Simulation of LSP Processing in 2024-T351 Aluminum Alloy

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Abstract: This paper is entirely devoted to the numerical modeling of the LSP process. First, we introduce the parameters required for numerical simulation based on the finite element method. One of our main objectives was to describe the fluctuations (or heterogeneities) in the residual stress field induced by a single laser impact. The numerically obtained residual stress profiles show good agreement with experimental results. LSP generates a layer of compressive residual stresses on the workpiece, with a thickness that can exceed a millimeter. The stresses are generally maximal at the surface and gradually decrease in depth.

Keywords: AA2024-T351, Johnson–Cook, LSP, FEM, Residual Stress.

1. INTRODUCTION

Laser Shock Peening (LSP) has emerged as a promising surface treatment technique for enhancing the mechanical properties and fatigue life of materials, particularly in aerospace and automotive applications (Abaqus, 2014). By inducing compressive residual stresses through the generation of shock waves using high-intensity laser pulses, LSP can significantly improve the fatigue performance and resistance to stress corrosion cracking of metallic components (Fig. 1).

Aluminum Alloy AA2024-T351 is widely utilized in aerospace structures due to its high strength-to-weight ratio and excellent fatigue resistance. However, surface treatments like LSP could further enhance its mechanical properties and extend its service life. In this study, we aim to simulate the LSP processing of Aluminum Alloy AA2024-T351 using computational methods to understand the effects of processing parameters on the resulting residual stress distribution and optimize the treatment process for improved performance (Clauer et al., 1979) (Peyre et al., 1995).

The objective of this numerical simulation is to calculate the mechanical state of residual stresses induced in a structure by LSP. Therefore, we modeled a specimen representative of the fuselage structure of an aircraft based on AA2024-T351 aluminum. This thin specimen (about 2 mm thick) is treated by applying a single circular laser impact. This numerical model is developed in ABAQUS/Explicit using the same laser shock parameters already mentioned in the experimental work by (Smith et al., 2000). This model relies on the application of the Johnson-Cook behavior law.

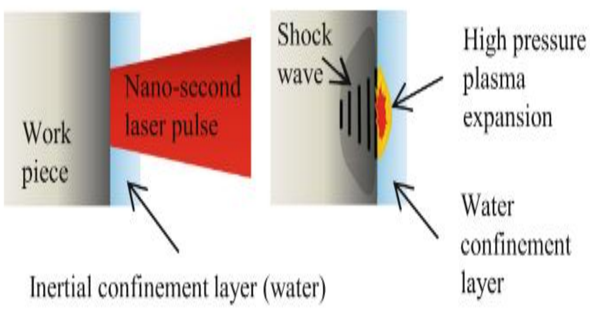

Figure 1. Schematic of the LSP Experimental steps (Ding et al., 2006).

2. TECHNICAL TREATMENT OF LASER SHOCK PEENING

Laser Shock Peening (LSP) is a specialized surface treatment technique used to induce compressive residual stresses in materials. Here are the general steps involved in the LSP process (Ding et al., 2006):

1. **Surface Preparation:** The surface of the material to be treated is cleaned and prepared to ensure proper adhesion of the peening process.
2. **Laser Setup:** A high-energy pulsed laser is focused onto the surface of the material. The laser parameters such as intensity, pulse duration, and spot size are carefully controlled to achieve the desired peening effect.
3. **Shock Wave Generation:** When the laser pulse hits the material surface, it rapidly heats a small volume of material, causing it to vaporize and create a plasma. This rapid expansion of the plasma generates a high-pressure shock wave that propagates into the material.
4. **Shock Wave Propagation:** The shock wave travels through the material, inducing plastic deformation and creating compressive residual stresses beneath the surface. The depth of the compressive layer depends on factors such as the laser parameters and material properties.
5. **Overlap Control:** Multiple laser pulses are typically applied to overlap and cover the desired surface area uniformly. The spacing and overlap of the laser shots are optimized to ensure consistent coverage and distribution of compressive residual stresses.
6. **Surface Cooling:** After each laser pulse, the material undergoes rapid cooling due to the expansion of the shock wave and the dissipation of energy. Proper cooling methods may be employed to control the temperature rise and prevent thermal damage to the material.
7. **Post-Treatment Analysis:** The treated material may undergo various analyses to assess the effectiveness of the LSP process. This can include measuring residual stress distribution, evaluating microstructural changes, and performing mechanical testing to assess improvements in mechanical properties such as fatigue resistance.
8. **Optional Surface Protection:** Depending on the application, a protective coating or surface treatment may be applied after LSP to further enhance the material's performance or provide corrosion resistance.

By following these steps, Laser Shock Peening can significantly improve the mechanical properties and fatigue life of materials, making it a valuable technique for various engineering applications.

3. MATERIAL PROPERTIES

The mechanical properties of Aluminum 2024-T351 are shown in Table 1:

Table 1. Mechanical properties of Aluminum 2024-T351

Properties	Value
Density (tonne/mm^3)	2.75E-09
Young's modulus (MPa)	72000
Poisson's ratio	0.33

The plastic properties of Aluminum 2024-T351 (Johnson et al., 1985) are shown in Table 2, based on Johnson-Cook behavior, see Equation (1):

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + ln\dot{\varepsilon}_p^*\right)(1 - \bar{T}^m)\#(1)$$

$$in\ which$$

$$\bar{T} = \frac{T - T_{room}}{T_{melt} - T_{room}}$$

Table 2. Johnson-Cook Law Parameters for 2024-T351

Material	A (MPa)	B (MPa)	n	m	T_f (K)	T_t (K)	C	ε_0 [1/s]
Aluminium 2024-T351	369	684	0.73	1.7	775	293	0.0083	1

4. BOUNDARY CONDITIONS AND LOADING

In our study, we considered the base of the specimen to be fixed (Fig. 2): U1 = U2 = U3 = UR1 = UR2 = UR3 = 0. To address the loading, we considered only the mechanical effect of the LSP process, which takes the form of a quasi-instantaneous time-variable pressure P(t). We investigated the dynamic response of the specimen subjected to a circular laser mono impact, where a spatially constant pressure-time law is applied to a section of the treated piece's surface. Fig. 3 and Fig. 4 illustrate the profile and the loading induced by LSP.

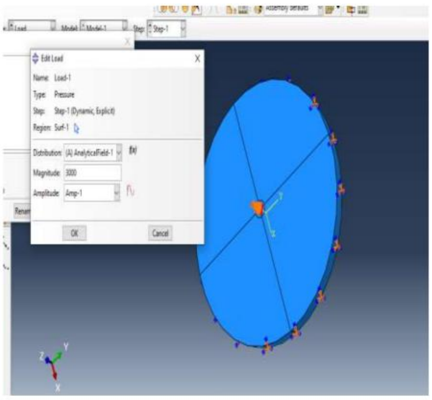

Figure 2. Boundary conditions of the specimen impacted by LSP.

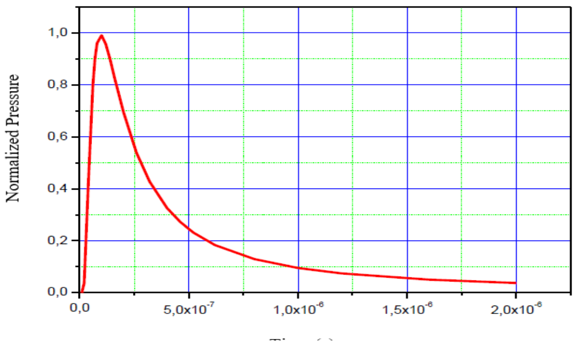

Figure 3. Evolution of the normalized pressure P=f(t).

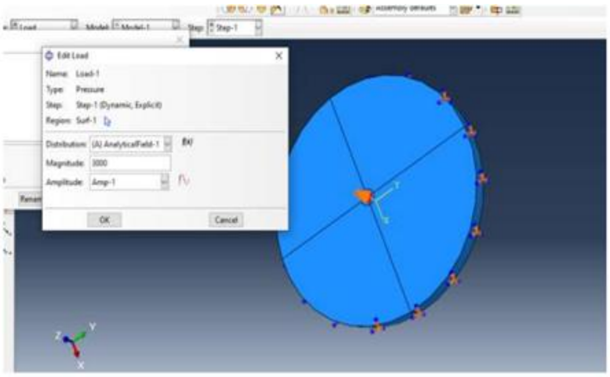

Figure 4. Loading introduced into Abaqus code.

5. RESULTS AND DISCUSSIONS

The main interest of numerical simulation of laser shock is to provide a predictive approach that allows users to optimize treatment conditions without resorting to lengthy and costly systematic experimental characterization (Song, 2010). The curves characterizing the distribution of residual stresses on the surface along the two axes of the spot, X and Y respectively, are illustrated in Fig. 5 and Fig. 6. The analysis of surface residual stresses shows that:

- Circular spots cause non-uniform surface stress along the radius of the spot, with the stress rising in the middle of the spot.
- The residual compressive stresses are localized at the center of the impact. This is attributed to the simultaneous focusing of the waves emitted from the edges of the impacted zone, leading to non-uniform surface stress.
- The heterogeneity of the residual stress field (max stress / min stress).
- The anisotropy of residual stresses is more pronounced on the Y-axis than on the X-axis.
- The maximum levels of residual compressive stresses analyzed on the surface are of the order of σ_{11}=-387MPa, σ_{22}=-454 MPa on the X-axis, and σ_{11}=-384MPa, σ_{22}=-483 MPa on the Y-axis.

In our case, in Fig. 5 and Fig. 6, we observe peaks in its amplitude due to mesh refinement in depth even though our wave is purely elastic. Therefore, we concluded that the impact edges, which exhibit a strong loading discontinuity, could lead to incompressibility in this area.

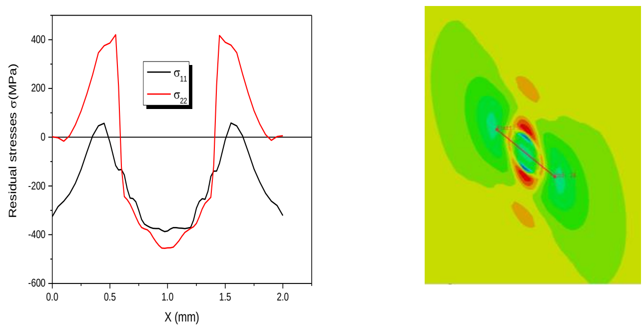

Figure 5. Distribution of surface residual stresses along the X- axis.

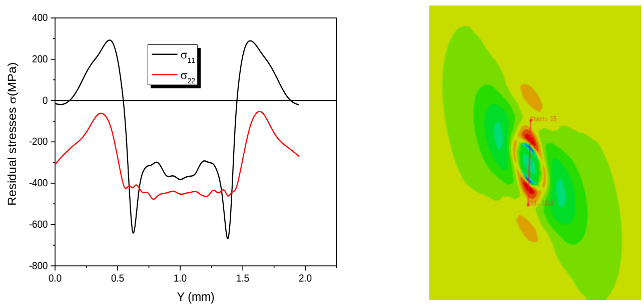

Figure 6. Distribution of surface residual stresses along the Y-axis.

A typical profile of residual stresses obtained by LSP (Frija et al., 2018) was used for the validation of our model (Fig. 7).

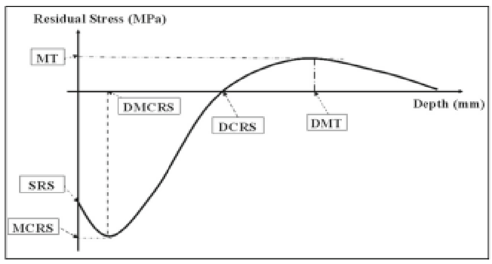

Figure 7. Typical profile of residual stresses generated by the LSP process.

With:
- **MCRS**: Maximum compressive residual stress (MPa).
- **DMCRS**: Depth of maximum compressive residual stress (mm).
- **DCRS**: Depth of compressive residual stresses (mm).
- **SRS**: Surface residual stress after laser shock (MPa).
- **MT**: Maximum tension (MPa).
- **DMT**: Depth of maximum tension (mm).

The profile of the distribution of compressive residual stresses generated by the LSP treatment exhibits two parts, one negative and the other positive. The curves characterizing the distribution of residual stresses as a function of depth are illustrated in Fig. 8. The distribution of compressive residual stresses σ_{11} and σ_{22} shows the same profile.

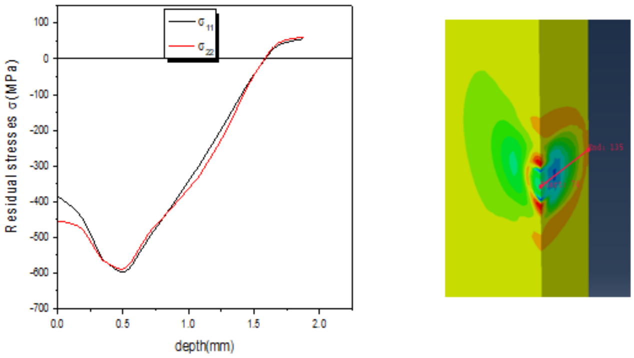

Figure 8. Distribution of residual stresses as a function of depth.

6. CONCLUSIONS

This work analyzes a specimen representative of the fuselage structure of an aircraft made from AA2024-T351 aluminum using the finite element method. This thin specimen (approximately 2 mm thick) is treated by applying a single circular laser impact with a diameter of 9 mm, a maximum pressure of 3 GPa, and a power density of 4 GW/cm². This numerical model is developed under ABAQUS/Explicit and relies on the application of the Johnson-Cook material behavior law.

The obtained results allow us to draw the following conclusions:

- The formation of residual stresses induced by LSP occurs in two stages: a) the material undergoes uniaxial indentation during the laser-matter interaction. b) After the pulse disappears, compressive stresses are created around the impacted volume.
- The laser shock generates a layer of compressive residual stresses in the piece, with a thickness that can exceed one millimeter. The stresses are generally maximal at the surface and gradually decrease in depth. The peak of maximum compressive stress is commonly found at or very close to the surface.
- Circular spots cause non-uniform surface stress along the radius of the spot, with the stress rising in the middle of the spot.
- The residual stresses at the edge of the LSP-treated zone more distinctly transition to tensile.

The stresses are maximal at the surface and gradually decrease in depth. The anisotropy and heterogeneity of the residual stress field are limited to the surface of the material to about 0.5 mm.

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