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Effects of Simulation Parameters on Residual Stresses in 3D Finite Element Laser Shock Peening Analysis

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Abstract- Laser shock peening (LSP) is an innovative surface treatment technique, which is successfully applied to improve fatigue performance of metallic components. After the treatment, the fatigue strength and fatigue life of a metallic material can be increased remarkably owing to the presence of compressive residual stresses in the material. Recently, the incidences of cracking in Alloy 600 small-caliber penetration nozzles (CRDM (control rod drive mechanism) and BMI (bottom mounted instrument)) have increased significantly. The cracking mechanism has been attributed to primary water stress corrosion cracking (PWSCC) and has been shown to be driven by welding residual stresses and operational stresses in the weld region. For this reason, to mitigating weld residual stress, preventive maintenance of BMI nozzles was considered application of laser shock peening process. Effects of parameters related to finite element simulation of laser shock peening process to determine residual stresses are discussed, in particular parameters associated with the LSP process, such as the maximum pressure, pressure pulse duration, laser spot size and number of shots. It is found that certain ranges of the maximum pressure and pulse duration can produce maximum compressive residual stresses near the surface, and thus proper choices of these parameters are important. For the laser spot size, residual stresses are not affected, provided it is larger than a certain size. Magnitudes of compressive residual stresses are found to increase with increasing number of shots, but the effect is less pronounced for more shots.

Keywords: *FE analysis, LSP (laser shock peening), residual stress.*

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Effects of Simulation Parameters on Residual Stresses in 3D Finite Element Laser Shock Peening Analysis

Ju Hee Kim [α] & Jong Woo Lee [σ]

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- Nomenclature

Le = element length

n = number of shots

$Pmax$ = maximum peak pressure

td = pressure pulse duration

tp = solution time for dynamic analysis

ts = stability time limit

xp = laser spot size

σy^d = dynamic yield strength

HEL = Hugoniot elastic limit

LSP = laser shock peening

FE = finite element

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I. Introduction

Laser shock peening (LSP) is an innovative surface treatment technique, producing compressive residual stresses near the surface and thus improving fatigue performance of metallic components [1, 2]. Through the LSP processing, the surface of the metallic target is exposed to an intense laser beam with high density (in the GW/cm2 range) for short duration (tens of nanoseconds). The thermo-protective coating (black paint or taping) is vaporized because of the high-energy laser pulse, forming a plasma that reaches temperatures in excess of 10,000 °C. An extremely high pressure (the order of GPa) on the metal surface is generated bythe extremely rapid expansion of the heated plasma [1-3]. The high pressure then propagatesinto the material interior. As a result, plastic deformation occurs and a hardened layer is formed on the surface of the metallic target, enhancing mechanical properties such as hardness, fatigue strength, and stress corrosion cracking resistance.

In the present work, effects of parameters related to finite element (FE) simulation of LSP process to determine residual stresses is discussed. Simulations were performed using the general purpose FE program ABAQUS [4].

II. FE Analysis

a) Simulation Procedures

As the LSP process involves high speed impact and dynamic wave propagation, explicit time integration FE codes need to be employed, for instance, using the ABAQUS/Explicit code [4]. There can be two approaches to simulate the LSP process. The first approach is to use explicit time integration FE codes only(procedure ②). Although this approach is relatively easy to perform, it requires long computation times. This is because calculation times should be chosen to be sufficiently long, as full development of plastic deformation in the material during the LSP process takes much longer than the duration of the pulse pressure, due to reflection and interaction of shock waves propagating in the target.

The second, more efficient, approach is to combine ABAQUS/Explicit and ABAQUS/Implicit codes (procedure ①). In this approach, dynamic analysis is firstly performed using the ABAQUS/Explicit code. When the dynamic analysis is completed, the deformed element data with all transient stresses and strains information are then imported into the ABAQUS/Implicit code to calculate residual stress fields using static analysis. For cases considered in this paper, it is found that the above two approaches give the same results, and thus the latter (and more efficient) approach is used throughout the paper.

b) Modeling Pressure Loading

Assuming a constant absorbed laser power density I_o in the confined ablation mode, the maximum peak pressure induced by plasma, $P_{\max}$, is given by [1, 2, 5-7]

$$P_{\max}(\mathrm{GPa}) = 0.01\sqrt{\frac{\alpha}{2\alpha+3}}\sqrt{Z}\sqrt{I_o} \tag{1}$$

where α is the efficiency of the interaction; and Z is the reduced shock impedance between the material and the confining layer [1, 8].

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{2}$$

Although the pressure–time history for simulating LSP is usually described using a Gaussian temporal profile, it is in fact very close to a triangular ramp because of very short pressure pulse duration (order of 100ns), as shown in Fig. 2. Thus, in this work, the pressure is assumed to increase linearly to the maximum pressure, P_{max}, and then decrease linearly for a total pulse duration, $2t_p$, as shown in Fig. 2.

c) Modeling Plastic Deformation Due to Shock Wave

As the shock wave propagates into the metal, plastic deformation occurs up to a depth at which the peak stress equals the Hugoniot elastic limit (HEL) of the material. The HEL is related to the dynamic yield strength at high strain rates, σ_y^d, according to [1, 2, 5-8]

$$HEL = \frac{(1-\nu)}{(1-2\nu)}\sigma_y^d \tag{3}$$

where ν is Poisson's ratio.

III. Sensitivity Analysis for LSP Simulation

a) Geometry and FE mesh

As a generic problem, the present work considers one-sided laser peening on an infinite plate. The impact zone is assumed to be rectangular with a half-length x_p, as schematically shown in Fig. 3a. Corresponding three-dimensional (3D) FE quarter model is shown in Fig. 3b. The FE analysis domain has a half-length x_f (which is fixed to x_f =5 mm in this work). Outside the domain, infinite elements are used to simulate an infinite plate. For the element type, the first order elements (C3D8R for finite elements and CIN3D8 for infinite elements within ABAQUS) are used.

b) Material Properties

The material is assumed to be the 35CD4 50HRC steel alloy, of which physical and mechanical properties, taken from Ref. [1], are given in Table 1. Other parameters used in simulations are;

α=0.1, Z1=3.6 106(g/cm-2s-1) and Z2=0.165 106(g/cm-2s-1) [1, 8]

c) Parameters for Sensitivity Analysis

There are many parameters possibly affecting FE simulation results of the LSP process. They can be broadly categorized into two groups. The first group includes parameters associated with dynamic FE analysis, such as the mesh size L_e, solution time for dynamic analysis, t_s, time step, Δt_s and dynamic yield strength, σ_y^d. The other group includes parameters associated with the LSP process, such as the maximum pressure, P_{max}, pressure pulse duration, t_d, laser spot size, r_p and the number of shots, n. For sensitivity analysis, the reference values for these variables are chosen, as given in Table 2.1 Each variable is then systematically varied to see its effect on simulation results.

d) Validation

Before presenting results of sensitivity analysis, the present analysis is validated by comparing with existing experimental data [9]. The material was the 35CD4 50HRC steel alloy that is the same as the one considered in the present work. Laser peening parameters (P_{max}, t_d, x_p and n) were the same as the reference values given in Table 2. More detailed information on experiments can be found in Ref. [9].

Simulated residual stresses are compared with experimental results in Fig. 4. Figure 4a compares variations of σ_x and σ_y residual stresses in the surface (at y=z=0) with distance x. Variations of σ_x and σ_y residual stresses with depth z (at x=y=0) are compared in Fig. 4b. Experimental data show that both residual stresses, σ_x and σ_y, are similar. Despite differences between experimental and simulated residual stresses, overall trends in experimental data can be 1 Note that reference values for Pmax, td, xp and n were chosen to compare with existing experimental data, as will be described in the next subsection captured by simulation.

Considering uncertainties in experimental residual stress measurement, results in Fig. 4 suggest that FE simulation of the LSP process is reliable. Figure 5 shows a 3D profile of predicted residual stresses (von Mises stress) on the surface and in the depth directions, impacted at a spot size of x_p=2.5mm.

IV. Sensitivity Analysis Results

a) Effect of the Mesh Size

It is known that FE LSP simulation results are not affected by the element size, provided it is less than about 5% of the spot size, x_p [1, 5]. The critical element size is 125 μm for the present problem. To see the effect of the mesh size, three different FE models were prepared, having the element size ranging from L_e=100 μm to L_e=250 μm, and results are shown in Fig. 6. In Fig. 6 as well as in subsequent figures, two residual stress profiles are presented. The first one is variations of the σ_x residual stresses at the surface (y=z=0) with distance x, shown in Fig. 6a. The second result is variations of the σ_x residual stresses at the center of the laser spot (x=y=0) with depth z, shown in Fig. 6b. Results in Fig. 6 confirm the existing finding that simulated residual stresses are not affected when the element size is less than 5% of the spot size, x_p.

b) Time Step for Stability

In dynamic analysis, the time step, Δt_s, should be chosen to be smaller than the stability limit for numerical stability. The stability limit can be estimated from [1, 10, 11]

$$\Delta t_s = \frac{L_e}{C_d} = L_e\sqrt{\frac{\rho}{E}} \tag{4}$$

where L_e denotes the smallest element size; C_d is the wave speed of material; E is Young's modulus; and ρ is the mass density. For the present problem, C_d= 5.193×10^3 m/s with L_e=125 μm gives $\Delta t_s \approx$5.78 ns. For the sake of space, results are not shown but simulated residual stress results are found not to be affected by the time step, provided that it is less than Δt_s, given by Eq.(4).

c) Solution time for dynamic analysis (t_s)

To obtain residual stress fields due to dynamic wave propagation by LSP, the solution time in dynamic analysis must be taken much longer than the laser duration time. Figure 7 shows dynamic stress profiles at four different times during dynamic analysis. Results show that simulated dynamic stress profiles are affected by t_s.

After t_s=2,000ns, the dynamic stress profile in the depth direction gradually becomes steady, but the dynamic stress profile at surface become steady only after t_s=5,000ns. Results suggest that the solution time for dynamic analysis should be chosen to be larger than 5,000ns, which is about hundred times larger than the pulse duration t_d=50ns.

d) Dynamic Yield Strength ($\sigma_y{}^d$)

As the strain rate during the LSP process is faster than $10^{-6}s^{-1}$, plastic deformation is determined by the dynamic yield strength, $\sigma_y{}^d$. As information on $\sigma_y{}^d$ may have uncertainty, the effect of $\sigma_y{}^d$ is investigated by varying $\sigma_y{}^d$ from 1.0GPa to 1.5GPa, and the results are shown in Fig. 8. Results show that magnitudes of compressive residual stresses decrease almost linearly with increasing $\sigma_y{}^d$, due to the fact that increasing the material yield strength tends to increase material resistance against plastic deformation [11].

e) Maximum Pressure (Pmax,, see Fig. 2)

The plasma pressure pulse induced by LSP depends on the laser power density, as shown in Eq. (1). Increasing laser power density increases the magnitude of the pressure pulse on the material surface. The plastic deformation in the material depends mainly on the HEL. No plastic deformation occurs in the material for P_{max} <HEL. The plastic strain occurs with a purely elastic reverse strain for HEL< P_{max} <2×HEL, and the plastic strain fully occurs for P_{max} >2×HEL [1, 2, 6].

To see the effect of the laser power density on residual stresses, simulations are performed for P_{max}, ranging from 2.5GPa to 5GPa, and results are shown in Fig. 9. Note HEL=2.1GPa for the present problem. Results show that magnitudes of compressive residual stresses near the surface increase with increasing P_{max} up to P_{max} =4GPa. For P_{max} =5GPa, the magnitudes of compressive residual stresses in the surface are overall smaller than those for P_{max} =4GPa.

Along the depth direction, the plastically affected zone size increases with increasing P_{max}. For P_{max} =2.5GPa and 3GPa, magnitudes of compressive residual stresses decrease monotonically. However, for P_{max} =4GPa and 5GPa, they increase near the surface and then decrease. Results in Fig. 9 suggest that the case of P_{max} =4GPa can produce optimum laser peening treatment, which is fully consistent to the existing finding that materials can be optimally treated with P_{max} = (2–2.5)×HEL range [1, 6]. Results show that the choice of the laser power density is important in the LSP process to produce desired residual stress profiles.

f) Pressure Duration (td)

In addition to the laser power density, the pressure duration is another important parameter associated with the LSP process. Figure 10 shows the effect of the pressure duration of laser pulse on simulated residual stresses. In the surface, residual stress profiles for t_d =30ns and 50ns are similar. However, for t_d =100ns, residual stresses near the center become less compressive. For t_d =150ns, they can be even tensile. Along the depth direction, the plastically affected zone size increases with increasing t_d. For t_d =30ns and 50ns, magnitudes of compressive residual stresses decrease monotonically with the depth. For t_d =100ns, they increase near the surface and then decrease. For larger t_d, such trend is more pronounced. Results in Fig. 10 suggest that the pressure duration should be chosen properly to obtain desired residual stress profiles.

g) Laser Spot Size (x_p)

To see the effect of the laser spot size, simulations are performed for various laser spot sizes (r_p) ranging from 0.5mm to 2.5mm, with the fixed P_{max}=3GPa and pulse duration of t_d=50 ns, and results are shown in Fig. 11. The affected zone size of compressive residual stresses in the surface obviously increases with increasing laser spot size. However, residual stresses in the depth direction are not affected by the laser spot size, provided it is larger than 1.5mm.

h) Number of Shots (n)

In practice, the multiple LSP process can be performed to produce more compressive residual stresses. The effect of multiple LSP process (from single to four times) on simulated residual stresses is shown in Fig. 12. In simulation, the parameters associated with the LSP process are fixed; P_{max}=3GPa, x_p=2.5mm and t_d=50ns. Multiple LSP is applied to the same area. Results show that magnitudes of compressive residual stresses increase with increasing number of shots, but the effect on residual stresses is less pronounced for more shots.

i) FE results using LSP optimal process parameters

The surface and depth residual stress distributions resulting from the optimum parameters of LSP system are shown in Fig. 13. Then optimum LSP parameters such as peak pressure (2×HEL=4.2GPa), laser spot size (2.5mm), and laser pulse duration (100ns) are used in same conditions. As shown in Fig. 13a, after one impact using optimum LSP parameters on same area, the surface residual stresses have increased remarkably. It shows that the maximum compressive residual stresses increase to about 567MPa, which is 62% higher than that for P_{max}=3GPa, td=50ns. The distributions of the depth residual stresses plotted in Fig. 13b. Along the depth direction, the plastically affected zone size(L_p) decreases to about 1.42mm, which is 136% higher than that for P_{max}=3GPa, td=50ns. Therefore, residual stresses due to the LSP optimal process parameters result in a more effective residual stress.

V. Conclusions

In the present work, effects of parameters related to finite element (FE) simulation of LSP process to determine residual stresses are discussed. Two groups of parameters are considered: one those associated with dynamic FE analysis, such as the mesh size, solution time for dynamic analysis, time step and dynamic yield strength; and the other associated with the LSP process, such as the maximum pressure, pressure pulse duration, laser spot size and number of shots.

Conclusions can be summarized as follows.

- The mesh size should be chosen to be smaller than 5% of the spot size.
- The solution time for dynamic analysis should be chosen to be sufficiently long, about hundred times larger than the pulse duration.
- The effect of the dynamic yield strength on simulated residual stresses is almost linear.
- Certain ranges of the maximum pressure and pulse duration can produce maximum compressive residual stresses near the surface, and thus proper choices of these parameters are important.
- Residual stresses in the depth direction are not affected by the laser spot size, when it is larger than a certain size.
- Magnitudes of compressive residual stresses increase with increasing number of shots, but the effect is less pronounced for more shots.

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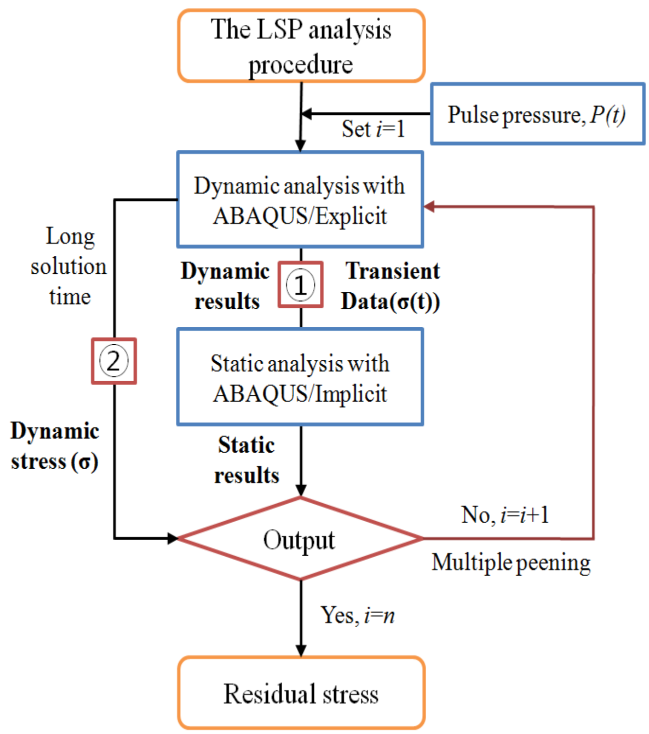

Figure 1 : Procedure of LSP simulation

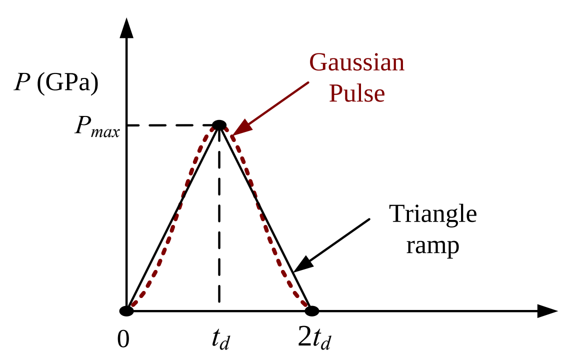

Figure 2 : Pressure-time history for LSP simulation

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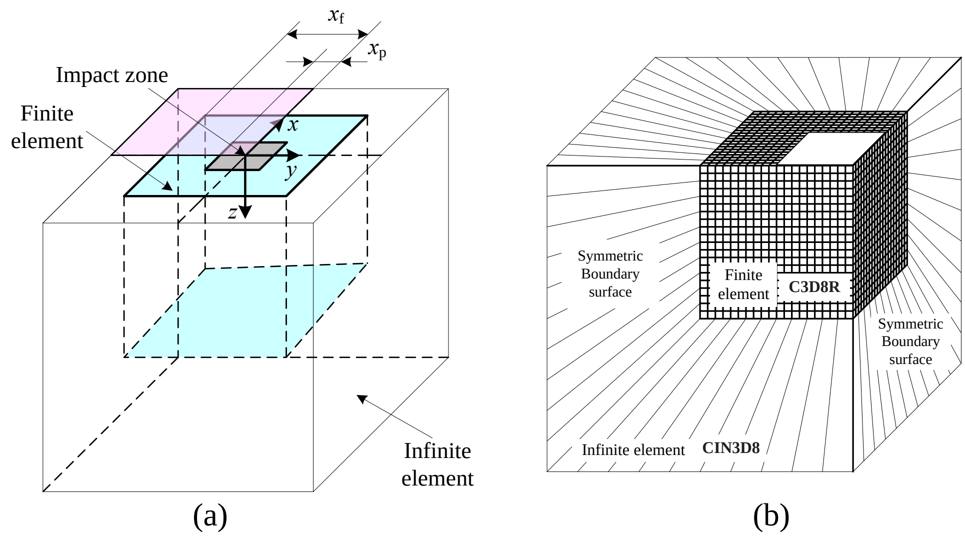

Figure 3 : (a) Geometry of LSP and (b) 3D FE mesh (quarter model)

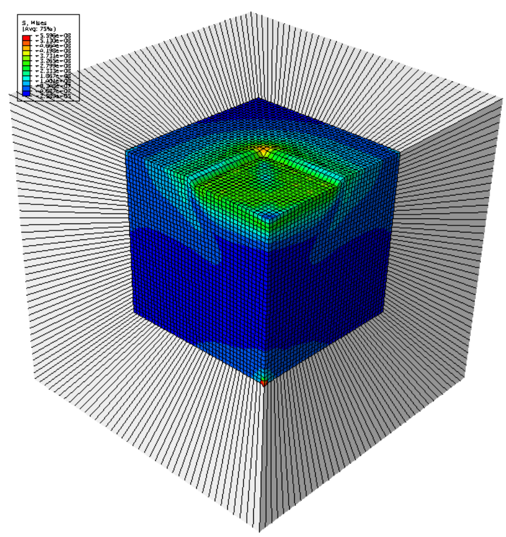

Figure 4 : Distribution of residual stresses along the surface and in depth for single LSP

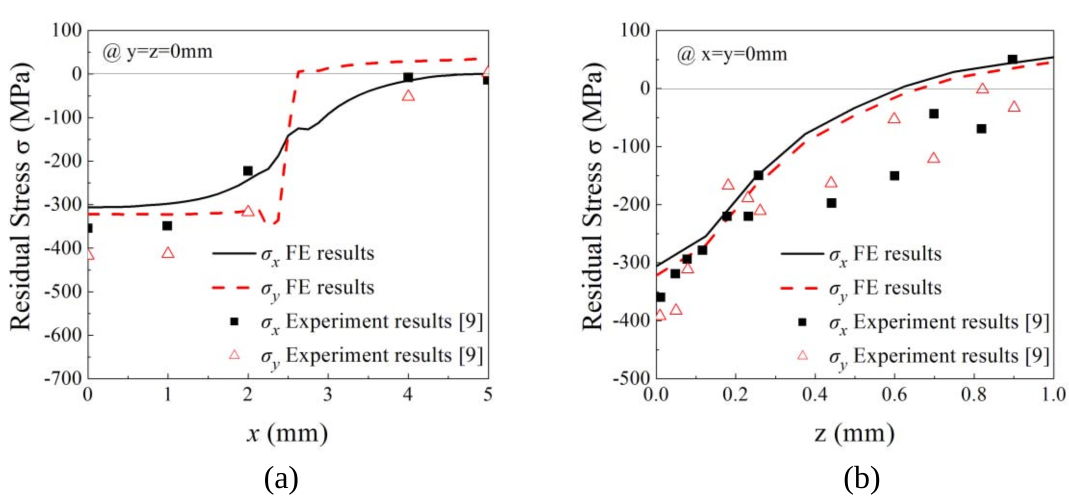

Figure 5 : Comparison of simulated FE residual stress results with experimental data [9]

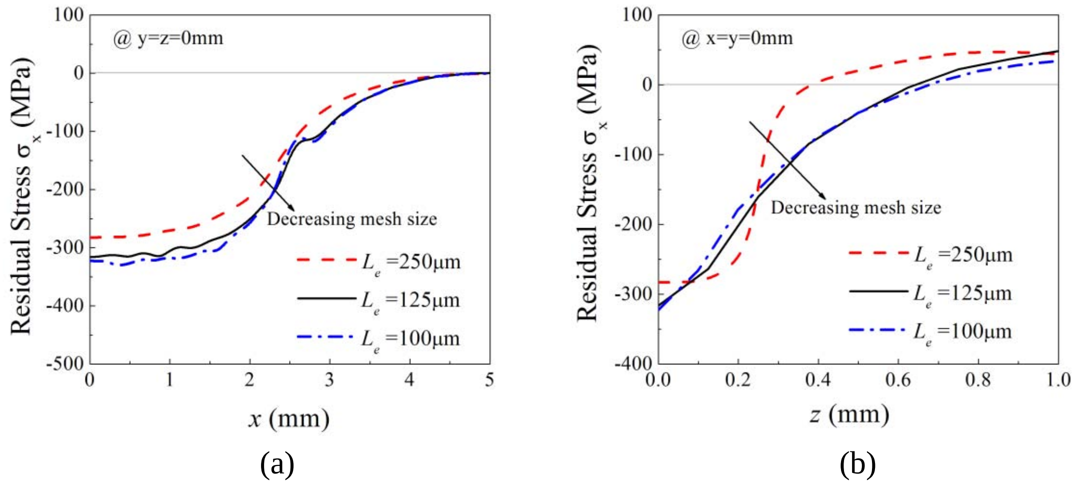

Figure 6 : Effect of the mesh size on simulated residual stress profiles

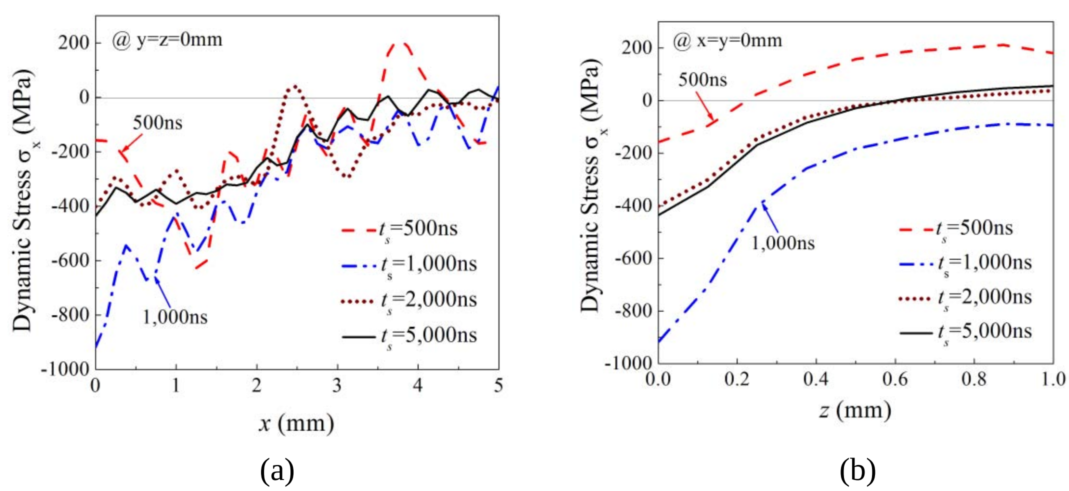

Figure 7 : Effect of the solution time for dynamic analysis on simulated dynamic stress profiles

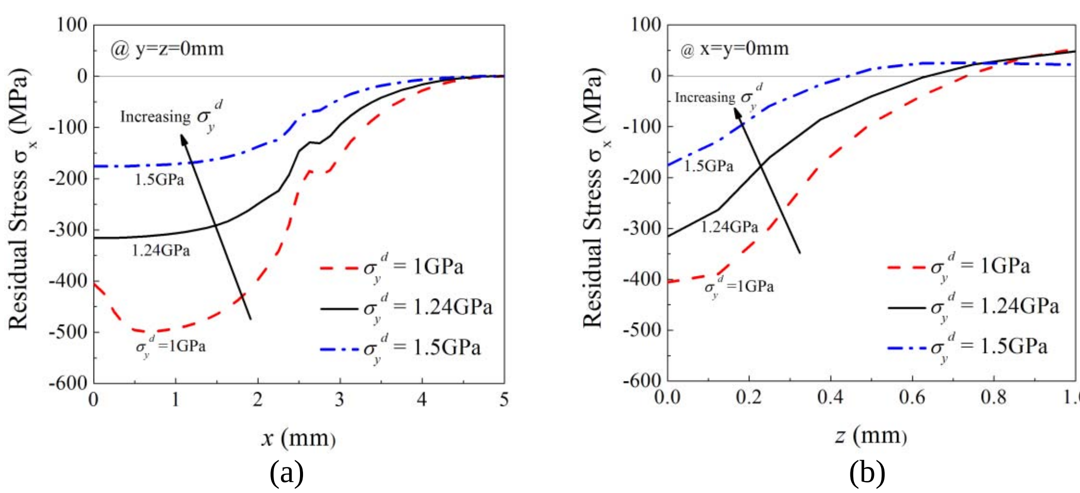

Figure 8 : Effect of the dynamic yield strength on simulated residual stress profiles

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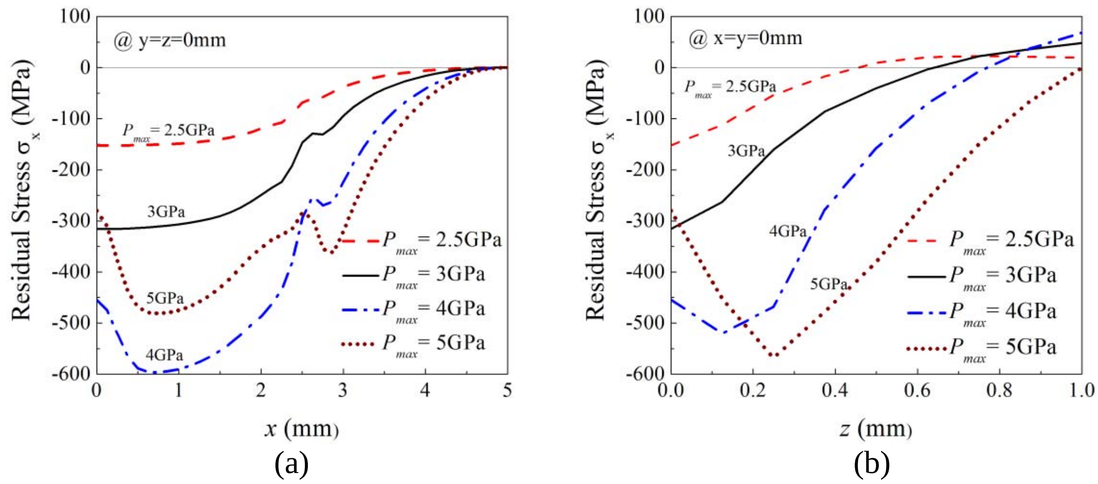

Figure 9 : Effect of the peak pressure on simulated residual stress profiles

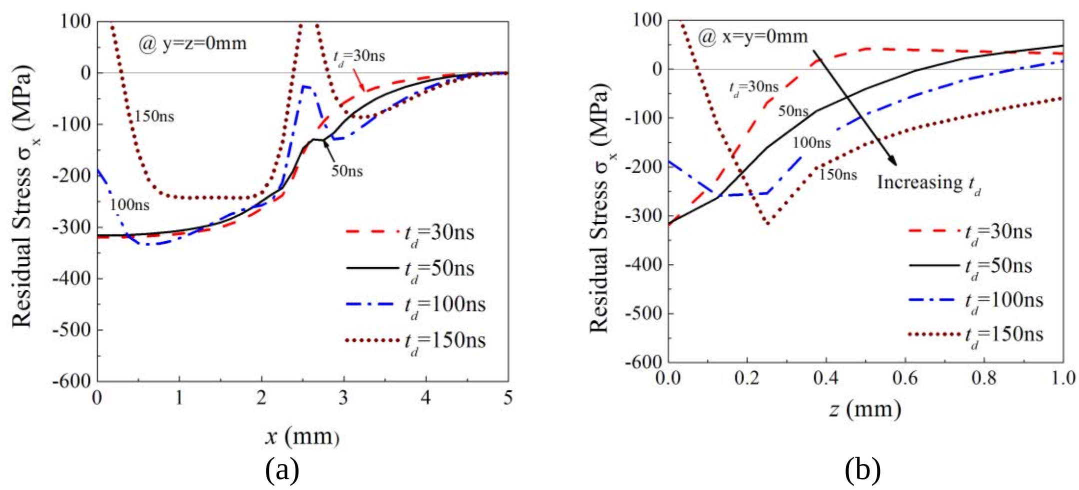

Figure 10 : Effect of the pressure durations on simulated residual stress profiles

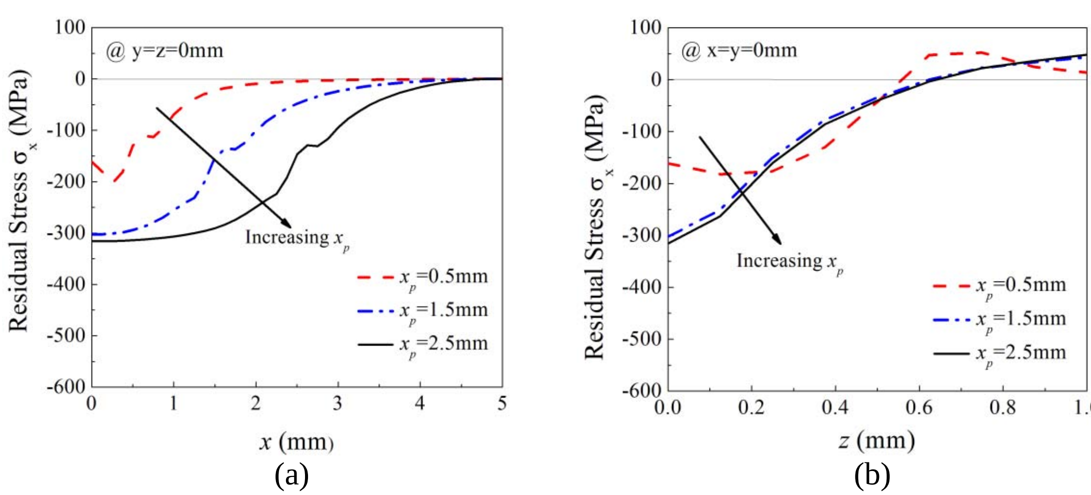

Figure 11 : Effect of the laser spot size on simulated residual stress profiles

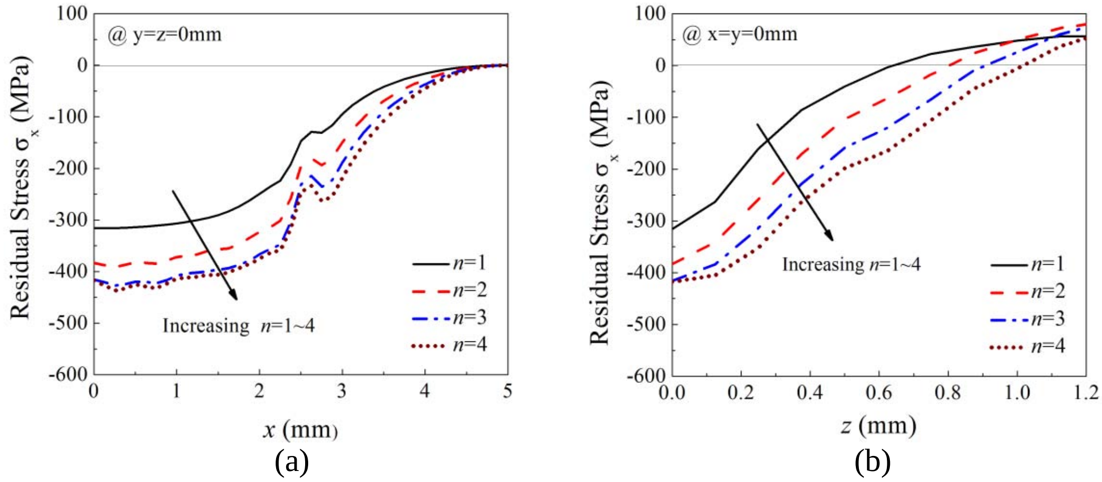

Figure 12 : Effect of the multiple laser impacts on simulated residual stress profiles

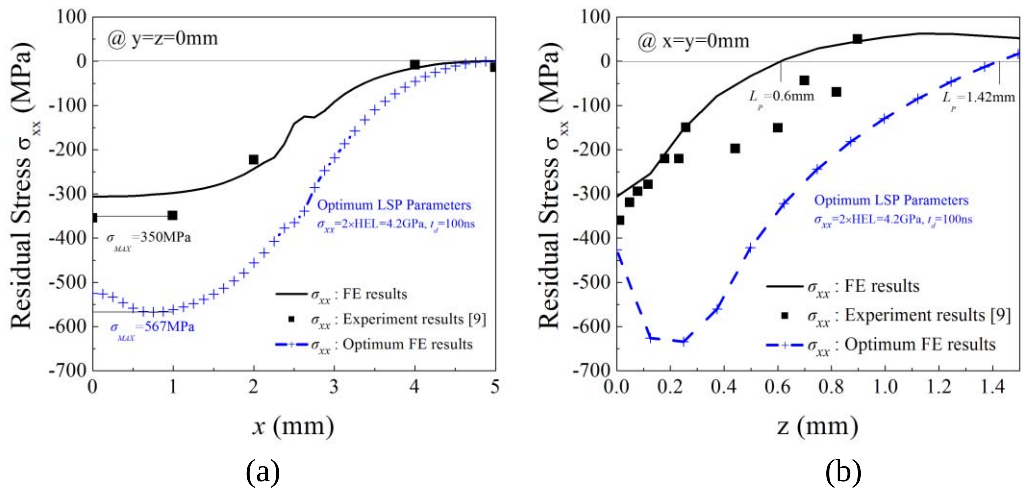

Figure 13 : Comparison of the Fe and experimental results with FE simulated results by optimum LSP parameters

Table 1 : Mechanical properties of the 35CD4 50HRC steel alloy [1]

ρ (kg/m^3)	ν	E (GPa)	σ_y^d (GPa)	HEL (GPa)
7800	0.29	210	1.24	2.1

Table 2 : Parameters and their ranges for sensitivity analysis

Parameter	Ref.	Ranges
Mesh size, L_e (mm)	**0.125**	0.25-0.1
Solution time for dynamic analysis, t_p (ns)	**5,000**	500-5,000
Dynamic yield strength, σ_y^d (GPa)	**1.24**	1-1.5
Maximum pressure, P_{max} (GPa)	**3**	2.5-5
Pressure pulse duration, t_d (ns)	**50**	30-150
Laser spot size, x_p (mm)	**2.5**	0.5-2.5
Number of shots, n (shot)	**1**	1-4

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