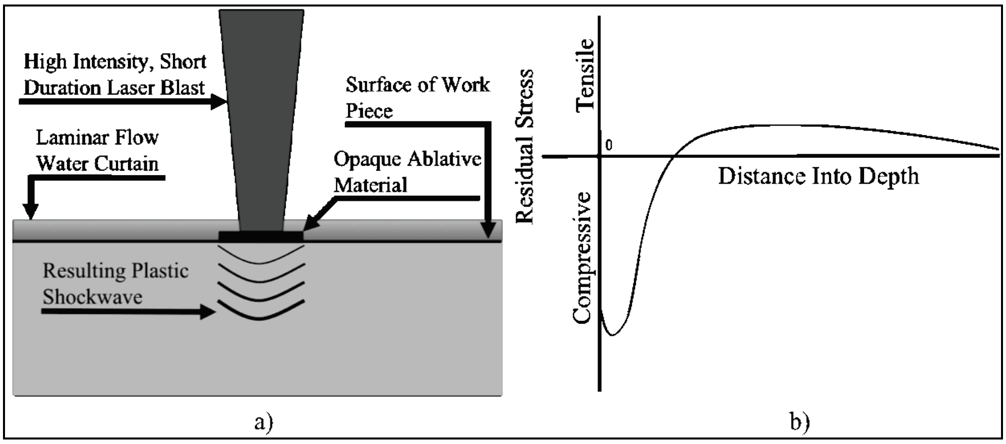

Figure 1: LP Process Fundaments a) Process Setup and b) Generic Residual Stress Profile

A symmetry cell is the smallest unit of a repeating pattern: placing symmetry cells of the same adjacent next to one another reproduces the original, larger pattern. An example of this technique can be seen in Figure 2. In this illustration, a symmetry cell containing 50% overlap between columns and rows is used to re-create the large pattern whence it came, resulting in the larger pattern at fraction of the computational cost. From a simulation standpoint, a symmetry cell such as this can be used to drastically reduce simulation times for large-scale peening. As will be discussed in the next section, an essential element of any symmetry cell is the determination of the critical distance between two sequential LP spots.

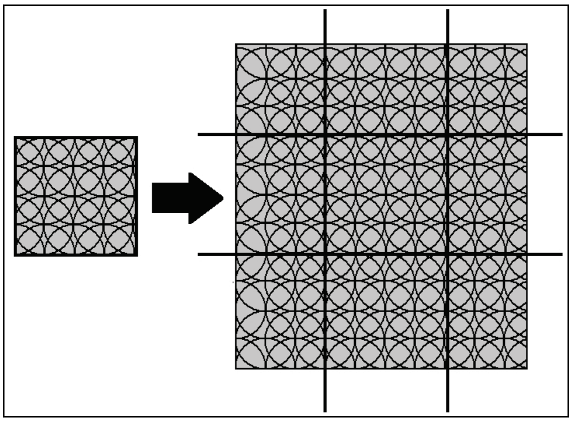

Figure 2: Unit Symmetry Cell (Left) Being Used to Reproduce a Larger Pattern (Right)

Critical Distance

The critical distance between two sequential spots is defined, for this work, as the distance between two LP shots at which they no longer interact: their residual stress fields are independent of shot sequence. This distance allows for construction of a symmetry cell in which adjacent shots to the cell itself are able to affect the residual stresses within the cell; this is a consideration that was lacking in prior work. Critical distance is theorized to be a function of LP peak pressure and material. Using a 2D axisymmetric approach, these critical distances can be quickly identified on any modern workstation computing system. The infinite portion of the model should begin 4-8 mm away from the edge of the LP spot elements. For this work an LP spot radius of 1 mm was used, resulting in a maximum finite region 9 mm wide by 2 mm deep with an element size of 0.1 mm wide by 0.05 mm deep.

The first step in the process is the construction of the 2D axisymmetric model. The FE model consists of two sections; the first is a square region comprised of 4-node bilinear reduced integration finite element hourglass control (ABAQUS CAX4R), which is surrounded by 4-node one-way linear infinite elements (ABAQUS CINAX4) on all faces except for the centerline of the axisymmetric model and the LP work face (Figure 3). The LP shot is simulated by applying a high intensity, short duration pressure to a region of surfaces that represent the footprint of the LP spot (Figure 3). This footprint has a uniform spatial pressure distribution and follows a pressure temporal profile seen in Figure 4. The time step for the explicit analysis is 0.2 ns, while the total time period is 2 μs [6]. An Elastic-Perfectly Plastic (EPP) material model was used that calculated the yield point of the material at various strain rates. These yield points at various strain rates were calculated using the Johnson-Cook material model for a plastic strain value of 0 (Eq. 1):

$$\sigma_{eq} = A(1+C\mathit{ln}(\varepsilon'/\varepsilon'_0) \qquad (1)$$

where A is the initial yield stress of the material, C is the strain rate sensitivity of the material, ε'_0 is the reference strain rate, and ε' is the strain rate of interest. The material constants for the AISI 1045 steel used in this work can be seen in Table 1.

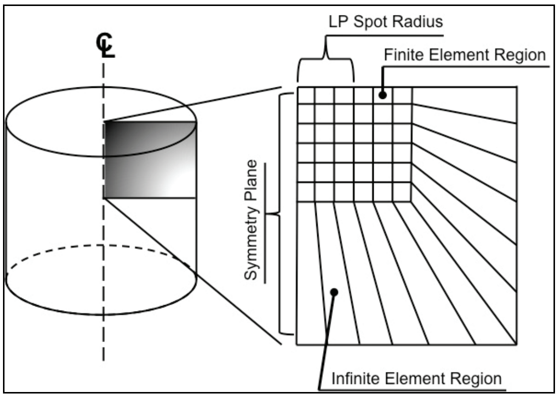

Figure 3: 2D Axisymmetric FEA Model with Detail

Table 1. AISI 1045 Steel Material Constants [6]

A (MPa)	C	ε'_0	E (GPa)	υ	δ (kg/m^3)
507	0.064	1	206	0.3	7850

Based on information from previously conducted FEA 2D axisymmetric convergence studies, the infinite portion of the model should begin 4-8 mm away from the edge of the LP spot elements. For this work a radius of 1 mm was used, resulting in a maximum finite region of 9 mm x 9 mm with an element size of 0.0208 mm.

Using this concept, the simulation of a single LP shot in a 2D axisymmetric model of an infinite plate was conducted with the conditions outlined above. Using the LP equivalent plastic strain (ABAQUS: PEEQ) results from across the surface of the model, the location where the value falls below 1 milli-strain is recorded. Once the equivalent plastic strain drops below 1 milli-strain, it is assumed that the effects that it has upon the residual stress state are negligible and that is the closest point at which it can be placed to another shot without plastically interacting with it. Because this work focuses on LP shots 1 mm in radius, 1 mm is then added to the recorded location to account for the spacing from the equivalent strain drop-off location and the previous shot center. This combined value is the critical distance between two LP shot centers for the pressure profile and LP peak pressure used in this material. Critical distances between two spot centers for various peak pressures can be seen in Figure 5.

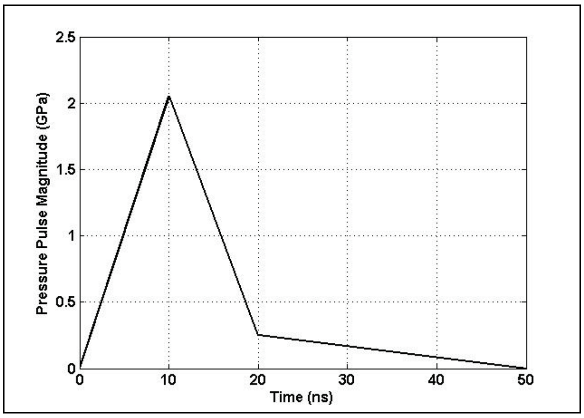

Figure 4: Temporal Profile of LP Peak Pressure

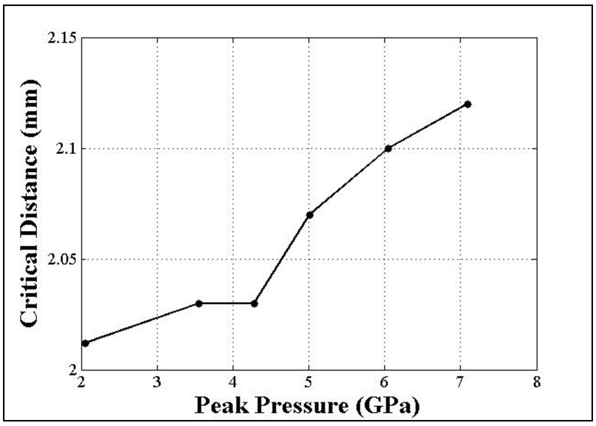

Figure 5: Critical Distance Between Two LP Spot Centers for Various Peak Pressures

Symmetry Cell

Construction of the amended symmetry cell places one spot at the absolute center of the model, and then constructs the remainder of the model around that spot. Because the pattern used for this work is a 50% overlap raster-type pattern, the symmetry cell surface required is only 2 mm by 2 mm and will contain 9 separate LP spots (Figure 6a). Because LP shots outside of the symmetry cell effect the residual stresses within it: additional LP shots are required up to the critical distance outside of the cell, thus requiring material that is the critical distance away from the symmetry cell boundary. To ensure that the infinite boundary conditions do not affect the LP residual stress response of the model, there will need to be another 4 mm of material added to the end of the finite region (Figure 6b): every other row and column of spots was left un-highlighted to improve visualization. The depth of the model was set to 2 mm for similitude and comparative purposes to prior work [6]. Figure 6c shows the completed infinite plate model: the finite region of the model (Figure 6b) surrounded by 8-node one-way elastic infinite elements (ABAQUS CIN3D8). The finite elements used were 8-node reduced integration linear brick elements with hourglass control (ABAQUS C3D8R). The LP shot spatial pressure and temporal profiles used for this portion of the work are identical to those used in the 2D portion. Demonstration of the symmetry cell will use the peak pressure of 2.05 GPa (the experimental work being used for validation used this peak pressure as well). Each element for the 3D model was dimensioned 0.1 mm wide by 0.1 long by 0.05 mm deep per the element dimensions used in the work conducted by Hu & Yao [6].

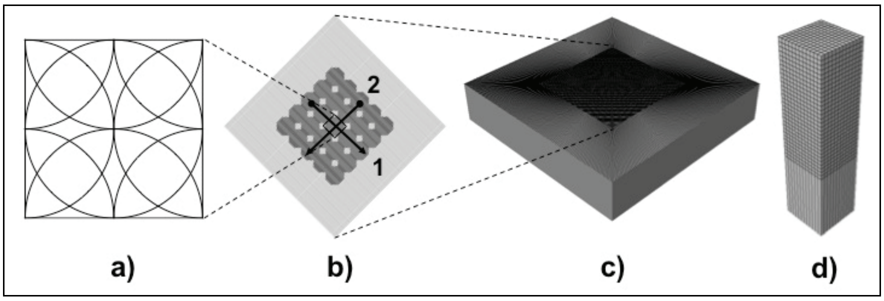

Figure 6: Creation of a Symmetry Cell Using Critical Distances: a) Symmetry Cell, b) Finite Region of Symmetry Cell FEA Model, c) Total Model with Both Finite and Infinite Element Regions, d) Hu & Yao Type Symmetry Cell

Because previous methods failed to account for critical distances and boundary condition effects on LP residual stress fields, this method is assumed to be the absolute minimum amount of simulation needed in order to accurately create an LP symmetry cell on an infinite plate. The pre-existing alternate symmetry cell technique uses a model that does not account for critical distances or sufficient infinite boundary conditions. This pre-existing technique, created by Hu & Yao, was utilized to create a model that corresponds to the amended symmetry cell model created in this work, so that a comparison between the two methods could be made (Figure 6d).

Results

Both models were compared with the X-Ray Diffraction (XRD) experimental residual stress results provided in Hu & Yao's work. To compare analytical residual stress results with the experimental values, primary direction residual stresses were averaged over the entire area of the patterns' center spot as this was the area targeted by the XRD work from Hu & Yao using a 2 mm diameter aperture. If the shock plane (top most surface, unconfined by infinite boundary conditions) rested in the XY plane, then all nodal values under the center-most spot would be averaged in the x-direction (σ_x). Both the x-direction result and the y-direction result should be the same as LP residual stresses are theoretically hydrostatic.

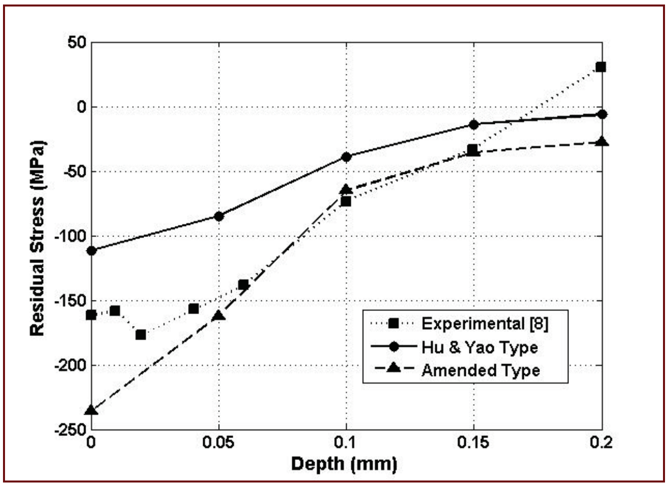

Figure 7: LP σ_x Residual Stress

When the two different versions of the symmetry cell approach are compared with the experimental results, two trends immediately appear; Hu & Yao's symmetry cell underestimates the residual stresses throughout the depth, while the amended approach agrees well with the experimental data and diverges slightly further into the depth of the model (Figure 7). The reason that the Hu & Yao type symmetry cell underestimates the residual stresses within the symmetry cell is due to the boundary conditions used: instead of infinite boundary conditions, which allow the kinetic energy to dissipate as they would in a sufficiently large plate, they have chosen to use plane-symmetry boundary conditions which continually reflect the shockwave back into the model. The symmetry cell outlined in this work allows the kinetic energy from the LP shots to travel through the adjacent material, plastically deforming applicable elements and then dissipating through the infinite boundary conditions. The Hu & Yao type symmetry cell traps the kinetic energy by reflecting the LP waves back and forth between plane symmetry conditions; kinetic energy is allowed to dissipate solely through the infinite elements located at the bottom of the model. This wave reflection causes the material to yield both upon LP impact loading and again once the wave travels back through the same region of the model: this re-yielding distorts LP residual stress field results. The Hu & Yao model has been shown to under-simulate the required infinite plate model while the new method establishes the minimum required dimensions that simulation should contain.

Conclusions

The critical distance between two sequential LP shots in AISI 1045 steel has been identified using a converged 2D FEA model at various peak pressures. These critical distances were then incorporated into a new symmetry cell creation algorithm that applies appropriate boundary conditions such that a symmetry cell could be simulated for an infinite plate with a 50% overlap raster type pattern. The pre-existing symmetry cell method developed by Hu & Yao was used to create a similarly treated symmetry cell so that a comparison to the newly created method could be made. The following is a list of conclusions that can be drawn from that comparison:

- The Hu & Yao type symmetry cell does not accurately create a symmetry cell for use on an infinite plate.
- Application of LP shots within the critical distance of a symmetry cell will affect the stresses contained therein.
- Comparison of the established method and the new method residual stress fields show better agreement between the XRD residual stresses and the new method.
- The new method represents the minimum dimensions and boundary conditions, which should be used to create, simulate, and apply an LP symmetry cell.

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